UNIVERSITAT DE BARCELONA

Agroecological Landscape Modelling as a Deliberative Tool

Learning from Social Metabolism Assessment of Historical Transitions to Industrial Agriculture for Future Sustainable Food System

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PhD in Economic History

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SUSTAINABLE FARM SYSTEMS

LONG-TERM SOCIO-ECOLOGICAL METABOLISM IN WESTERN AGRICULTURE

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List of Abbreviations

SFS	*International research team on "Sustainable Farm Systems: long-term socio-ecological metabolism in western agriculture"*

SFRA	*Sustainable Farm Reproductive Analysis*
ELIA	*Energy-Landscape Integrated Analysis*

HANPP	*Human Appropriation of Net Primary Productivity*
LACAS	*Land Cost of Agrarian Sustainability*
ALEP	*Agricultural Labour Energy Productivity*
AWU	*Agricultural Working Units*
EROI	*Energy Return on Investment*
FEROI	*Final Energy Return on Investment*
EFEROI	*External Final Energy Return on Investment*
IFEROI	*Internal Final Energy Return on Investment*
NPP_{act}EROI	*Actual Net Primary Productivity – Energy Return on Investment*
A-FEROI	*Agroecological Final Energy Return on Investment*

UB	*Unharvested Biomass*
LP	*Land Produce*
LFP	*Livestock-Final Produce*
TP	*Total Produce*
BR	*Biomass Reused*
FW	*Farmland Waste*
FP	*Final Produce*
LS	*Livestock Services*
LW	*Livestock Waste*
FCSI	*Farmland Community Societal Inputs*
ASI	*Agroecosystem Societal Inflow*
Lb	*Labour*
FCI	*Farmland Community Inputs*
EI	*External Inputs*
TIC	*Total Inputs Consumed*

DU	*Domestic Unit*
MRU	*Minimum Reproduction Unit scenario*
PRU	*Peasant Reproduction Unit scenario*
MSS	*Maximum Specializated Surface scenario*

CD	*Current Diet scenario*
HD	*Healthy Diet scenario*
MO	*Maximizing Output scenario*

ME	*Metabolizable Energy*
CP	*Crude Protein*
CAP	*European Unions' Common Agricultural Policy*
SM	*Social Metabolism*

Publications derived from or linked to this PhD thesis

Three Chapters of this PhD thesis have been originally published or submitted in the following journals and international publishing companies included in the Web of Science.

- Chapter 3: Marull, J., Font, C., **Padró, R**., Tello, E., Panazzolo, A. (2016). Energy-Landscape Integrated Analysis: A proposal for measuring complexity in internal agroecosystem processes (Barcelona Metropolitan Area, 1860-2000). *Ecological Indicators* 66: 30–46. https://doi.org/10.1016/j.ecolind.2016.01.015. [JCR IF: 3,898; Q1 in Environmental Sciences].
- Chapter 4: **Padró. R**., Marco, I., Cattaneo, C. Caravaca, J., Tello, E. (in press, last proofs corrected in November 2017). Does your landscape look like what you eat? In: Fraňková, E., Haas, W., Singh, S.J. (eds.), *Socio-Metabolic Perspectives on the Sustainability of Local Food Systems Insights for Science, Policy and Practice*. New York: Springer International Pub., Human-Environment Interactions Series num. 7, pp. 133-164. https://doi.org/10.1007/978-3-319-69236-4_5, ISBN: 978-3-319-69235-7.
- Chapter 6: **Padró, R**., Marco, I., Font, C., Tello, E. (submitted in 2017 and in review). Beyond Chayanov: A Sustainable Farm Reproductive Analysis of Peasant Domestic Units and Rural Communities (Sentmenat; Catalonia, 1860). *Ecological Economics*. [JCR IF: 2,965; Q1 in Economics and in Environmental Studies].

During the elaboration of this PhD thesis I have also co-authored the following articles published in journals included in the Web of Science, which are tightly linked with my research in the International SFS research project.

- Tello, E., Galán, E., Sacristán, V., Cunfer, G., Guzmán, G.I., González de Molina, M., Krausmann, F., Gingrich, S., **Padró, R**., Marco, I., Moreno-Delgado, D. (2016). Opening the black box of energy throughputs in farm systems: A decomposition analysis between the energy returns to external inputs, internal biomass reuses and total inputs consumed (the Vallès County, Catalonia, c.1860 and 1999). *Ecological Economics* 121: 160–174. https://doi.org/10.1016/j.ecolecon.2015.11.012. [JCR IF: 2,965; Q1 in Economics and in Environmental Studies].
- Galán, E., **Padró, R**., Marco, I., Tello, E., Cunfer, E., Guzmán, G., González de Molina, M., Krausmann, F., Gingrich, S., Sacristán, V., Moreno-Delgado, D. (2016). Widening the analysis of Energy Return On Investment (EROI) in agro-ecosystems: socio-ecological transitions to industrialized farm systems (the Vallès County, Catalonia, c.1860 and 1999). *Ecological Modelling* 336: 13–25. https://doi.org/10.1016/j.ecolmodel.2016.05.012. [JCR IF: 2,363; Q2 in Ecology].
- Tello, E., **Padró, R**., Font, C., Marull, J. (2016). Los paisajes agrícolas, forestales y ganaderos: una herencia histórica (1850-2000). *Estudios Rurales*, 11 (6), 184-204. http://ppct.caicyt.gov.ar/index.php/estudios-rurales/article/view/10900. [Incluida en Latindex, Cuartil D de Ciencias Sociales CIRC Ec3 metrics].
- Olarieta, J.R., **Padró, R**. (2016). Investment in landesque capital in semiarid environments: dry-stone terraces in Les Oluges (La Segarra, Catalunya). *Annales Series Historia et Sociologia*, 26(3): 487-498. http://zdjp.si/annales-series-historia-et-sociologia-26-2016-3/. [SJR Scimago IF: 0.15; Q2 in History, Q3 in Social Sciences (miscellaneous); incluida en la lista ERIH Plus de la European Science Foundation].
- Cervera, T., Pino, J., Marull, J., **Padró, R**., Tello, E. (2017). Understanding the long-term dynamics of Forest Transition: From deforestation to afforestation in a Mediterranean landscape (Catalonia, 1868-2005). *Land-use policy*, published on-line first.

https://doi.org/10.1016/j.landusepol.2016.10.006 [JCR IF: 3,089; Q1 in Environmental Studies].

- Marco, I., **Padró, R**., Cattaneo, C., Caravaca, J., Tello, E. (2017). From vineyards to feedlots: A fund-flow scanning of sociometabolic transitions in the Vallès County (Catalonia) (1860-1956- 1999). *Regional Environmental Change*, published on-line first. https://doi.org/10.1007/s1011 [JCR IF: 2,919; Q2 in Environmental Sciences].
- Gingrich, S., Marco, I., Aguilera, E., **Padró, R**., Cattaneo, C., Cunfer, G., Guzmán Casado, G., MacFadyen, J., Watson, A. (2017). Agroecosystem energy transitions in the old and new worlds: trajectories and determinants at the regional scale. *Regional Environmental Change*, published on-line first. https://doi.org/10.1007/s10113-017-1261-y. [JCR IF: 2,919; Q2 in Environmental Sciences].

CHAPTER 1. WHY THE AGROECOLOGICAL TRANSITION IS A NEED AND MUST BE COLLECTIVE

1. A brief personal justification of the road towards the commitment for agroecological landscapes

1.1 A mistake or an unconventional path?

A forestry engineer teaching history lessons in a faculty of economics seems either a mistake or the beginning of a joke. This is what I thought when they told me I had been awarded with a four-year fellowship to do my PhD in a research group on Sustainable Agrarian Systems at the University of Barcelona (UB).

After a while, I realized that it was not a mistake. It probably has a strong random component. But when I entered the research group of Barcelona, at that time formed by the nucleus of Enric Tello, Elena Galán and Inés Marco, I started tying up loose ends. They were a historian, an environmental scientist and a feminist economist. However, the elements they shared were much more decisive than differences: a common goal, a desire to work together and, above all, humanity, essential to be able to satisfy the two previous elements.

Thus, from January of 2014 I became part of this team. There inside, main research they were already developing was rethinking energy balances in agriculture in historical perspective to analyze the socio-ecological transition of organic societies to industrials. They draw from an initial study of Cussó et al. (2006) and Tello et al. (2008) done in four municipalities of the Vallès County (Catalonia, Spain). Nevertheless, at that time the challenge completely exceeded the area of study.

Before my arrival, the team led by Enric Tello integrated into an international proposal. Its main goal was creating a conceptual and methodological framework that would allow comparable studies of sociometabolic balances in agriculture in historical perspective. All this in order to understand the transition on a global scale and to figure out its driving forces, both social and environmental. The project, funded by the Social Sciences and Humanities Research Council of Canada, takes the name *Sustainable Farm Systems: long-term socio-ecological metabolism in western agriculture* (SFS from here on).

Therefore, the work team becomes a matter of scale. During these four years, we have shared the day in the UB with the initial team and with new colleagues (Claudio Cattaneo, Lucía Díez, Andrea Montero, Marc Maynou and Álex Urrego). But within the Barcelona group itself, there is also constant collaboration with the Institute of Regional and Metropolitan Studies of Barcelona. In this second part of the team, we have been working on relating landscape ecology and energy balances in agriculture, mainly with Joan Marull, a biologist, and Carme Font, a mathematician. An increasing complexity of the work team.

However, there is also a logical scale jump. Within international collaboration, debates have also been fundamental to advance. In annual meetings and congresses with the rest of members of the Andalusian, Austrian, Colombian and Canadian teams, we have shared, debated, backed down when it was necessary and, finally, agreed with an important part of methodologies used in the first part of this thesis (Chapters 2 to 4).

The thesis I present below then has a strong collective component, especially in the first part, but also in the second has been essential to be able to develop some proposals. Thus, it is difficult at some moments to discern between individual work and what is fruit of a collective scientific process. That is why I try to be as honest as I can separating, when possible, individual contributions of collective ones, noting in each chapter these in the beginning.

In order to understand my personal contribution I also want to make some notes about my individual trajectory, to go deeply into the reason for the research I will present.

1.2 The personal scale in a collective project

A collective path is fruitful and synergistic as long as it is not a mere sum of individualities. In scientific research, as in any area of life, it is necessary to share common spaces in order to make possible this synergy. These common spaces are just some core ideas that allow knowing that you are working under a similar goal, trying not to fall into apriorisms because of this.

I personally consider that science alone is difficult to be a common space. Science is nothing more than a set of practices designed to gain knowledge about principles and causes of facts. The question is why we want to do science, under what objective. What intentionality behind science is, as we will see later. This is a subjective question about world's vision. A subjective position, however, that should always be based on deep scientific foundations and a materialistic analysis of reality.

As expected, with the largest part of our team we share common spaces. This space is the conviction that current crisis in its broadest sense demands rethinking foundations of society's functioning. Both internally and in the way societies relate to nature. A common space in which we are not alone, but is the main frame of the Strong Sustainability Science.

However, these common spaces, when they meet together, are result of the path that each one has traveled. That is why I think it is necessary to explain my path, trying to limit myself to what might be useful to make me understand. Unraveling the driving forces that lead me to do research, led me to become part of the SFS team at the University of Barcelona and carried me to the commitment of the *Sustainable Farm Reproductive Analysis* models (SFRA from now onwards), which occupy the second block of the thesis (from chapters 5 to 7).

At the University of Lleida, where I studied Forestry and a Master's Degree on Soil and Water Management, in 2007 I started working with the soil scientists Jose Ramón Olarieta and Rafael Rodríguez. There, I participated as a scholarship holder in a first research on the role of *'formiguers'* as historical fertilization practices. In UdL and together with these two professors I learned the foundations of relations between society-nature regarding the impact they have on soils. Because of this research, and the subsequent work initiated in energy balances, I contacted with the UB group. This is therefore a fundamental and formal point of entry into research.

Nevertheless, I forged my interest in the study of organic societies throughout the period of doctoral thesis, both inside and outside university. At that time, I began to participate in movements and collectives for Food Sovereignty, such as Terra Franca. There we work for access to land in Catalonia. As well, I collaborated in the creation of a local organic consumer cooperative. These truly dialectical processes, between social and scientific life, are which gradually bring me to realize this need for effective proposals to solve current ecological crisis. At the same time, my engineer training demanded to ask myself if developing certain territorial planning tools could facilitate these processes for solving the crisis. It is not about creating anything new from science, but seeing how we can establish some synergies between what already exists and see what the limits of what is possible.

The historical perspective of this thesis, born with the need to understand past paths. To see how, indeed, history matters in the process of transition towards solving the current impasse

(Tello, 2005). Teaching some world history classes within university, with the training process it requires, has also been essential. Although I am aware of my short training in this discipline, which is often overwhelming for myself, I have tried to respect it. It has become for me, a tool that I use from an applied history's point of view to make some first steps in modelling of agrarian systems. However, it was a fundamental lesson to understand how societies choose their way, breaking with the mechanistic visions and willingness to control that we often have the engineers.

Finally, the third branch I have met throughout my PhD has not been trivial. Economics are something that shine for its simplicity in engineering. The chances to deepen it with participation in seminars and classes of the Master's in Economic History have given me an insight, still little consolidated but sufficient to begin to unravel the fundamental reasons. Likewise, participating in the Seminar on Critical Economy *Taifa* allowed me to learn in critical analysis. Together with the generosity of colleagues from UB, and especially to Enric Tello and Inés Marco, I was able to complement progressively my economic knowledge with the discovery of views on reproductive economics.

Finding the link between forest engineering, history and economics, can be a problem when not having a systemic vision on how are they interrelated. However, humbly, I believe that during the process of doctoral thesis, I have seen some connections, thanks to all the learnings Therefore, I tried to take some steps to make them converge. As a personal process above all, but I hope that it is also, as small steps, as a scientific process.

1.3 A dialectic path, and therefore non-linear

Therefore, as you can see, in the process of entry and development of this thesis I did not follow a conventional sequence. This means strengths and weaknesses. Obviously, this is not a thesis where I initially considered a fundamental theoretical framework and the application of a specific methodology to some case study, as is now happening in most PhD. Therefore, I developed the learning of the theoretical framework in several phases. However, I strongly wanted to maintain a chronological structure in this compilation. Therefore, throughout the thesis, some approaches change, or I later develop some parts that in first chapters can be less treated.

The first year and a half, together with Inés Marco, we worked on the re-elaboration of energy balances within the socio-ecological transition of advanced organic agricultures to industrial for a case study (chapter 2). This will be a test bench for methodological proposals throughout the doctoral thesis: four municipalities of the Vallès County (Sentmenat, Castellar del Vallès, Caldes de Montbui and Polinyà). Due to its richness in historical sources and previous studies, it is an ideal bench test. This basis of energy balances, in a debate proposed by the colleague Eva Fraňková on the significance of this transition in terms of food systems, allowed us to move forward later in understanding the relevance of agroecosystems as elements that guarantee satisfying needs for society (Chapter 4).

After completing this first phase, during the second year, I spent most of time on the research corresponding to Chapter 3, in which we made efforts to link energy balances with landscape ecology, proposing what we called the *Energy-Landscape Integrated Assessment*.

As of this moment, due to debates on biophysical limits of organic societies, I started working on a reproductive model: the *Sustainable Farm Reproductive Analysis* (Chapters 5 to 7). Here, the initial driving aim came through a debate on agro-silvo-pastoral mosaics. The first question was what distribution of land-uses, in 19th century, would guaranteed sufficient land for the closure of metabolic cycles on food, nutrients and livestock? Moreover, the following question was which agro-silvo-pastoral mosaics in future to allow recovering a rationalized and efficient social metabolism do we need? In short, can we infer how the structure of sustainable agrarian systems should be?

From here, I started a path with collaboration of the rest of colleagues, including Mar Grasa, Carme Font, Enric Tello and Inés Marco. Thus, we were able to approach a methodology that would allow solving some scientific obstacles reaching a first proposal to define horizons of agroecological landscapes.

As we will see, this thesis has a strong methodological component. I think these are the biggest contributions I made. Based on these new methodologies I tried to reach some results and conclusions, confronting them with debates of corresponding disciplines. In some cases, I think that in a more successful way, in others there is probably still a lack of knowledge on the field. This is possibly one of the weaknesses of carrying out systemic studies, which face multiple disciplines and scientific approaches. Nevertheless, precisely if we do not confront science to solve systemic problems, we are condemned to keep us in a partial vision.

2. First notes on the object of study and foundations of the scientific approach

In this previous section, I wanted to raise the personal and collective interest of research. From the following chapter we present theoretical developments, methodologies and results of this doctoral thesis. It is therefore clear that main interest of this thesis is studying agrarian systems. Moreover, we want to do it from a systemic vision that allows tracing paths as society in order to solve the current situation.

In the rest of sections of this chapter I want to present the current state of the object of study and challenges that science of strong sustainability has as an epistemological approach. Thus, later, in section 3, we will present some plausible goals in which to contribute in this doctoral thesis.

2.1 The object of study, agrarian systems

2.1.1 *The path of traditional organic societies until the Green Revolution*

Within the range of relations established between society and nature, agricultural activities imprinted the major impacts on territories, at least until the beginning of last century (Krausmann and Fischer-Kowalski, 2013). We understand as agrarian activities all those that suppose a direct interaction with elements of biosphere in order to obtain organic products useful for society. Therefore, in its entire spectrum of possibilities, this implies several productive subsystems: agriculture, livestock, forestry and fishing. We left fishing out of the object of our study, because we focus on territorial agrarian systems, and not on water bodies.

From a thermodynamic point of view, we can understand that historically these agricultural activities worked as perfect machines for society. In these, through the introduction of human labor, farmers obtained more energy than invested in the process. This is thanks to the ability of plants to fix solar radiation and of human labor to increase storage of energy on the ground and on other elements of agrarian systems, thus retarding the inevitable final increase of entropy (Podolinsky, 1880). This is the Podolinsky's principle, who raised a deepening from the thermodynamics to the proposal of the theory of value proposed by Marx (Martínez Alier and Roca, 2006).

Agricultural activities, before the great transformation of the Green Revolution, were mainly circumscribed within biophysical capacities of local areas. Constrained by a whole series of physical, chemical, biological and social factors that kept a certain balance. As we will see throughout the thesis, this balance could be higher or lower. However, there was always a multidirectional relationship between all elements of agrarian systems (people, livestock, soils, plants). Indeed, we will see this was a fundamental property for its functioning.

This relationship, which linked different activities in the territory, conformed cultural landscapes, as an expression of the relationship between society and nature. In the Mediterranean systems that happened in the form of agro-silvo-pastoral mosaics, in which the key point was the relation of each piece of the territory among others (Antrop, 2005; Krausmann, 2004; Margalef, 1991).

We do not intend to idealize this situation in the nineteenth century, in the context of advanced organic agricultures (Wrigley, 2006). In the European countries, this balance of agrarian activities with nature cope with class societies with strong inequalities among them. If we focus on the analysis in the region of Catalonia, northeast of the Iberian Peninsula, an important part of population suffered from the 17th century a progressive process of proletarianization. They lose most part of collective and individual ownership of the means of agrarian production (Garrabou, 2006). Therefore, although it is interesting to analyse these historical processes from environmental history, we must not forget about its social dimension when it comes to considering possible outputs to current situation.

During the 18th and 19th centuries, in Catalonia there were significant changes at the social and technical level of agriculture. For the first time since the Roman era, we observe relevant technical changes, such as introduction of new crops or a growing productive specialization between regions encouraged by improvement of communications. But all these agricultural technical changes were made in a relatively progressive way (Tarradell et al., 1983).

The turning point that really broke with the previous paradigm explained of agrarian systems did not become until the second half of the 20th century. More than a transition, we can call it a revolution, for the brief period of time in which it developed. As of the 60-70s, in Spain, there has been an unprecedented change in agricultural systems. Massive diffusion of fertilizers, biocides, mechanization and introduction of new varieties, both plant and animal, together with an energy transition that offered large amounts of fossil fuels, endowed a true technological revolution, under the name of "Green Revolution".

2.1.2 *Impacts of the Green Revolution and the demographic explosion on agrarian systems*

From the Green Revolution, agriculture went from being a provider to a net energy consumer (Pimentel et al., 1973). It is key in all this, the process of energy transition from organic sources, such as wood, to fossil fuels, which began at the end of 19th century. Indeed it is revolutionized as of 1950s with an exponential increase in oil consumption (Gales et al., 2007).

This meant a radical change on the elements with which society interacts with environment. It went from an agricultural production limited mainly by biophysical potential of territories, to an increased production through exploitation of stocks, like fossil fuels. In addition, this effect in agriculture was true as well for livestock and forestry. That reality confronted with what Georgescu-Roegen (1971) considered that agricultural activity should be, i.e., *not only production of useful biomass but also reproduction of the elements required to produce it*. Agrarian systems, through the subsidy that supposed oil, undergone a substitution of ecological processes by external inputs and a certain disregard for the elements that take part of them.

In a context of global crisis in the Cold War, with a world divided into two major blocs (capitalist and communist), the US and European allies, raised the Green Revolution as an alternative to Red Revolutions (Picado, 2011). Thus, this process of technological change promised feed the world without the need to transform functioning of capitalism and its institutions. This would be possible with a process of replacing traditional organic practices through importation of external inputs into agriculture. This, on the one hand, led to a large increase in global agricultural productivity, and a consequent fall in prices of agricultural products. However, on the other hand led to strong environmental and social impacts. Fifty years later, the Green Revolution has not been able to end world hunger, despite having enough food for everyone (FAO, 2017).

In this process of intensification of agricultural activities, we must sum an increase of pressure on natural resources derived from an explosive tendency of population density worldwide. It increased by 1.53 between 1900 and 1950 and by 2.41 in the last half of 20th century. Although at the European continent this increase was not so pronounced, over last century, it went from a density of 42 to 72 inhabitants/km^2, increasing to 75% the share of population that lives in cities, together with the increase of urban areas and infrastructures (Klein Goldewijk et al., 2010).

All this has involved a transformation in society-nature relations. This is what we call a socio-ecological transition, in which consequences on a global scale are unsustainable. Meadows report (1972), in light of the first oil crisis, already pointed out this. They indicated that if we maintained *trends of growth in population, industrialization, pollution, food production and exploitation of natural resources without variation, the absolute limits of Earth's growth would be achieved over the following 100 years*. Obviously, not all these consequences came from agricultural activities, but they play a very important role.

Forty years later the tendency, as well as the obsession of orthodox economists, continues to be sustained growth. Global impacts on agrarian systems have led to a profound transformation of land-use, alteration of biogeochemical cycles, an untenable increase in the use of continental waters and a marked loss of biodiversity (Foley et al., 2005; Vitousek et al., 1997b).

In terms of biogeochemical cycles, on the one hand changes in nitrogen cycles made it much more available and circulating (Vitousek et al., 1997a). Something very pronounced in Spain, especially with massive importation of external products (Lassaletta et al., 2014). This represents a strong risk of eutrophication and destruction of habitats (Tilman et al., 2001). On the other hand, phosphorus cycles are much more restrictive, and some researchers observed that on a global scale 50% of phosphorus annually circulating is lost, which largely ends in seas and oceans (Liu et al., 2008).

We cannot understand all these tendencies without the change of scale of agrarian processes. Globalization has led to a brutal increase in circulation of biomass, which increased by 5 between 1962 and 2010 (Mayer et al., 2015). According to this report, most lands transformed to agricultural uses into South Global countries have done so with the objective of exporting their agricultural products. Thus, Spain is now a net importer of biomass. These flows have multiplied by 12 in the last four decades of the 20th century (Soto et al., 2016).

Moreover, in Catalonia, together with energy transition, these processes also had strong impact on forests. Farmers, even before the Green Revolution, abandoned marginal areas of cultivation. In turn, forestry activity has dramatically diminished from the 50-60s onwards. This has led to an increase in forest fires and disappearance of agro-silvo-pastoral mosaics (Cervera et al., 2017; Marull et al., 2015).

We consider essential understand how these processes happen to analyse the driving forces in these socio-ecological transitions and the bottlenecks in changes. As we can see, causal relationships are multiple and difficult to face if we do not use a systemic perspective, with tools that allow us to identify these changes together.

2.1.3 *Current challenges of agrarian systems*

Therefore, increasing food demand, together with global environment deterioration, raises the challenge of designing more sustainable agricultural systems capable of maintaining food production within appropriate biophysical limits to guarantee ecological functions.

There are growing claims so as to relocate agri-food chains to advance towards agroecosystems' sustainability (Sayer et al., 2013), and to rethink land-use planning and rural development programmes linked to nature conservation policies (Stoate et al., 2009). New plans and programmes addressed to tackle this current food-biodiversity dilemma require new indicators and models to combine all these dimensions and approaches.

The European Union is a society with a high population density and high socioeconomic pressure for its high level of consumption (Giampietro, 1997). Thus, reducing environmental impacts of its agricultural production is a fundamental challenge. However, the European Unions' Common Agricultural Policy (CAP) is not responding to these needs. Those policies suppose a growing consolidation of unequal North-South global relations (Fritz, 2012), dependence on external inputs, and impoverishment and lack of resilience of local agrarian systems. We believe that policies should face global agrarian systems in order to be able to respond these challenges. Instead, CAP maintains a perspective of high intensity and subsidized agriculture, which is consistent with a global food regime, based on the criteria of capital accumulation, which confronts with growing local strategies that are posed as to alternatives (McMichael, 2009).

Among these alternatives to the current global food regime, the one has had a greater spread and route, thanks to La Vía Campesina, is Food Sovereignty. This proposal aims to reverse processes of globalization on food system, in order to guarantee the right of people to culturally and environmentally sound food and a decent life for farmers (Levidow et al., 2014). The proposal of Food Sovereignty, from a certain moment, assumes agroecology as a paradigm from which to make this transformation (Altieri and Toledo, 2011; Silici, 2014). This means to resemble anthropic processes in agrarian systems to own ecological processes of natural ecosystems of those bioregions (Gliessmann, 1998). Therefore, understand how these systems worked in past, can give us keys to rethink current challenges.

However, the proposal of Food Sovereignty may often remain as an ethereal claim, where aspects such as relationship between distance and food sovereignty, role of food deficit regions or scales of management are not resolved (Edelman et al., 2014). In the same way that with agricultural policies like the CAP, we need novel methodologies and indicators for advance towards resolution of these questions. In any case, in order to design how we can make this transition towards sustainable agrarian systems, we consider agroecology as the paradigm, but we must take into account both the scale, ecological, institutional and social challenges that it poses (De Schutter and Vanloqueren, 2011; Duru et al., 2015).

2.2 Scientific approach

2.2.1 *The Strong Sustainability Science*

Addressing the social and scientific challenge of identifying how we can move out from inefficient industrialized agrarian systems towards sustainable agrarian systems requires then a systemic approach.

Strong Sustainability Science, as a multidisciplinary field, born with the objective of working together from various scientific disciplines to break partial approaches and find solutions to the ecological crisis (Martínez Alier and Roca, 2006). It is not about making a pyramidal science, but about coordinating efforts from different scientific paths, as Otto Neurath already said at the beginning of the 20th century (Martínez Alier, 1987).

A fundamental principle of this science is that it does not admit substitutability of all the elements that participate in productive processes as Neoclassical Economics do. On one hand, Weak Sustainability, through the methodology of cost-benefit analysis with Environmental Economics, also assumes that in a productive process in relation to nature, work, natural resources and capital are substitutable. On the other hand, science of strong sustainability, with Ecological Economics as paradigm for calculation, founded the principle that different elements that participate in any productive process are not commensurable. That is, we cannot use uniform units for calculations among them.

This means that we have to analyze separately the different effects that a process involves, from different units and even different scientific approaches, in order to take a decision. In addition, this decision must be of a social and non-technical nature. Thus, Ecological Economics proposes to assess the process that generates a lower impact or is more beneficial in terms of the interaction between society and nature with a multi-criterial perspective.

2.2.2 *Deliberative processes*

This last element, the non-comparability with a single unit of measurement of different elements that participate in the production in agrarian systems, is fundamental and has strong methodological but also social implications. Assuming complexity of functioning of agrarian systems, implies recognizing we need multicriteria analysis in order to be able to do social deliberation (Martinez-Alier et al., 1998). We need democratizing processes of decisions, which do not try to hide complexity through technocratic calculations that represent a simplification of reality, i.e. we cannot value work, natural resources and capital in the same way.

We cannot plan incommensurable, as Otto Neurath said, but we need to identify the limits of what is possible to put forward what is our goal. In other words, it is about identifying possible 'ecological utopias' as Martínez-Alier (1987) says, using developed tools that do not attempt to simplify reality to absurd. Only in this way can we advance towards democratic agrarian systems that respond to social needs (González de Molina and Caporal, 2013; Tello and González de Molina, 2017).

In short, Ecological Economics aims to create an alternative to neoliberal economic model in order to design sustainable relations between society and nature through the construction of a new framework of relations. This is what we call Substantive Economics. We work for a new economy in which nature and work are not treated as simple production factors, but also as living elements they are, through its decommodification (Gerber and Gerber, 2017).

2.2.3 *Social Metabolism*

Within Ecological Economics, the predominant approach is Social Metabolism (SM). This will be the theoretical and methodological starting point, which we will complement with other scientific areas such as landscape ecology, reproductive economics, territorial planning or political ecology.

Social Metabolism is the way in which human societies organize exchanges of energy and materials with nature (Fischer-Kowalski, 1997). The theoretical approach of SM considers societies as living organisms: they grow, reproduce, maintain their structures and responds to stimuli. Therefore, in order to do so, societies appropriate goods and services from nature in the form of energy and material flows.

Interaction of societies with the rest of nature, however, is not a unidirectional process. As we can see in Figure 1.1, we classify this interaction into five main processes: appropriation of resources, circulation, transformation, consumption and excretion. At the entrance of the organism there are natural resources used, while in the exit wastes that return to the environment (González de Molina and Toledo, 2014). If we analyze the agrarian systems only from this perspective, the fundamental thing would be how societies make this appropriation of natural resources (the goods necessary for the maintenance of population) and the way in which the remnants of the metabolic process return to environment once consumed.

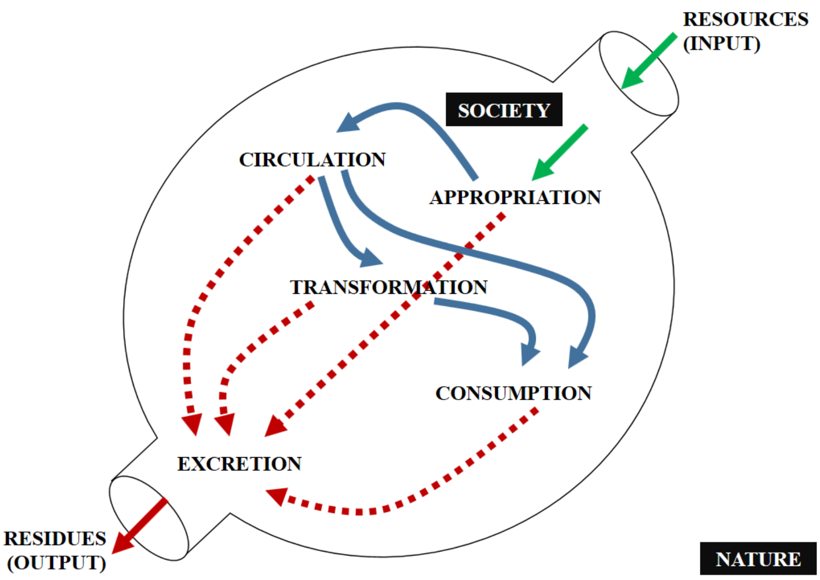

Figure 1.1. Five principal processes of the metabolism between society and nature. Source: Adapted from Toledo (2013)

However, as we will see throughout the thesis, another key element in those processes is the effort made by society towards nature as work done on agricultural systems. In order to make these processes of appropriation, society must allocate some resources (in the form of labor), and sometimes external resources (from other sectors of the economy, such as machinery). There is a metabolic tension between work in agrarian systems, and the appropriation for consumption that societies make of production (Marco et al., forthcoming). Thus, we take a reproductive vision on this interaction between society and nature. Despite we do not formulated it mathematically in purely economic terms as Sraffa or the economists of the reproductive approach (Barceló, 1994).

Society, therefore, structures itself in order to meet energy and material flow needs, and deal with these biophysical tensions. However, in order to maintain this structure, societies also need another part of metabolism that is immaterial. This is the whole series of social relationships set in order to organize metabolic processes, with institutions such as family, market, rules of access to resources, political power, taxation, etc. (González de Molina and Toledo, 2014). All this sociological approach, as well, is also a relevant part of the discipline of SM.

This theoretical basis, as we shall see, allowed the analysis of the socioecological transitions of organic agriculture to industrial, as well as creating solid frameworks for accounting for energy flows and materials, e.g. the Material and Energy Flows Analysis (MEFA) we will use in this thesis but also the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Gerber and Scheidel, 2018).

Our commitment to this thesis is to take a first step towards generating new tools within the SM field. The aim is to advance in the modeling of agroecosystems in order to be able to raise horizons of agroecological landscapes, to facilitate deliberative processes necessary for this required transition.

3. From the collective challenges of sustainability to the transited objectives

It is obvious that with a doctoral thesis the contribution that I can make to the challenges of a global ecological crisis will be quite few in the best case. With the resulting proposal, the *SFRA* model, we want to question academy but above all society as a whole, in order to work towards transcending a technocratic vision of social organization processes. We cannot resolve the ecological crisis without a complete transformation of relationships, which means that we require collective socialization and deliberation processes.

The final aim of this thesis is proposing a tool to facilitate deliberative processes in order to define horizons of sustainable agrarian systems. We want to develop a model where, by measuring each flow within agrarian system in its units, we can generate prospective scenarios at the landscape level.

We will propose a methodology to define horizons of agroecological landscapes that we have reached thanks to developments and results obtained on the functioning of agrarian systems in advanced organic agricultures. Indeed, at the same time we want to confront some challenges involved for relocalizing flows. In short, we need a defining process of de-globalization in which biophysical limits of territories determine the possibilities for the development of these strategies (Tello and González de Molina, 2017). We try not to fall into apriorisms or essentialisms to identify objectively the limits in comparison to current functioning.

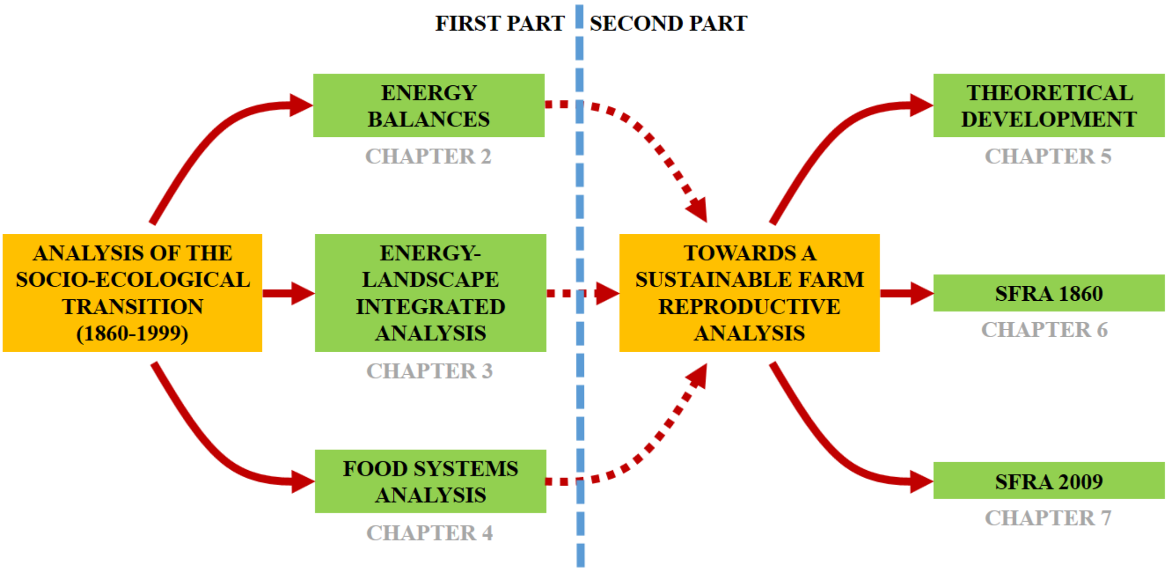

Figure 1.2. Structure of this thesis. Source: Our own.

To reach this final goal, we present the various partial objectives that we transited to this reflection and the tools we designed. They are very general objectives, which we concretize in each chapter regarding the theoretical framework developed.

In relation to the process, we divide this thesis into two clearly differentiated parts (Figure 1.2). In the first part, we dedicate our efforts to deepen into the historical understanding of socio-ecological transitions of traditional organic societies to industrial, involving SM with other approaches such as landscape ecology or food systems analysis. In the second, based on the methodologies developed and the knowledge generated and collected from bibliographic research, we set the theoretical and methodological basis for a socio-ecological modeling of sustainable agroecosystems.

As we have already pointed out, we will develop the whole thesis using a local case study, specifically in the region of Vallès County (Catalonia, Spain). This is a logical scale from a landscape point of view, as it allows us to consider the closure of metabolic cycles as well as its landscape patterns and processes. Therefore, it has been key in order to be able to think about a sustainable reproductive approach. However, as we will see, it also represents a strong constraint in order to extrapolate its results, due to its current particularities of being a highly densed populated region close to Barcelona.

3.1 Analysis of socio-ecological transitions

From various disciplines and approaches, several scientists studied the socio-ecological transitions of organic societies to industrial (Cussó et al., 2006; Krausmann et al., 2012; Krausmann and Fischer-Kowalski, 2013; Tello et al., 2004). Therefore, in this sense, the aim of my study was to deepen in certain key elements of this research with some new approaches, always keeping in mind the difficulties for quantitative analysis in historical perspective.

Methodological objectives

- Define a clear and coherent methodology for developing energy balances in agriculture. This is a collective goal in which I have contributed, Chapter 2
- Relate energy balances with landscape ecology, setting some hypothesis about its relation, Chapter 3
- Relate social metabolism with other disciplines such as the study of food systems, landscape ecology and political ecology, Chapter 4

Historiographic objectives

- Identify the effect of the socio-ecological transition on behavior of each fund (society, agriculture, forestry, livestock and soil), Chapter 4
- Analyze the impact of changes in metabolism on agro-silvo-pastoral mosaics and on the material conditions for farm-associated biodiversity, through a first methodological proposal, Chapter 3
- Assess the impact of current global food regime in the case study area and its links with other agroecosystems, Chapter 4

3.2 Towards a Sustainable Farm Reproductive Analysis

All in all, leads us to the second part of the thesis, in which we propose an epistemological step from assessment to modeling in SM (Zhang, 2013). We divide the proposal of the *SFRA* model into three chapters: a first theoretical one; a second in which we applied it for the first time in an advanced organic agriculture; and a third one in which we make a first agroecological proposal for deliberation about landscapes of the future.

Methodological objectives

- Carry out a review of contributions in the field of social metabolism, territorial planning and reproductive economic studies to establish the theoretical foundations of a reproductive model, Chapter 5
- Adapt the *SFRA* model to conditions of an organic society in the mid-nineteenth century, Chapter 6
- Adapt the *SFRA* model to current social and technological conditions, taking advantage of strategies for integrating funds resulting from the study of advanced organic societies, Chapter 7
- Include non-linearity in socio-ecological modeling as an element to better capture complexity of the interactions between funds, Chapter 7

Historiographic objectives

- Conduct a counterfactual analysis in a case of advanced organic agriculture, to contribute to the debate on the relationship between population density and technical change, Chapter 6
- Identify, by counterfactual analysis, social and environmental pressures in the organization of territories during the 19th century and the similarity of the actual landscape to the optimal distributions defined by the *SFRA* model, Chapter 6

Objectives for the applicability in current processes of agroecological transition towards more sustainable scenarios

- Identify the key elements of the functioning of organic societies, in terms of applied history, that we can translate to current conditions for an agroecological transition, Chapter 6
- Approach the potentials of changing from industrial agriculture to scaling up agroecological strategies at landscape level and assessing biophysical limits of both, Chapter 7

The logical path I have presented here is practically chronological in the development of the doctoral thesis. However, we already published some chapters as scientific articles so in others we proceed to amend concepts or assumptions that in some of them we made, as well as some chapters do not follow exactly the same structure. As well, due to the iterative processes we made during the whole process, some results experienced slight changes in the specific values compared to the already published research, which do not affect at all the interpretation of results. We understand that this is part of the learning process of any scientific research, and of my doctorate in particular. However, I apologize in advance if at any time this may cause some confusion or indefinition.

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CHAPTER 2. FOUNDATIONS AND METHODOLOGICAL IMPROVEMENTS ON ENERGY BALANCES[1]

1. Introduction

As indicated in the introductory chapter, the Green Revolution has been much more than a paradigm shift in the functioning of agricultural activities. Following the first oil crisis that expanded throughout western economies in 1973, some first studies on the impact of energy consumption in agriculture were conducted. Especially relevant from our present perspective were those of Pimentel et al. (1973) and Leach (1975), which laid the foundations for what are now known as agricultural energy balances.

In this second chapter we are going to present the methodological improvements made recently by our research group on *Sustainable Farm Systems* (*SFS*), specifically within the Catalan Team following the publication of a first case study by Cussó et al. (2006) and Tello et al. (2008). The objective is to present the basic assumptions on which we base our studies in this research area, in order to highlight what contributions I have made in this framework with the development of this thesis. As we will see, here the aim is not to reach conclusions on the transition but to present the basis of what we will analyse in Chapters 3 and 4.

In order to contextualize these contributions, first of all I consider necessary to make a brief introduction to these agricultural energy balances, and explain what the basics of this methodology are, the contributions made by the SFS multi-EROI approach, and finally present some first results found in this regard. The following sections on the accounting method of energy balances in agriculture deal with the novel scientific approach developed by the international SFS research group. In subsequent sections the contributions and examples explained are the results of my own research.

2. Energy balances in agriculture

2.1 <u>The energy crisis and the first balances</u>

The first energy balances were undertaken stemming from the interest to find out the energy cost of agricultural production. The pioneer study of Pimentel et al. (1973) was an initial estimation of the evolution of agricultural inputs spent to produce corn in the United States from 1945 to 1970. This research observed a drop in energy efficiency from 3.70 kcal of maize returned by each kcal spent as input in 1945, to 2.80 in 1970. It raised for the first time a great concern on the energy impact of an industrial agriculture that, as a result of the Green Revolution, was becoming increasingly dependent on fossil fuels as well as on herbicides and pesticides which made agriculture more vulnerable to pests.

The Leach study (1975), in turn, was the first to introduce a comparative view between very different agricultural systems. He argued that traditional agricultural strategies could be key to overcome the dependence on a high expenditure of energy inputs, thanks to their higher energy return rate. Figure 2.1 illustrates that pre-industrial systems were able to obtain rates of energy returns greater than the industrialized systems of the United Kingdom. Obviously, comparisons between tropical and temperate systems had to be taken cautiously because of their different

[1] In this chapter, we clearly split the collective advances towards the methodological developments of energy balances, from the individual ones. However, I want to point out that for the construction of the energy balances we worked together with Inés Marco for reaching the aggregated values. I devoted my greatest efforts on what I explain in section 4.

biogeographic contexts.

From these two studies, a research field on energy studies in agriculture developed and became very prolific (Arizpe et al., 2011; Conforti and Giampietro, 1997; Dalgaard et al., 2001; Giampietro et al., 1992; Hamilton et al., 2013; Ozkan et al., 2005; Pracha and Volk, 2011; Refsgaard et al., 1998; Smil, 2000; Smil et al., 1983; Steinhart and Steinhart, 1974; Tzilivakis et al., 2005).

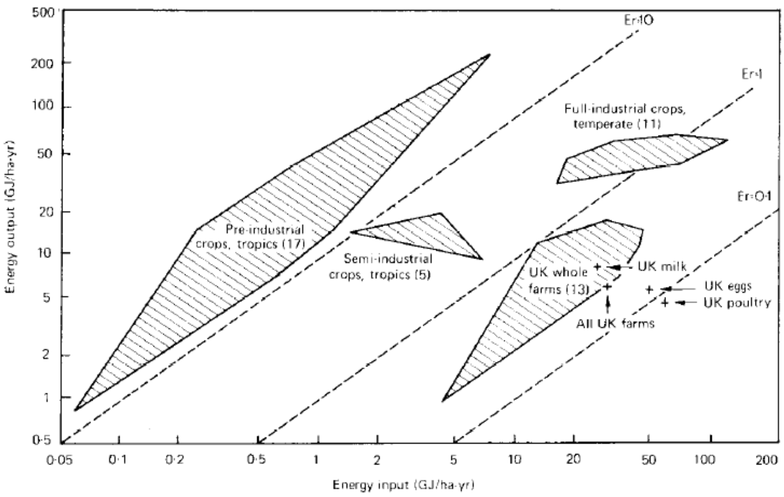

Figure 2.1. Energy input and output of different agricultural systems. Source: Leach (1975).

Among all these researches we want to highlight the one developed by Bayliss-Smith (1982), because it was based on a comparison of different production systems along time and space. It bring in for the first time a socio-ecological perspective that approached the institutional perspective into quantitative energy studies. Egalitarian tribal communities were compared to class agrarian societies, taking as examples a farming community in New Guinea, another organized by castes in India, going through the impact of collectivisations in the USSR. He compared in all of them the role of the different energy inputs invested in agriculture as well as the distribution of resources and final products obtained by the labouring people within each type of society.

Part of these energy studies became progressively detached from a more strictly agronomic view to embrace the socioecological study of agrarian systems. As we have seen in Chapter 1, this means considering the whole agrarian system from a metabolic point of view, i.e. by focusing on the relationships that are established between society and nature. This is the approach we consider useful to meet the purposes of our research, because with it we also can understand the roles social agents played in socioecological transitions.

2.2 The EROI concept

One of the main aims of doing research in energy balances of the agricultural system is to calculate efficiency indicators that show the rate of return on the investments made by farmers. This means setting an indicator based on the quotient between the outgoing outputs and the inputs used.

This basic indicator is called *Energy Return On Investment* (*EROI*), and was used for the first time in ecology to analyse fish migrations (Hall, 1972). Soon, however, it was applied as an indicator of energy return from oil extraction (Hall and Cleveland, 1981).

In our case we apply it to farm systems. As in any efficiency indicator, it is a fundamental issue to determine which units will be used to calculate *EROI*s and at what point of the processes this efficiency is going to be measured. While in the case of oil extraction it may be easy to define the limits of the extractive system studied, in the case of living systems such as agroecosystems, these limits can be diffuse or admit a multi-scalar approach. As a result of these diverse bookkeeping criteria, and different system boundaries adopted, many *EROI* results obtained from balance sheets of farm systems are not comparable one another. This was the first reason that led the *SFS* international research project to develop a consistent and theoretically sound methodology to make historical comparisons of *EROI*s possible.

3. The *SFS* methodology of agricultural energy balances

In order to set the basis of a consistent methodology, we need to define the limits of the system we want to analyse and its components (section 3.1), the calculation methodology (section 3.2) and the efficiency indicators we propose (section 3.3). In the following sections, the elements that characterize the energy balances of farm systems are outlined according to the novel approach developed by the international group *SFS* and published in Tello et al. (2015).

3.1 Agrarian systems analysed from a social metabolism standpoint

3.1.1 *Adopting a metabolic view of agroecosystems as a starting point*

In their interaction with nature, and from a social metabolism point of view, farmers modify ecosystems and turn them into what we call agroecosystems. These are, therefore, ecosystems modified by the intervention of human labour with the aim to obtain products that are useful for society. At the same time, however, agroecosystems have to maintain the ecological processes so that farmers and society can take advantage of the photosynthetic fixation capacity of plants, as well as of a large array of other natural processes that have been grouped into what we call ecosystem services (Brookfield and Stocking, 1999; Gliessmann, 1998; Millenium Ecosystem Assessment, 2005).

Approaching agroecosystems from the social metabolism, i.e. from an Ecological Economics viewpoint, means to account for the various flows that occur within and beyond its limits and affect the agricultural activity. It is about quantifying those flows that circulate among the different fund elements of the farm system according to the relationship established between those who manage the agroecosystem (the Farming Community) and the different compartments thereof. Thus, we propose a basic model that identifies the various components of the agroecosystem which are self-reproducing funds, grouped into the functions they perform, in a way that allows establishing the main flows circulating among them (Figure 2.2). These funds are those ‘elements that are part of a process, which provide services for a certain period but are never physically incorporated in the product’, as defined by Georgescu-Roegen (1971). Specifically, those of biological basis which are alive (despite being organisms or living systems) are self-reproducing funds whose maintenance requires reinvesting regularly to them a certain amount of resources of the agroecosystem (Giampietro et al., 2013).

The model proposed by the SFS research project identifies five of these fund elements: the society, the farming community, the livestock, the farmland and the farm-associated biodiversity. On the one hand, we differentiate between society and the farming community that manage directly the agroecosystem, because this allows us to identify the flows that are established between them (and, as we will see below, quantify in this way what is called the Podolinsky principle). On the other hand, the differences between the fund elements that remain within the limits of the agroecosystem are characterized by the way in which farmers’ labour takes place. While livestock or farmland are actively maintained through the flows supplied through farmers, the farm-associated biodiversity, as we will see, is partly maintained with that share of biomass produced in the agroecosystem that is not appropriated by humans.

Along the thesis, we will approach for what we call the material conditions for farm-associated biodiversity. The proposal will remain as a hypothesis, because we do not deal with empirical databases for confirming or rejecting it. But here is important to make some brief explanation on what we deem this fund is. We consider farm-associated biodiversity as all those species that are not directly planned by farmers but take part of agrarian systems, to which at to some extent contributes to farming activities through the ecosystem services they provide (Altieri, 1999; Tello et al., 2015). Many recent researches have pointed that a lot of species of very different taxa, could be enhanced by combining certain degrees of land cover spatial heterogeneity and appropriate levels of human disturbance, always regarding many different aspects of the landscape patterns (Bengtsson et al., 2003; Harper et al., 2005; Loreau et al., 2003; Tscharntke et al., 2012). No doubt, this farm-associated biodiversity cannot include the whole biodiversity of a given territory, because some rare highly-specialist species are unable to withstand recurring disturbances. In other chapters we will deal with the different strategies that exists for dealing with biodiversity maintenance in agroecosystems. However, it is important to keep in mind to which kind of biota are we referring when approaching this farm-associated biodiversity.

A fundamental modelling issue is where we set the limits of the agroecosystem. This decision will be key to calculating efficiency indicators, as it places the boundaries where entries and exits are observed in the system. Here we adopt what we call an agroecosystem boundary in such a way that the Farming Community and the Society are virtually separated from the other fund elements. Thus, we will consider an input all that is provided by these two funds (*ASI*, *L* and *FCI*, explained later), whereas we will account as output all what is received from them (*FP*).

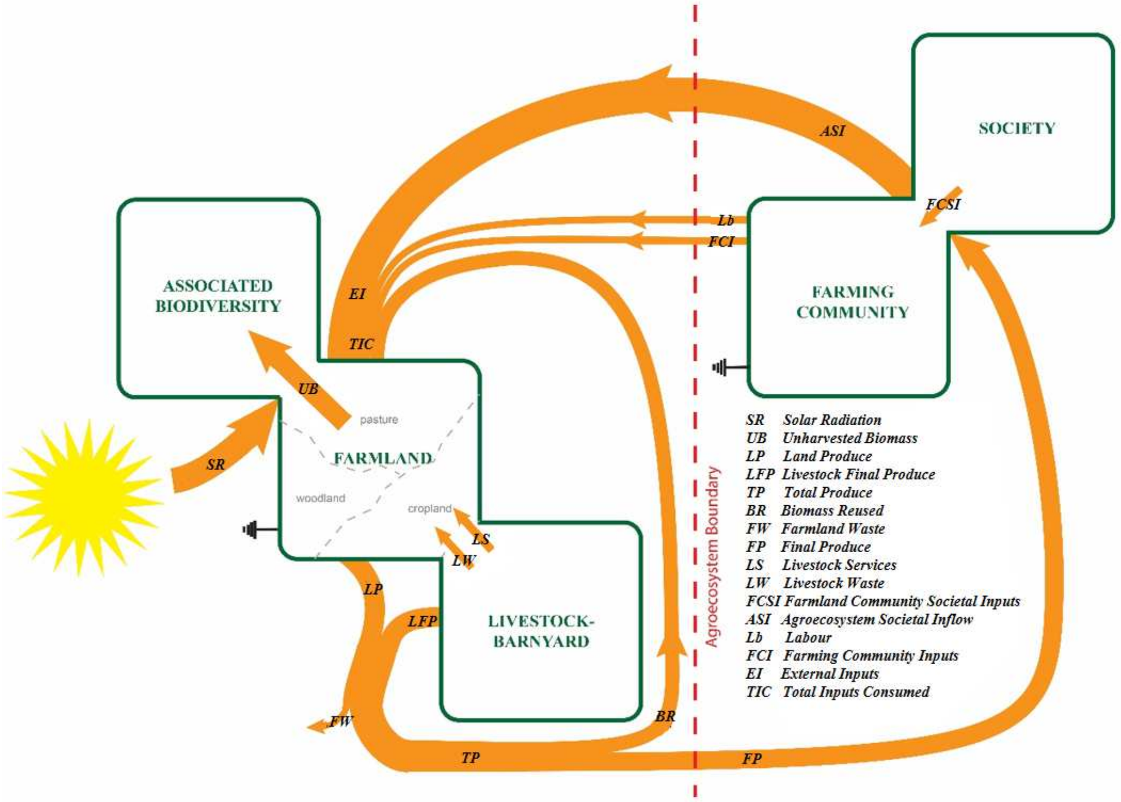

Figure 2.2. Agroecosystem's fund-flow model and boundaries. Source: Our own (Tello et al., 2015)

3.1.2 *The flows circulating in an agroecosystem*

Since it is a dynamic and alive system, we also need to set a time scale in which we calculate the flows in the energy balance. Given the conditions set both by the available sources of information, and by the seasonal logic of operation of a farm system, we will take by definition an annual schedule.

As we said, the main contribution of energy flowing in an agroecosystem derives from the ability of photosynthetic fixation of plants that allows the production of biomass in the different land covers of farmland. In this methodological approach we consider the contribution of solar energy (SR) as a 'gift of nature', not as a cost. Once the photosynthetic process of the autotrophic organisms (mainly plants) is fixed, this energy circulates within the agroecosystem or outside of it.

Next, the phytomass produced over a year fulfils multiple functions and can take different directions. A part can be used to feed livestock of the farm system, or to maintain soil fertility (*Biomass Reused*, *BR*). Another, may be available for non-domesticated species (*Unharvested Biomass*, *UB*), which is a fundamental flow in order to guarantee certain ecosystem services such as pollination, pest control, or other regulating, supporting and cultural services. Finally, another important part is the one that actually leaves the limits of the agroecosystem considered to go towards the Farming Community and the rest of Society (*Final Produce*, *FP*).

Inside what we consider the *Total Produce* of the system (*TP*) there is something more than what has been photosynthetically produced and is intended to be *BR* or *FP* (the *Land Produce*, *LP*). There is also the production coming from the livestock hut (*Livestock Final Produce*, *LFP*). As we shall see later in section 4.2, a part of this *LP* may end up losing much of its functions within the agroecosystem, when it becomes *Farmland Waste* (*FW*).

All of these are not the only flows that circulate within the agroecosystem. The Livestock fund can also return flows to the Farmland in the form of draught power and manure (*Livestock Services*, *LS*). Yet, depending on how they are managed, they can also become *Livestock Waste* (*LW*).

Regarding the Farming Community, which modifies the ecosystem to turn it into an agroecosystem, *Labour* (*L*) is always a basic flow that becomes the minimum condition for dealing with a farm system. Farmers can also provide other flows, such as domestic residues and, in some historical periods, human excreta (humanure), which we include in *Farmland Community Inputs* (*FCI*).

It was not until the so-called Green Revolution that other flows coming from the rest of the compartments of society would experience a skyrocketing increase, such as synthetic fertilizers and machinery together with the fossil fuels embodied in their production and delivery. These are grouped into the category of *Agroecosystem Societal Inflows* (*ASI*).

All the inputs that come from outside the agroecosystem (*ASI*, *L* and *FCI*) are called *External Inputs* (*EI*). Then the sum of *EI* and *BR* will be all the energy costs spent in agricultural production, either internal or external, and account for the *Total Inputs Consumed* (*TIC*) by farmers. A relevant element of this model is that it calculates not only the contributions made by external inputs to the agroecosystem, but also that part of biomass products harvested that remain on it and are intended to guarantee its production over time. This involves adopting an agroecological perspective through which we show how *BR* cycles are indeed a cost to the farm system as such. *BR* could be a flow extracted from the agroecosystem, but farmers decide to reinvest it so as to ensure the agroecosystem's reproduction.

3.2 Accounting method of energy flows

Once we defined the structure of funds and flows considered within the agroecosystem, another fundamental element we need to have a consistent methodology is to specify how we are going to account these flows.

Given that the aim is to obtain indicators of energy efficiency of agricultural activity, all biophysical flows have to be accounted in comparable units. From this standpoint we interpret these flows not as simple circulation of mass, but as energy carriers. Thus, we have to quantify them by their own energy content and taking into account as well all the energy that has been spent to reach their destination site in the agroecosystem, under the desired conditions. The main problem for doing this calculation is that there is no scientific consensus as to how to perform this energy valuation of flows (Brown and Herendeen, 1996). When all the *TIC*s spent in an agricultural production are added, we have to bear in mind that biophysical flows with very different qualities and levels of energy are being merged. In fact, is not the same a flow of straw that can be buried into the soil as a flow of diesel used to fuel a tractor or other mechanical machinery. These are sources of energy of very different qualities. How can we resolve this reduction of different energy qualities into homogenous energy quantities? There are two methodological ways to address this accounting problem.

The first approach was proposed by Howard T. Odum (1984 and 2007) through *emergy* analysis. In his studies, Odum defined *emergy* as ‘an expression of all the energy used in the work processes that generates a product or service in units of one type of energy’. The solar *emergy* of a product is the solar energy equivalent required to generate it. Thus, we can calculate each flow as all the amount of solar energy that has been required in order to be able to find it in the conditions of arrival and functioning within the agroecosystem considered.

The second approach is the energy analysis, in which the accounted element is enthalpy. This thermodynamic concept defines the amount of stored energy that can be converted into heat under standard conditions. Besides counting the amount of energy that a flow contains, it can also account for what is called embodied energy. In a similar way to the *emergy* analysis, this embodied energy adds all the energy that has been consumed, in the form of enthalpy, so that this flow reaches the agroecosystem considered. For example, synthetic fertilizers have zero enthalpy value, but in order to have them into this agroecosystem a relevant amount of energy has been spent on extracting ores, producing the fertilizer, packaging and transporting them to the point of use. The embodied energy can be accounted by the sum of the enthalpy of each of the energy carriers spent throughout these production and delivery chains.

When both approaches are compared, it is obvious that *emergy* analysis provides a more consistent and linear accounting way to differentiate between the different qualities of energy flows and products. However the *emergy* accounting also entails a major difficulty. When a process of energy conversion results in two or more products (e.g. grain and straw), the *emergy* methodology allocates the whole solar *emergy* added to both, considering that there cannot be one without the other, and both need all the previous *emergy* chain to be created. Then, in order to avoid double counting, *emergy* analysis has to select either one or another, leaving the other apart, so as to follow the *emergy* chain to the end. This is called the principle of ‘nonadditivity of by-product flows’ set forth by Odum (1984), and creates unsurmountable problems when dealing with systems that have feedback loops. This is the case of *BR*, which is an agricultural product that becomes also a necessary element for the production of *FP*. Yet, according to the above principle, we cannot account *BR* loops as costs in *emergy* analysis despite their vital role to keep the agroecosystem reproduction.

In the energy analysis, instead, we usually account for metabolic energies and we do not include primary energy sources. Hence, this is why we consider solar energy as a ‘gift of nature’. This allows taking into account how the internal energy loops, which are so intrinsic to agroecosystems, can circulate and enable the farming community to get what we call an energy surplus on which they sustain the whole society. This means accounting for the Podolinsky principle, throughout the metabolic chains that turn solar energy into biomass flows up to the forms required to meet human needs (Podolinsky, 1880).

Therefore, we took the decision to use energy analysis by means of accounting enthalpy values and embodied energy flows, in order to bring to light those internal flows and loops that circulate within agroecosystems and link their fund elements. Only in this way we can find out and analyse the circular complexity of the energy processes taking place in farm systems (Ho and Ulanowicz, 2005), as a first step towards new developments of a research approach of strong sustainability science that always seeks to become more systemic, holistic and dynamic.

However, this is not an easy task nor free from criticism (Brown and Herendeen, 1996; Giampietro et al., 2008). It is obvious by using the same enthalpy values accounted along industrial production chains and contained by the agroecosystem biophysical flows, we do not solve the qualitative differences between different energy carriers. The inevitable reductionism of our energy efficiency indicators is something that always must be kept in mind, and pointed out in a transparent manner.

To conclude, we will account those flows that emanate from the agroecosystem for only enthalpy values, while we will calculate those that come from outside with their enthalpy value plus the entire enthalpy consumed in the production process and transport to this agroecosystem.

3.3 Energy efficiency indicators: A multi-*EROI* approach

One last aspect of the methodological development carried out by the SFS team on energy analysis of farm systems is that of the efficiency indicators that we can calculate from this model. Let us take *Energy Return On Investment* (*EROI*) as a starting point, as explained in section 2.2. In the light of the various flows and circular relationships set among different fund elements of agroecosystems, we consider that based on them we can establish different indicators in order to highlight the multidimensionality of the energy costs carried out by farmers to produce biomass useful for society. Therefore, instead of seeking a reductionist simplification with a single efficiency indicator intended to explain everything, we have adopted a multi-*EROI* approach by using a set of interrelated *EROI* indicators that may allow a deeper understanding of the different sides of an agroecosystem functioning.

Here we are interested in presenting three of them[2]: *Final EROI* (*FEROI*), *External Final EROI* (*EFEROI*) and *Internal Final EROI* (*IFEROI*).

The first of these, the *Final EROI* (*FEROI*), takes into account the amount of useful biomass produced by farmers (*FP*) in relation to all costs, internal and external, required to do so (*TIC*)—as seen in equation 1:

$$FEROI = \frac{FP}{TIC} = \frac{FP}{EI+BR} \text{ (Eq.1)}$$

As we explained, *TIC*s includes all those external flows that enter the agroecosystem coming from Society and the Farming Community (*EI*), together with all those internal reinvestment flows coming from the farmland harvest (*BR*). Therefore, we can decompose this initial F*EROI* into two different indicators shown in equations 2 and 3, which are the external cost to the agroecosystem biomass production (*EFEROI*), and the corresponding internal cost (*IFEROI*). While the first one is closer to the calculations usually made when accounting for conventional energy efficiency so far (without considering the internal costs), the second one is also interesting in order to bring to light the internal effort made by the Farming Community of reinvesting a part of the biomass harvested in order to maintain the agroecosystem functioning.

$$EFEROI = \frac{FP}{EI} \text{ (Eq.2)}$$

$$IFEROI = \frac{FP}{BR} \text{ (Eq.3)}$$

[2] Although in this thesis, as will be seen, some others will be used such as the *Agroecological-EROI*, *Actual Net Primary Productivity-EROI* or the *Final Energy Return on Labour* (Galán et al., 2016; Guzmán and González de Molina, 2015; Tello et al., 2015).

4. Contributions made by this thesis to the methodology of energy balance sheets

In the previous sections we presented the SFS developments with two main aims: i) to offer a consistent methodology that guarantees comparability between different case studies performed at different scales, from local to global, and with a historical perspective that seeks to understand the socioecological transition from traditional organic to industrial farming; and ii) to give account of the circular character of society-nature metabolic interactions which take place through farmers' labour within agroecosystems.

This innovative work started in 2010 within a multidisciplinary and international research project in which it is difficult to separate clearly personal contributions from common achievements, as they are the result of a collective intellectual process. However, I can mention some aspects of this methodological development which are contributions that arose from the process of doing energy balances in the Catalan case studies, in which I played a relevant role.

4.1 Basic assumptions and criteria for historical energy profiles

Dealing with historical data to reconstruct the energy profiles of farms systems in the past becomes a difficult task because of the lack of information about many biophysical flows which had no value in money terms, given that records were mainly kept for taxation or economic surveillance purposes. Yet we cannot limit our analysis to only those flows that were paid in cash, because all the others were also required for the agroecosystem functioning.

In order to fill the information gaps missing in the historical or statistic sources, the Catalan Team of the SFS international project has made some important assumptions to which I have particularly contributed. The starting point consists of adopting a set of accountancy criteria about how farmers would have more likely managed their funds, by keeping them exploited in a sustainable manner whenever possible following a hierarchical group of priorities. We can define this criteria a '*forced local fund sustainability assumption*', that we applied when accounting for past livestock management, nutrient cycles maintenance in cropped areas, and firewood and timber extraction. Following this assumption, our energy profiles are accounted for all the energy flows delivered, and for all the energy efficiency ratios calculated, under the condition of not exceeding the sustainability thresholds of each of these funds.

We are not assuming, of course, that farming was actually always carried out respecting such a sustainability condition. What we obtain under these criteria, and the accountancy method adopted, is a reference level to know —within the site-specific soil and climate conditions, and the available technology— how much effort would have been necessary to provide for and adequate livestock feeding, close soil nutrient cycles and keep forest exploitation sustainable. Only in such cases where we would have enough historical data to ascertain that it was not possible (or desired) to close some of these balances we would assume that the agroecosystem –or some of its fund elements— were exploited at an unsustainable level. Therefore, when reaching some results from those historical balances, we always have to keep in mind that are run under this assumption.

In any case, we have adopted the following hierarchal decision-making process when considering how these biophysical cycles had to be subsequently closed: first, maintaining a share of the total food and fuel for the farming community, whose population is known. This was obviously conditioned by the socio-metabolic regime to which the time point belongs. Then we balance the livestock feeding, estimating feed imports when they existed. After that, we calculated soil nutrient balances. Finally we verify that forest extractions do not exceed the annual growth of forest biomass.

These assumptions entail dealing with an accountancy complexity when we fill the balance sheets, greater than the simple calculation of what crops were used as animal feed, what the typical farm practices were, or which uses were given to the different by-products. Our assumption involves setting accurate nutrition balances (for the livestock-barnyard component) and soil nutrient balances (for cropland fertility maintenance), connecting them with the capacity of pastureland and forest to withstand biomass extraction. With all these checks, we try to do a first approach for ensuring that the values of flows accounted were not consuming the agroecosystem funds. However, as we will see later in Chapter 7, these assumptions could still be improved in order to guarantee higher reproducibility of the agroecosystem.

4.2 The triple check[3]

We started doing this check as a necessary step to improve the energy analysis of farm systems, at first only with the aim to reduce the degree of uncertainty stemming from the lack of information in historical and statistical sources. This led us to assume that we had to bear in mind certain conditions that could not be infringed without endangering the maintenance of the farm system as such.

Animal feeding poses the first and more demanding challenge. We know from statistical sources how many heads of different types of livestock there were (except of transhumant sheep and goats, which have to be indirectly estimated); the amount of land devoted to grow grains suitable for livestock feed (and for humans as well) and fodder crops; together with the average yields of these crops, and the extent of fallow, pastureland and forest which could also contribute to animal feeding. Some data on the common live weights of those animals is known. However, what exact composition of animal rations was actually used to feed each type of livestock? Which proportions of pasture and fallow grazing, straw, stubble, green shoots, pruning, acorns, cereal grain, forages, cereal husk, grinding remains, kitchen leftovers, and so on and so forth were used? No source provides a detailed answer to this question, on whether the animal feeding we are assuming in our energy balance was nutritionally equilibrated or not, and the quantity and composition of the manure obtained.

In order to assign the different possible sources of animal feeding available in the farm system considered, we start by following a cascade top-down ordered criterion: we first allocate the better feed available for each type of livestock prioritizing working animals over the rest. Then we follow filling the animal feed ratios resorting to the resources of lower nutritional quality up to the quantities needed according to the live weight and the number of heads. Before taking a decision, we have to check that the resulting mix became nutritionally equilibrated, and palatable. We have to distribute straw for stall bedding as well as a source of feeding. We add the remaining biomass not required for animal feeding and bedding to cropland *BR* flows, and then incorporated either to the manure heap or directly buried into the soil as vegetal fertilizers, according to the information available on the historical site-specific farm management.

Then we have to check whether all these feed rations adopted are coherent with the quantity and composition of manure we consider to be added into cropland soils. This requires performing a mass balance of entries and exits of livestock bioconversion. We use Gross Calorific Values (GCV) of enthalpy to turn into energy flows the weights obtained from the biophysical data provided by the original sources and statistics. We also know, from nutritional tables of human food and animal feed, the Metabolizable Energy (ME) contained in these substances. We can use the metabolizable fraction out of the gross energy content (ME/GCV) of each kind of animal feed to estimate through mass balancing the amount of the resulting manure. We estimate N content by discounting the share of N consumed that animals withheld and other losses (Brito et al., 2006; Hutton et al., 1967; IPCC, 2006; Jørgensen et al., 2013; Oenema, 2006). Beside mass

[3] We explain the procedure in more detail in Annex I.

balance, this animal nutrition check will also rely on standard coefficients of water drunk and urinated, as well as of livestock gaseous emissions estimated by the IPCC, including the straw used as stall beds. Finally, to estimate the actual amount and composition of manure available for soil N replenishment, we have to subtract the processing losses due to lixiviation and gaseous emissions while manure heaps are been composted (IPCC, 2006).

This mass balance of animal nutrition leads us to consider the N balance of harvested soils, assuming that this seemed to be the most limiting nutrient in the area, despite K was also relevant (Tello et al., 2012). We finally decided to only focus on N for this first approach as it was the one from which more information was known by scientific review. Here then, we only considered N flows, something that we later improved by also including phosphorus (P) and potassium (K) accountancy from chapter 6 onwards. To perform our second check requires accounting for other N entries besides manure, such as stubble and different sources of vegetal biomass buried into the soil either fresh or burnt, together with the incorporation of seeds. We introduce to the balance also other natural entries through deposition, and through free and symbiotic bacterial fixation, with the natural that exits through lixiviation and volatilization of N compounds. For all these assumptions we followed the proposal made by González de Molina et al. (2010) but Tello et al., (2012) as well. Once we completed this balance, we can check whether the N extracted by crops was replenished or not into the harvested soils.

Lastly, the two balances of animal nutrition and soil nutrient replenishment inevitably connect with forestland and pastureland biomass extraction. As we have seen, a share of animal feeding can be obtained through grazing natural pastures and forests. Another share of biomass extracted from these uncultivated lands was collected and buried, and sometimes burnt, as organic matter into cropped soils, like forest litter and fallen branches of trees. All these biomass removals added to firewood cut and used as fuel, and timber extracted as raw material from woods. Adding up all these flows, we then have to check whether they were lower, equal or greater than the yearly net primary production of biomass in the existing forestland and pastureland. To do so, we can rely on the current data provided by forest inventories and nearby sites where long-term ecological research is being conducted. This again, could entail some biases. However, we have not found enough reliable data on forest exploitation for the 19th century.

We interrelate and iterate the three checks (animal feeding, N soil replenishment and the capacity of uncultivated lands to withstand biomass extractions), several times before reaching a coherent distribution of biomass flows that we will assume in the overall energy balance of a farm system. This balancing method entails strengths and weaknesses. Its main utility is to test the biophysical reliability of either the data provided by the available sources, or the estimates made to fill the missing information by means of technical coefficients we took from scientific and technical literature. On the one hand, it becomes a powerful tool to perform source criticism, a basic methodological caution of historians' work. On the other hand, it sets a balancing check to the inevitable use of technical coefficients not provided by the historical or statistical sources available.

However, the main danger of our triple endurance check is we could overestimate the agroecological optimality of the actual functioning of the farm system we analyse. As acknowledged when explaining the meaning of the set of *EROI*s calculated, we have to be aware that an energy balance calculated at farm-community scale is not taking into account the multiple effects that inequality to the access to natural resources –the agroecosystem funds— would entail in their actual allocation and functioning. To put it bluntly, the analytical choice of placing the system boundaries at municipal level means getting a set of average results which would not correspond to any of the real farms endowed with very different amounts and qualities of land, livestock and labour. Again we have to bear in mind that the results obtained with this kind of energy balance can only set average reference levels. To go beyond them requires a socio-metabolic inequality analysis, which is underway within our SFS Catalan Team.

Another relevant aspect is that we rely in some aspects to current technical factors that could introduce some biases. Therefore, we have to be aware that those balances are not trying to answer specific quantitative values of all the functioning for agroecosystems, but can be relevant for analysing tendencies on them.

Then, after having developed this triple balancing method to test the funds' endurance condition, I realised that knowing a series of site-specific thresholds to keep the farm system maintenance over time, would also pave the way to a wider sustainable farm reproduction analysis. The sustainability check I have developed in the agricultural energy accountancy carried out by the SFS Catalan Team has laid the foundations for a much wider reproductive model that we will explain from chapter 5 of this thesis.

4.3 The flow of waste

The risk of overestimating optimality in the actual fund-flow allocation of agroecosystems must also deal with factors other than the distortion exerted by social inequality. The socioecological transition from past organic to current agro-industrial farm systems entailed a sharp decrease in fund-flow complexity that was replaced by a general disintegration of funds and linearity of flows. This also led to new types of technical non-optimal allocation and use of biophysical flows, which meant turning valuable resources and by-products into waste. Another contribution I made to the SFS Catalan Team methods has been introducing the waste accountancy in our energy balances. Before that, it was implicitly assumed that any flow that remained within the agroecosystem became part either of *BR*, *LS* or *UB*, according to the fund elements from where it came or to which it was delivered.

It is obvious that modelling is always a simplification of reality, and that in agroecosystems, as in any living system, it is difficult to clearly what is actually benefiting something or someone from what is not. But it is also true that modelling is useful when it allows to analyse the object studied under the theoretical framework in which we carried out the research. In our case we are studying the energy efficiency of farm systems by calculating the costs and benefits of biomass production and circulation not only for human society, but for the agroecosystem functioning as well. Therefore, overestimating the investments or the positive effects of any agricultural activity would mean introducing biases in our calculation that would result in less accurate results.

Mainly in industrialized farm systems there may be some biomass flows that remain within the farm system boundaries but cannot be considered as a proper reuse, because they neither contribute significantly to the renewal of the agroecosystem funds as *BR* and *UB*, nor keep up its complexity in the way we explained before. Therefore, we consider them waste in the same vein as Eugene Odum (1993) defines it. Waste is a natural resource out of place—meaning that this substance no longer fits the environmental conditions to which the ecosystem fund elements are adapted, either because of the amount and concentration attained or the place where it is located. The fact of being in an excessive quantity, in the wrong place, out of the right time, or all these things altogether, entails an environmental damage. The damage turns out to be real when the substance becomes a pollutant. But even if it does not, the very fact of throwing away a material that put on the right place and time, in adequate quantity, would lead to an environmental improvement also involves an environmental damage in terms of an opportunity cost.

Therefore, there are some processes and flows that we observe in current agro-industrial systems that fit this definition of waste. The clearest case in the study area presented in section 5 is the excess of animal dung. Due to leaching processes, this slurry coming from pigs, poultry and cattle bred in feedlots contaminates nearby aquifers with nitrates. Besides this worrying environmental impact, the problem is that its spatial concentration prevents a relevant share of all this manure to fulfil the function that it could do for soil fertility maintenance. It is, therefore, an out-of-place resource, in this case a *Livestock Waste* (*LW*).

Another example, less easy to evaluate, is the use made of vines' pruning that remains piled up close to vineyards. Currently, this pruning is stacked in a corner and burnt, in order to get rid of the costs of managing them properly. Although the remaining ashes, which are not incorporated into the soil, may have some sort of beneficial effect for the agroecosystem, the opportunity cost is surely much higher. This woody biomass could be used as a fuel, or be grinded and buried to restore soil fertility. Therefore, we will consider it a *Farmland Waste* (*FW*).

No doubt, defining what is reused or wasted is a grey line hard to assess. But we consider it relevant to take wastes into consideration in order to make apparent the existence of several biophysical inefficiencies in the current agro-industrial systems that end up entailing negative environmental externalities of the economic processes taking place in them. From an Ecological Economics standpoint, where the aim is to account for the metabolic processes carried out between society and nature, evaluating them from an environmental perspective is a relevant issue. We do not have enough information to know in what percentage a flow fulfils or not an agroecological function, or reaches its maximum positive impact. But defining the concept of waste allows starting to perform a quantitative separation between those flows that clearly help to keep the fund elements running, from those that do not.

5. Application in a long-term case study, the Vallès county (1860-1999)

We present below the first results of the work we carried out to apply all the above calculations of an energy balance in a specific case study.[4] The aim here is to illustrate the potential of this tool in order to analyse the relationship between society and nature, and not to carry out an historical analysis of socioecological transition, a subject addressed in Chapters 3 and 4.

This presentation of results is structured for two time points of 1860 (traditional organic system) and 1999 (agro-industrial system). We have accounted all the aggregated data, and the evolution of the indicators, in the system boundaries of the study area delimitated by four municipalities of the Vallès County.

5.1 Case study, Vallès County as a test bench

Here, we present the main features of the case study located in the Vallès County, which will be the main study area thorough the thesis. The Vallès is a small plain between the littoral and pre-littoral mountain ranges of Catalonia, and the four municipalities of the study area are located 30-40 km away from the centre of Barcelona city, within its metropolitan region: Caldes de Montbui, Sentmenat, Castellar del Vallès and Polinyà (Figure 2.3). It is a transect area going from top the hills in the pre-littoral mountains to the centre of the plain that includes different types of soils and slopes with a typical Mediterranean rainfall ranging from some 600 up to 800 mm a year. The four municipalities comprise a total surface of 11,996 ha with a low relief on its southern half, with altitude ranging from 130 to 250 m, but is mountainous on the northern half, with altitudes between 250 and 815 m. It is a well-endowed area of historical sources and maps, with a long-lasting research done on rural history (Cussó et al., 2006; Garrabou et al., 2010; Garrabou and Tello, 2008; Marull et al., 2010; Olarieta et al., 2008; Tello et al., 2008, 2012).

[4] The detailed calculation methodology is explained in Annex I, on the assumptions and sources for energy balances construction.

In this first example, we chose two temporal sections to illustrate the stages of the socio-ecological transition; the mid-19th century represents the traditional organic agriculture, and the end of the 20th century when the agriculture was fully industrialised.

In the mid-19th century it had a polycultural organic-intensive farm system which, after having experienced a long-lasting process of winegrowing specialization, exported wine and produced only half of the wheat needed for local consumption, importing the rest from inner Spain (Badia-Miró and Tello, 2014; Garrabou et al., 2009, 2007; Garrabou and Tello, 2008). Following the *Phylloxera* plague that ravaged all of the vines during the 1890s very few vineyards were replanted, so many small tenants searched for jobs in industry, and farming was reoriented towards selling dairy products and vegetables in nearby cities and industrializing towns (Badia-Miró and Tello, 2014; Garrabou et al., 2008). Some time after the Green Revolution, in 1999 the prevailing industrial farming was specialised in meat producing in feedlots (Cussó et al., 2006).

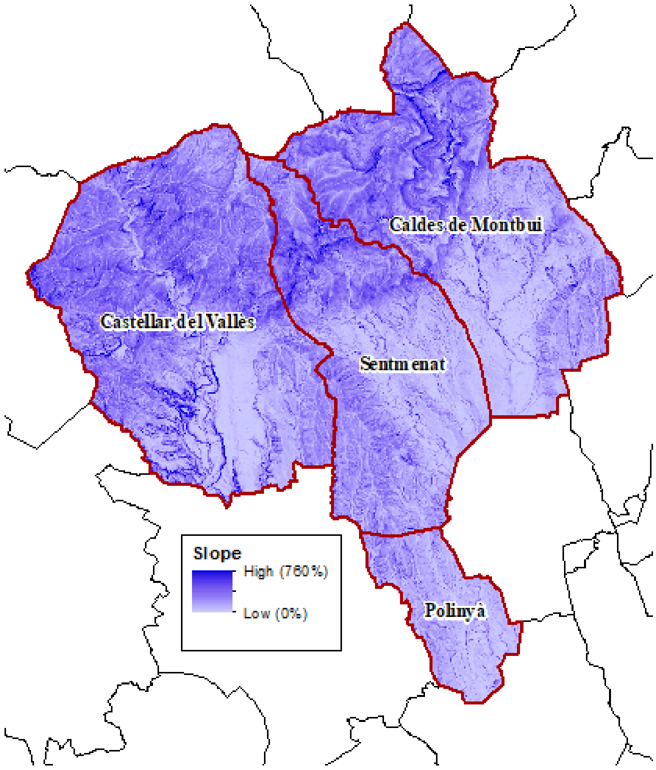

Figure 2.3. Slope map of the case study in the Vallès County. Source: Our own.

5.2 <u>An advanced organic agriculture specialized in vineyards: Vallès c.1860</u>

Figure 2.3 shows the flow diagram of the agroecosystem of the Vallès study area circa 1860. As we can see, this system was an advanced organic agriculture relying on what is now called a Low External Input Technology (LEIT; Tripp, 2008), where the labour flows and other entries coming from the farming community and the whole society represented a very small fraction of the overall set of energy flows. Thus, beyond the solar radiation flow (*Rs*), which is not accounted for in the balance sheet, the most relevant flows were those of *LP*, *FP* and *BR*, whereas *UB* was also significant (Table 2.1). We can observe how most of the annual incoming energy (*TIC*) came from the biomass production of the previous year (Figure 2.4).

If we look at Table 2.1, we can see how, in order to maintain soil fertility we estimated it would have been required to devote 60% of BR flows by means of burial of fresh biomass and charcoal burnt in small kilns on cropland (*formiguers;* Olarieta et al., 2011). The rest was used as animal feeding. Out of animal feeding, and after the corresponding metabolic bioconversion, farmers got the very important *LS* of draught power and manure, which in turn were also used to toil and keep up the farmland. Livestock, however, had a very low contribution (*LFP*) to the total product (*TP*), of some 0.6%.

Finally, 48% out of the total biomass production (*TP*) harvested had to be recirculated again towards the agroecosystem, while 52% was extracted outside as *FP*. Circa 1860 this *FP* showed a strong wine-growing specialization, where vineyard products exceeded the local food production accounted in energy terms. This was a time when vine cultivation peaked in the Vallès, shortly before the entry from southern France of the *Phylloxera* plague (Badia-Miró et al., 2010). Lastly, it is worth noticing that firewood produce, used as fuel by the Farming Community at home, and as charcoal for industrial activities, had a relevant weight within the *FP* obtained.

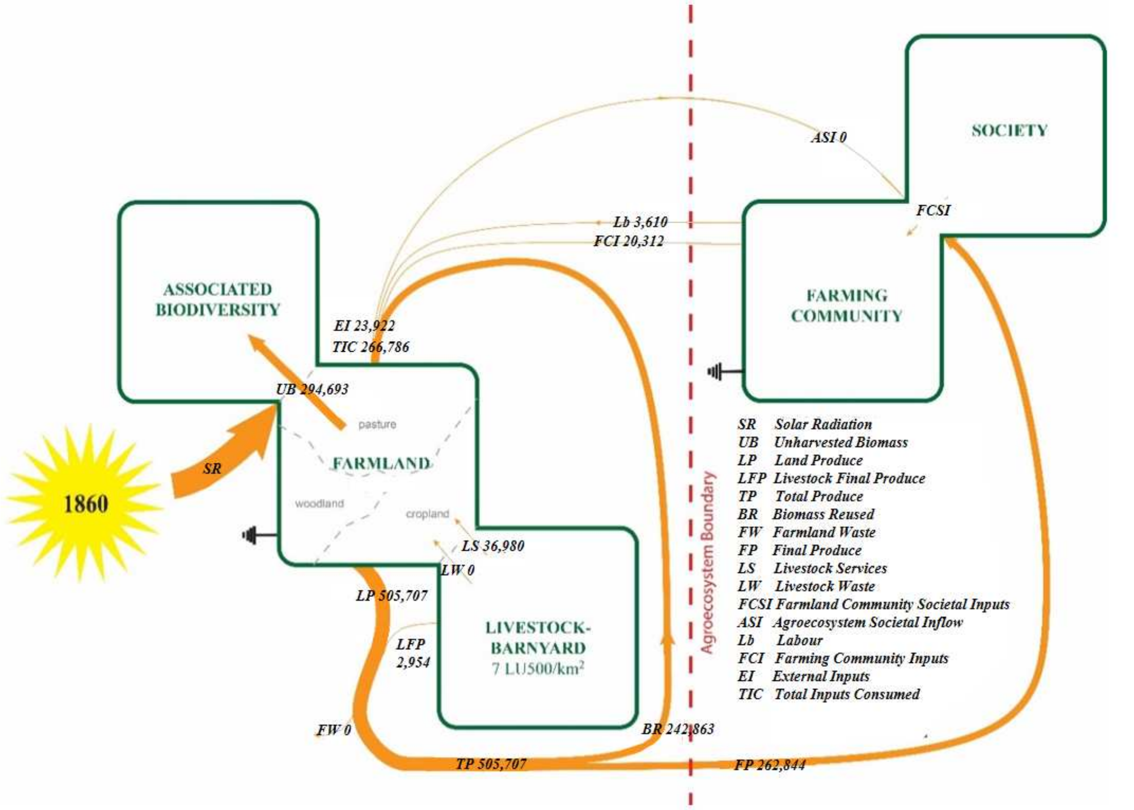

Figure 2.4. Flow diagram of the Vallès' agroecosystem c.1860. Source: Our own.

5.3 A livestock specialization detached from the territory: Vallès in 1999

When we move to the situation at the end of the 20th century a completely different paradigm appears (Figure 2.5). While the incoming-outgoing flows of the agroecosystem through *BR*, *FP* or *UB* were kept more or less in the same order of magnitude than before, external incoming inputs (ASI) to the agroecosystem had been transformed, in the long run, into an awesome flow. As we can see in Table 2.1, 15% of these external entries were the energy cost of tractors and other machinery. Yet 74% of them were animal feed used to fatten a huge livestock density that grew up to 241 LU500/km^2, against the 7 LU500/km^2 that existed c.1860.

This hypertrophic livestock component was kept disconnected from farmland funds, and the lack of proportion between livestock heads and cropland area has led to the existence of a large amount of *Livestock Waste*. This *LW* is all that amount of animal dung slurry that exceeded the fertilizing needs of agricultural fields. Pouring it into cropland generated problems of leaching, or at least made it difficult to handle it. The other side of the coin of this livestock specialization through industrial feedlots was the disproportion between the vegetal and animal products (*LP* vs, *LFP*) obtained in the agroecosystem: it was practically the same in energy terms—which meant an unsustainable food basket.

Finally, we observe a very significant increase of the *UB*, but mainly due to the increase of unmanaged forest biomass (Cervera et al., 2017) stemming from forest abandonment. As we will see in chapter 3, this has led to a polarization of agricultural disturbances into two types of land-uses either intensively cultivated or abandoned.

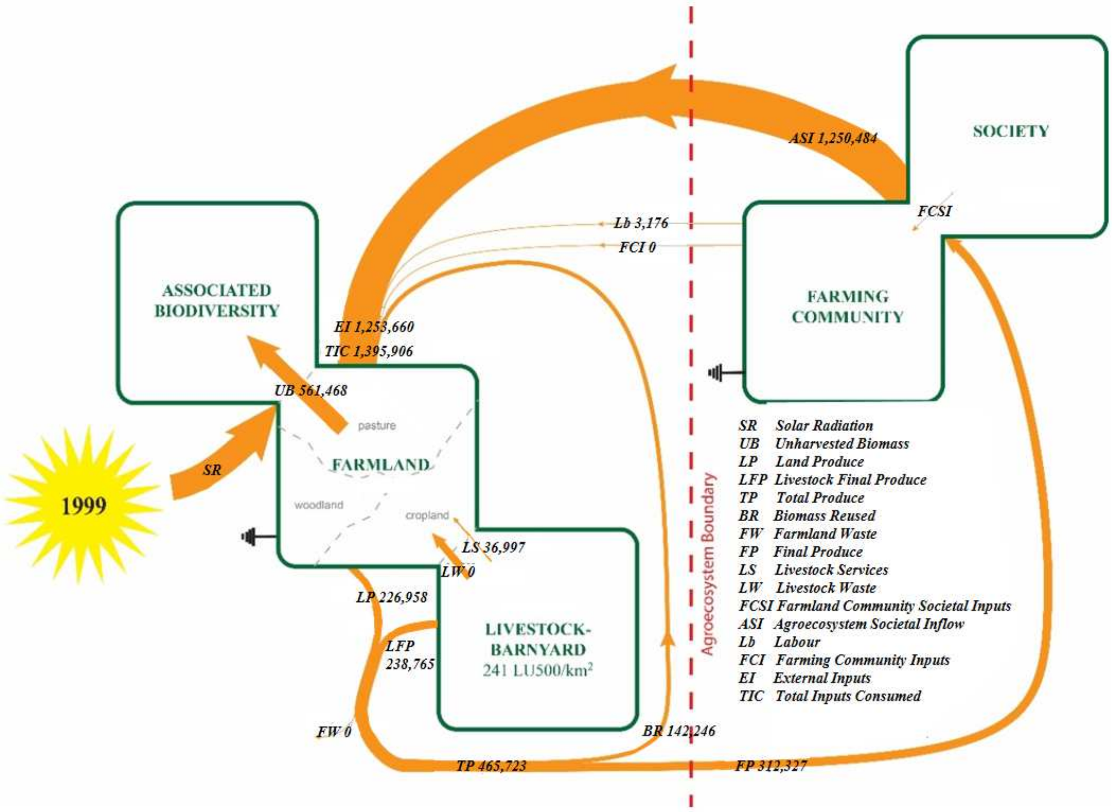

Figure 2.5. Flow diagram of the Vallès' agroecosystem in 1999. Source: Our own.

5.4 The changing multi-*EROI* profiles along socioecological transition

As a final point in this introductory chapter on energy balances, we are going to examine the information provided by the distinct energy efficiency indicators proposed. In Figure 2.6 we drawn the change in these multi-*EROI* patterns in the two extreme points of the socioecological transition, c.1860 and 1999. The behaviour of each indicator followed different paths. While there was a decrease in the *FEROI* and *EFEROI* values, the trend experienced by *IFEROI* was the opposite.

In the case of *FEROI*, we estimated a fall in the energy return (*FP*) on the agroecosystem per unit of the total energy inputs invested (*TIC*). While c.1860 for each GJ invested 1.03 could had been obtained, in 1999 the return was only 0.22. This meant a very significant fall of energy efficiency that was mainly due to the increase in *ASI*s, that is, the impact of livestock specialization in industrial feedlots and the corresponding massive imports of feed grain, together with the agro-industrial cropping with mechanization and agrochemicals. This is what our agroecological approach reveals, when internal as well as external energy costs are accounted.

If we analyze *EFEROI*, we see that the fall was even greater. This is the energy return indicator that does not consider internal costs. Here, we observe a drop from a return of 11.23 GJ for each GJ socially invested c.1860 from outside the agroecosystem, to a return of only 0.25 GJ for every GJ socially invested. This indicator clearly shows how the farm system changed from an agriculture that was a net supplier of energy with respect to the investment made by farmers and their society, to being a net consumer. This socio-metabolic change can only be sustained with the depletion of stocks, especially fossil fuels, which allowed both farm mechanization and the increase in the global circulation of traded biomass (Mayer et al., 2015).

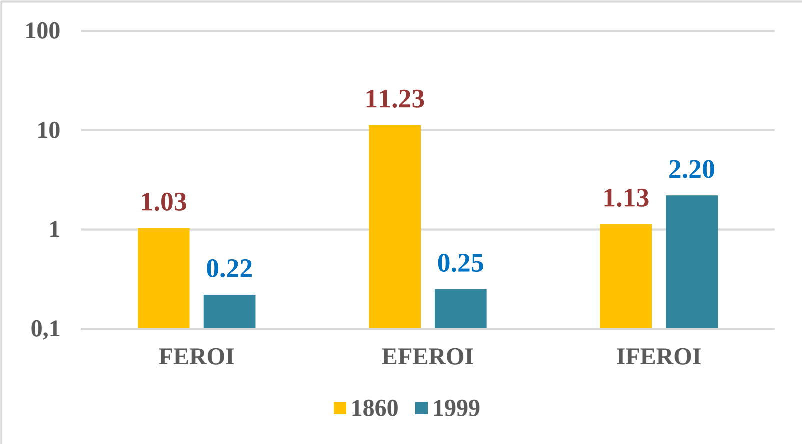

Figure 2.6. Evolution of the main EROI indicators for the agroecosystem of the Vallès study area c.1860 and 1999. Source: Our own.

Table 2.1. Main flows of the agroecosystem in the Vallès study area. Source: Our own.

	Units	1860	1999
1. Total Produce	**GJ**	**505,707**	**465,723**
2. Final Produce	**GJ**	**262,844**	**312,327**
2.1. Cropland Final Produce	%	**34.4**	**15.3**
2.1.1 Food, fibre	%	14.1	4.6
2.1.2. Vineyard and Olive By-Products	%	20.3	0.4
2.1.3. Animal Feed	%	0.0	7.7
2.1.4. Industrial Crops	%	0.0	2.7
2.2. Woodland Final Produce	**%**	**64.5**	**8.2**
2.3. Livestock Final Produce	**%**	**1.1**	**76.4**
3. Biomass Reused	**GJ**	**242,863**	**142,246**
3.1. Farmland Biomass Reused	%	60.3	8.7
3.1.1. Seeds	%	1.6	1.5
3.1.2. Buried Biomass	%	39.7	7.2
3.1.3 *Formiguers*	%	19.3	0.0
3.2. Livestock Biomass Reused	**%**	**39.7**	**91.3**
3.2.1. Feed (main products)	%	10.9	47.7
3.2.2. Feed (by-products)	%	19.7	17.9
3.2.3. Grass	%	5.6	0.7
3.2.4. Stall bedding	%	3.4	25.0
4. External Inputs	**GJ**	**23,922**	**1,253,660**
4.1. Labour	%	29.6	0.3
4.2. Humanure	%	20.5	0.0
4.3. Domestic Residues	%	49.9	0.0
4.4. Fertilizers & Biocides	%	0.0	1.6
4.5. Machinery	%	0.0	15.2
4.6. Feed	%	0.0	73.9
4.7. Energy consumption	%	0.0	8.7
4.8. Seeds	%	0.0	0.2
5. Unharvested Biomass	**GJ**	**294,693**	**561,468**

Finally, *IFEROI* shows the internal effort made to maintain the agroecosystem production over time. This indicator presents in this case study a growing trend unlike the others. Given that here we are measuring the result in terms of *FP* over the *BR* flow returned to land, this means that there was a shift towards a lower investment of *BR* per unit of *FP* produced, causing it to pass from a value of 1.13 c.1860, to 2.20 in 1999. At first glance this result might seem counterintuitive if we only read it in terms of energy efficiency, thus forgetting the meaning of this circular flow as a reinvestment in the agroecosystem funds. Yet it is consistent with a progressive replacement of *BR* with *External Inputs* (*EI*). No doubt, the Green Revolution has led to a huge increase in external inputs; but it has also led to the abandonment of organic fertilization practices and a lower recirculation of biomass within agroecosystems. This has entailed relevant impacts in terms of biomass available for many farm-associated species, either belowground or aboveground the farmland area considered.

In short, with this brief presentation we aimed at showing the potential of the novel SFS multi-*EROI* energy analysis of agroecosystems in order to interpret the historical agricultural change from a long-term socioecological perspective. We consider that both its circular flowcharts and the multidimensional energy indicators provide a good starting point in order to understand what has led to a lower energy efficiency of farm systems at present, and which are the key points and bottlenecks to be faced in order to overcome these biophysical and environmental inefficiencies.

However, in order not to fall into a Cartesian vision (i.e. the faith that a whole universe can be described by a set of equations, as Laplace put it), we have to be aware of the limits that any set of indicators used as explanatory variables of real processes have *per se*. They are key elements to allow for comparability; but, as Georgescu-Roegen stressed (1971), Ecological Economics has to avoid falling into an energy reductionism that would be incoherent with its criticism of the one-dimensionality of the economic analysis carried out by the orthodox Neoclassical Economics that reduces everything to cash flows. This means that we need to contextualise these indicators within the set of processes, patterns and environments from which they have been accounted, in order to attain a systemic comprehension that allows understanding reality in a deeper way.

That is why we consider energy balances only as a starting point for further methodological developments like the ones undertaken in this thesis. Together with the rest of the SFS Catalan Team, we understand them as a tool to be combined with other approaches and disciplines (such as Political Economy, Landscape Ecology, Land-use Planning, Agronomy and Political Ecology), in order to unravel the agroecological impacts on Mediterranean landscapes caused by the socioecological transition from past organic agricultures to current agro-industrial farming. We deem that only by working from a perspective of strong sustainability, taken as a basic epistemological choice, we can really understand and face the socio-environmental challenges of this current unsustainable food system.

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CAPÍTOL 3. ENERGY-LANDSCAPE INTEGRATED ANALYSIS [5]

1. Introduction

1.1. Sustainable farm systems: the global food-biodiversity dilemma

As we have said in chapters 1 and 2, farm systems are facing a global challenge amidst a socio-metabolic transition (Muradian et al., 2012; Scheidel and Sorman, 2012; Schaffartzik et al., 2014) that places them in a dilemma between increasing land-use intensity to meet the growing demand of food, feed, fibres and fuels (Godfray et al., 2010; Lambin and Meyfroidt, 2011), while trying to avoid a dangerous biodiversity loss (Tilman, 1999; Cardinale et al., 2012). The industrialization of agriculture through the 'green revolution' spread from the 1960s onwards has been a major driver of this loss (Matson et al., 1997; Tilman et al., 2002). However, it is increasingly acknowledged that well-managed agroecosystems can play a key role in biodiversity maintenance (Bengtsson et al., 2003; Tscharntke et al., 2005). From a land-sharing approach to biological conservation (Perfecto and Vandermeer, 2010; Tscharntke et al., 2012), there is a claim for a wildlife-friendly farming liable to provide complex agroecological matrices. An heterogeneous and well connected land matrix could maintain high species richness in cultural landscapes (Tress et al., 2001; Agnoletti, 2006, 2014; Jackson et al., 2007). Depending on land-use intensities and the type of farming, agricultural systems may either enhance or decrease biodiversity (Altieri 1999; Swift et al 2004). In turn, the adaptive capacities to farming disturbances and agroforestry land usages vary across species and biomes (Gabriel et al., 2013; Balmford et al., 2014).

Solving the global food-biodiversity dilemma requires a deeper research to know how species richness is kept or lost in different land-use patterns, according to the level (quantity) and character (spatiotemporal scale and quality) of the ecological disturbances that farmers carry out across the landscape (Fischer et al., 2008; Phalan et al., 2011). If human society wants to ensure all sorts of ecosystem services in the future, we need better operative criteria and indicators in order to assess when, where and why the energy throughput driven by farmers increases or decreases the mosaic pattern of cultural landscapes and their capacity to hold biodiversity (Gliessman, 1990; Pierce, 2014). This calls for an integrated research of coupled human-natural systems aimed at revealing complex structures and processes which are not apparent when studied by social or natural scientists separately (Liu et al., 2007; Marull et al., 2015a).

1.2. Aim and scope of this study

A growing consensus in conservation biology points to landscape heterogeneity as being a key mechanism that generates a dynamic biodiversity peak at intermediate levels of ecological disturbance in agroecosystems, thanks to the interplay between spatial diversity, ecosystem complexity and dispersal abilities of colonizing species either coming from less disturbed patches or the survivors in the most disturbed ones (Tilman, 1994; Elmqvist et al., 2003; Roxburgh et al., 2004; Harper et al., 2005; Perfecto and Vandermeer, 2010; Loreau et al., 2010). This opens a research field on how the complexity of energy flows driven by farmers shapes these types of

[5] I carried out this research together with Joan Marull, Carme Font, Andrea Panazzolo and Enric Tello. The first idea of working on the relation between social metabolism and landscape ecology was from Tello and Marull. My main contributions were on developing the graph (together with Font and Marull); setting a methodology for turning aggregate energy balances into spatially explicit ones; defining the formulas of the indicators E and I (although the original idea of applying Information Theory, Loopiness and Landscape patterns was from Marull); and on the writing and discussing the results together with the whole team. The research was published in the journal *Ecological Indicators* in 2016 (Marull, Font, Padró, Tello, & Panazzolo, 2016).

heterogeneous landscapes that can offer a great deal of habitats, food chains and ecological connectivity required by the associated biodiversity of farm systems. The *Energy–Landscape Integrated Analysis* (*ELIA*) of agroecosystems proposed in this chapter aims to contribute to this task by bringing to light the link between the anthropogenic energy carriers flowing among the components of a farm system, the information held within this energy network, and the land-cover diversity of cultural landscapes that arises with the spatial imprint of these farming energy flows. As we will see, however, it will remain as a hypothesis wether what we call "material conditions for farm-associated biodiversity" really implies an enhancement of the farm-associated biodiversity. This is something that further research will have to assess through empirical data on biodiversity surveys.

2. Theoretical development

2.1. Towards an energy-landscape integrated analysis

Living systems are capable of using metabolic energy carriers in order to maintain or even increase their organization (Schrödinger, 1944), when they attain a far-from-thermodynamic equilibrium set up with the organized information that allows transferring energy while maintaining their complexity, reproducing themselves, and evolving (Ho, 1998; Gladyshev, 1999; Ulanowicz, 2003). Applying this approach to agroecosystems requires analysing 1) the energy throughput and closure degree of socio-metabolic cycles; 2) the information carried by the spatially differentiated shape of these energy fluxes flowing across the land-matrix; and 3) the land-cover diversity of the landscape to which the species are adapted (Ho and Ulanowicz, 2005). Like any other ecosystem, in agroecosystems the energy dissipated in space also leads to the emergence of self-organized structures that experience historical successions ruled by adaptive selection (Morowitz, 2002). Thanks to the internal biophysical cycles that link organisms one another, these agroecosystems can enhance their own complexity, increase temporal energy storage and decrease entropy. This set of emergent properties translates into integrated spatial heterogeneity and biodiversity of landscapes (Ho, 2013; Ulanowicz, 1986). Their sustainability is directly related to the information-complexity interplay, and inversely related to energy dissipation (Prigogine, 1996; Ulanowicz, 1997).

In this vein, agroecosystems are seen as the historically changing outcome of the interplay between sociometabolic flows (Haberl, 2001), the land-use patterns set up by farmers, and ecological functioning (Farina, 2000; Wrbka et al., 2004). Despite the long-lasting work done on energy analysis of farm systems, which revealed a substantial decline in energy returns of agro-industrial management brought about by the massive consumption of cheap fossil fuels (Odum, 1984, 2007; Giampietro and Pimentel, 1991; Giampietro et al., 2011, 2013 and Chapter 2), the role played by sociometabolic energy throughput as a driving force of contemporary Land Cover and Land-Use Change (LCLUC) is not yet well understood (Peterseil et al., 2004). *ELIA* intends to link these two lines of research, the agroecological accounting of energy flows (Guzmán and González de Molina, 2015; Tello et al., 2015) and the study of LCLUC from a landscape ecology standpoint (Marull et al., 2015a). This requires specifying and measuring the pattern of energy flows and the information held in agroecosystems.

2.2. Cultural landscapes as socio-metabolic imprint

As explained in chapter 1, traditional organic farm systems with a solar-based metabolism, like the ones existing in Europe before the massive spread of the green revolution from the 1960s onwards, tended to organize their land usages according to different gradients of intensity, keeping an integrated management of the landscape because their whole subsistence depended on this. In order to offset the energy lost in the inefficient human exploitation of animal bioconversion –on which they had to depend to obtain the internal farm services of traction and manure (Guzmán and González de Molina, 2009)—, traditional organic farming kept livestock breeding carefully integrated with cropland, pasture and forest spaces (Krausmann, 2004). While the organic farm management strategy of closing cycles within an agroecosystem led to landscape mosaics, the socio-ecological transition to agro-industrial farm systems that rely on external flows of inputs coming from underground fossil fuels has enabled society to overcome the age-old energy dependency on bioconverters (Krausmann et al., 2003; Schaffartzik et al., 2014). As a result, integrated land-use management at a local or regional scale was no longer necessary—and overcoming this former necessity also led to losing its agroecological virtue (Cussó et al., 2006). The environmental damage caused worldwide by this lack of integrated management between energy flows and land usages urges societies to recover the former 'landscape efficiency' (the socioeconomic satisfaction of human needs while maintaining the healthiest landscape ecological patterns and processes) at present (Marull et al., 2010). Since the lack of an integrated management of energy flows and land-uses at different scales is part of the current global ecological crisis, its recovery becomes crucial for a more sustainable foodscape.

This line of research involves a wider and more complex approach to agroecosystems' energy efficiency. It requires not only accounting for a single input-output ratio between the final product and the external energy consumed, but looking at the harnessing of energy flows that loop within the system as well. The cyclical nature of these flows is important in order to grasp the emergent complexity and the information held within the agroecosystem, given that they involve an internal maximization of less-dissipative energy carriers—in the same vein as Ho and Ulanowicz (2005) explain the 'loopy' character of any living system. The temporal energy storage that these loops allow becomes a foundation for all sustainable systems (Ho, 2013). Hence, the usual methodology of energy flow analysis of social metabolism needs to be adapted and enlarged in order to give account of the cyclical character of agroecosystems' processes (Giampietro, 2004; Guzmán and González de Molina, 2015).

3. Methodology

3.1. Energy flows of an agroecosystem as a graph

Graph modelling is a well-known mathematical structure that allows us to chart natural phenomena as a set of 'nodes' and 'edges' (Urban et al., 2009). *ELIA* treats the pattern of flows in an agroecosystem as a graph where energy carriers are 'nodes' whose 'edges' represent their interaction. Figure 3.1[6] shows how the total amount of phytomass obtained from solar radiation through the autotrophic production by plants, that accounts for the *actual Net Primary Production* (NPP_{act}) (Vitousek et al., 1986; Smil, 2011; Krausmann et al., 2013; Guzmán et al., 2014), is the natural endosomatic energy source for all heterotrophs living there. From this starting point, we analyse the pattern adopted by the subsequent energy processes carried out, the internal loops they generate, the final product extracted or the external inputs introduced from outside the agroecosystem.

The whole biomass included in NPP_{act} that becomes available for all species is split into *Unharvested Biomass* (*UB*) and the share of *Net Primary Production harvested* (NPP_h) (Figure 3.1). The *UB* remains in the same place where it has been primary produced to feed the populations of the farm-associated biodiversity (Altieri, 1999). It becomes a source of the whole *Agroecosystem Total Turnover* (*ATT*) that closes the first cyclical subsystem called 'Natural' in Figure 1a, because it allows for the production of NPP_{act} again through the trophic net of non-domesticated species either in the edaphic processes of the soil or aboveground. This does not

[6] Variables: Actual Net Primary Production (NPP_{act}); Unharvested Biomass (*UB*); Harvested Net Primary Production (NPP_h); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input (*FEI*); Livestock External Input (*LEI*); Livestock Total Input (*LTI*); Livestock Produce and Services (*LPS*); Livestock Final Produce (*LFP*); Livestock Services (*LS*); Final Produce (*FP*); Agro-ecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*).

mean, however, that the entire NPP_h which has been appropriated by farmers goes out of the agroecosystem. In turn, NPP_h is subdivided into *Biomass Reused* (*BR*) inside the agroecosystem and *Farmland Final Produce* (*FFP*) that goes outside to be consumed by humans (Figure 1). The *BR* share is an important flow that remains within the agroecosystem as a farmer's investment addressed to maintain two basic renewable funds: livestock and soil fertility. Hence, *BR* closes the second basic loop called 'Farmland' subsystem in Figure 1b.

Then *BR* is split into the share that goes to feed the domesticated animals as *Livestock Biomass Reused* (*LBR*), which is added to the whole amount of *Livestock Total Inputs* (*LTI*), whereas another share of *BR* is *Farmland Biomass Reused* (*FBR*) which adds up to *Farmland Total Inputs* (*FTI*) as seeds, green manure and other vegetal fertilizers (Figure 3.1). In this way the 'Farmland' subsystem, which comes from the NPP_{act} in the 'Natural' one, becomes linked to the third 'Livestock' subsystem (Figure 1c). These energy linkages in the graph enable us to make apparent how they relate to an integrated land-use management.

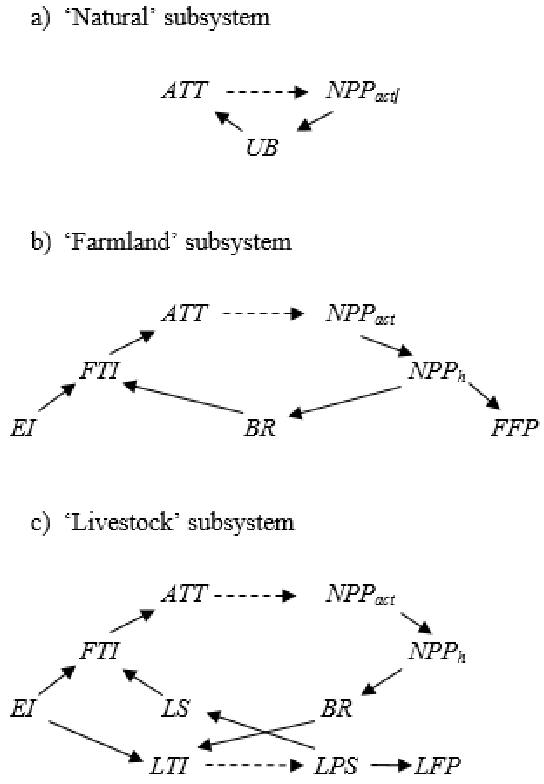

Figure 3.1. Graph model of energy carriers into three subsystems of an agroecosystem. Source: Our own.

Afterwards, *LBR* flows to domestic animal bioconversion and then it splits into *Livestock Final Produce* (*LFP*) and internal *Livestock Services* (*LS*) obtained by farmers as draft power and manure (both make up *Livestock Produce and Services LPS*). In this way the two subsequent loops called 'Farmland' and 'Livestock' subsystems are partially closed within the agroecosystem, while offering a *Final Produce* (*FP*) to be consumed outside—as well as receiving a lower or higher amount of *External Inputs* (*EI*). Therefore, the amount of *UB*, *BR* and *LS* provide the internal flows that lead to a stronger or weaker 'loopiness' in the pattern of energy networks of agroecosystems (Figure 3.2). As well, these *BR* fluxes devoted to farmland and livestock, are also relevant for farm-associated biodiversity, as all heterotrophs that are part of edaphic ecosystems are also part of that farm-associated biodiversity. Then, fluxes such as *FBR* or *LS* (where manure is the largest part) contribute, together with *UB*, to the energy available as food chains for farm-associated biodiversity.

Notice that when only the 'Natural' subsystem is in place, but some *Final Produce* (*FP*) is extracted, we are looking at a very simple gathering or forestry systems. If all the human-appropriated NPP_{act} is diverted towards livestock bioconversion, we are facing a purely pastoral system. In an agro-industrial monoculture of grains, almost all NPP_{act} would be appropriated, except some weeds or herbivores that survive pesticide application, while the greatest share of the energy carriers would flow from outside as *EI* or would go outside as *FP*, except some remnant *BR* like the stubble ploughed in the soil.

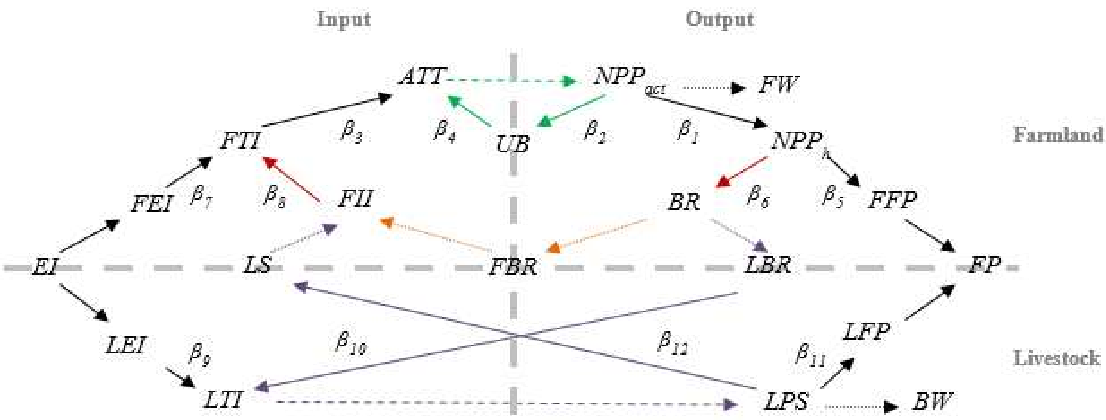

Figure 3.2. Graph model of interlinked energy carriers flowing in a mixed-farming agroecosystem. Source: Our own.

Once we have dissected the agroecosystem, Figure 3.2[7] shows the three subsystems coupled in one that becomes an outline of a mixed farming that integrates cropping and forestry with livestock breeding. It goes without saying that the complexity reached and the information needed to run an integrated mixed farming like this is much higher than with forestry exploitation, a monoculture or a pastoral system carried out separately. This explains why we are going to use this graph model (Figure 3.2) to calculate the level of energy storage within the agroecosystem provided by its 'loopiness', as well as the information embedded in this network of flows.

3.2. Energy carriers stored within agroecosystems

The agroecosystem can behave in a cyclical manner because the outputs of one subsystem become the inputs of the next one (Figure 3.2). This, in turn, provides the base for its 'loopiness' that allows storing energy carriers and information within the dissipative structure (Ho and Ulanowicz, 2005). There is an exception to this rule though, when some energy carriers circulating inside the agroecosystem are turned into what Odum (1993) named a 'resource out of place', as we explained in chapter 2. As seen in Figure 3.2, sometimes a fraction of NPP_{act} can be wasted. The same may happen with a fraction of the *LPS*, such as dung slurry coming from agro-industrial feedlots that are spread in excess into cropland and end up contaminating the water table. If they exist, these *Farmland Waste* (*FW*) and *Livestock Waste* (*LW*) do not contribute to the renewal of the agroecosystem's funds, neither to enhance its internal complexity, nor to meet human needs. Accordingly, the enthalpy of these energy carriers cannot be taken into account in our graph modelling as fluxes that contribute to keeping up the agroecosystem reproduction—although they have to be included as cost.

In the integrated graph (Figure 3.2) we can identify six main subprocesses. In all of them the flow that exits from a node can be differentiated between the portion that remains within the agroecosystem and the other which goes to other subsystems or out of the system. Accordingly, there is always a pair of incoming-outgoing flows for each subprocess of the agroecosystem. Hence, we propose twelve coefficients (β_i) along the edges of the graph (Eq.1-12).

[7] Variables: Actual Net Primary Production (NPP_{act}); Unharvested Biomass (*UB*); Harvested Net Primary Production (NPP_h); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input (*FEI*); Livestock External Input (*LEI*); Livestock Total Input (*LTI*); Livestock Produce and Services (*LPS*); Livestock Final Produce (*LFP*); Livestock Services (*LS*); Final Produce (*FP*); Agro-ecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*). β_i's are the incoming-outgoing coefficients.
Relationships between variables: $NPP_{act} = UB + LP$; $NPP_h = BR + FFP$; $BR = FBR + LBR$; $EI = FEI + LEI$; $LTI = LEI + LBR$; $LPS = LP + LS$; $FP = FFP + LFP$; $ATT = FTI + UB$; $FTI = FII + FEI$; $FII = FBR + LS$.
Note: The colours of the arrows represent the 'natural' (green), 'farmland' (red) or 'livestock' (purple) subsystems.

$$\beta_1 = \frac{NPP_h}{NPP_{act}}, \beta_2 = \frac{UB}{NPP_{act}}, \beta_3 = \frac{FTI}{ATT}, \beta_4 = \frac{UB}{ATT}, \beta_5 = \frac{FFP}{NPP_h}, \beta_6 = \frac{BR}{NPP_h}$$
$$\beta_7 = \frac{FEI}{FTI}, \beta_8 = \frac{FII}{FTI}, \beta_9 = \frac{LEI}{LTI}, \beta_{10} = \frac{LBR}{LTI}, \beta_{11} = \frac{LFP}{LPS}, \beta_{12} = \frac{LS}{LPS}$$
(Eq.1-12)

These β_i's account for the proportion in which every flow is split into two in each crossroads within the network. Then, we can differentiate between even and odd β_i's, where the even ones account for the energy carriers looping inside the agroecosystem. Any pair of the same subprocess sum 1, except for those processes that have a third direction (waste). This is the case of NNP_{act} and *LPS,* which affects β_1, β_2, β_{11} and β_{12}. Another advantage of using β_i's is that they are bounded (between 0 and 1), which allows comparing different case studies or historical examples.

In Figure 2 we differentiate between three shapes of arrows. Solid arrows show the energy flows we are most interested in, as they represent the internal and external exchange of energy carriers. Dashed arrows indicate fluxes that require biological conversion (i.e. photosynthesis). Finally, point-line arrows show energy carriers that are not diverted inside or outside but remain as 'resources out of place' (i.e. waste). Tables 3.1 and 3.2 give a complete description of an agroecosystem's energy carriers and coefficients.

3.3. Turning agroecosystems' energy graphs into spatially-explicit ones

Once we have the agroecosystem's energy network graph (Figure 3.2), we are interested in the relationships of the evolving complexity of the internal energy loops with the information they contain and the diachronic LCLUC. The next step is converting the incoming-outgoing coefficients (β_i's) to their land-matrix expressions, by calculating the mean estimated values of energy fluxes flowing across each land-use (in MJ·ha^{-1}). That means to transform the energy balances shown in Chapter 2 into spatially-explicit values.

In most of fluxes there are no difficulties when assigning a value for each land-use if they form part of the first two subsystems ('natural' and 'farmland'; Figs. 3.1 and 3.2). In the 'livestock' subsystem the key point is to set the weight of the whole internal loop which corresponds to each land-use, by taking into account that part of the animal bioconversion that goes to each type of farmland (see Tables 3.1 and 3.2). In order to allocate the full energy cost of livestock to different land-uses, we not only weighted the values of *LS* (manure and traction), but *LW* (dung wasted) as well. Moreover, we have to solve the problem of the energy carriers that flow from one land-use to another within farmland when we calculate spatially-specific values of biomass reuses included in *FBR* and *LBR*. We may have, e.g. a biomass flow coming from forest clearing that is buried into cropland, or the pruning of vineyards that is burnt and added to the soil of cereal-growing areas, etc. Although these fluxes cancel one another when they are accounted at aggregated level, for the land usages involved in these inter-farmland flows the values for *FBR* and *LBR* have to be differentiated depending on whether we are considering a flow entering or going out from each spatial unit of analysis.

Then, in order to link this network of energy flows with the land-matrix, we have to correlate both types of data (ingoing and outgoing flows) measured in the same spatial unit of analysis (sample cell). This also requires specifying and measuring the variables we are going to study. Recall that our aim is to analyse the agroecosystem's energy pattern of flows, as a dissipative structure (Prigogine, 1996). Hence, what is relevant here is not only the magnitude of each energy flow as such but two other things captured by our graph modelling: i) the specific part of this network of flows that provides negentropy by storing energy carriers within the agroecosystem and allows for the enhancement of its complexity; and ii) the increasing information embedded in this energy network.

Table 3.1. Agroecosystem energy carriers taken into account and their values in the Valles case study (1860s, 1999). Source: Our own.

	Energy carriers	Formula	GJ a year 1860	GJ a year 1999
Single variables	**Farmland External Input *(FEI)***	-	5,553	193,383
	Unharvested Biomass *(UB)*	-	294,693	561,468
	Farmland Waste *(FW)*	-	0	11,150
	Farmland Biomass Reused *(FBR)*	-	146,555	12,424
	Livestock Biomass Reused *(LBR)*	-	96,308	129,822
	Final Farmland Produce *(FFP)*	-	262,844	73,562
	Livestock External Input *(LEI)*	-	18,369	1,060,277
	Livestock Waste *(LW)*	-	0	256,502
	Livestock Services *(LS)*	-	36,980	36,997
	Livestock Final Produce *(LFP)*[1]	-	2,954	238,765
Composed variables	**Actually Net Primary Production *(NPP$_{act}$)***	$NPP_{act}=UB+NPPh+FW$	800,400	788,421
	Harvested Net Primary Production *(NPP$_h$)*	$NPP_h=BR+FFP$	505,707	215,808
	Agroecosystem Total Turnover *(ATT)*[2]	$ATT=UB+FTI$	483,781	804,267
	Livestock Total Input *(LTI)*	$LTI=LBR+LEI$	114,677	1,190,098
	Livestock Produce and Services *(LPS)*	$LPS=LS+LP+BW$	39,934	532,264
	Farmland Total Input *(FTI)*	$FTI=FII+FEI$	189,088	242,805
	Farmland Internal Input *(FII)*	$FII=FBR+LS$	183,535	49.421
	Biomass Reused *(BR)*	$BR=FBR+LBR$	242,863	142,246
	Final Produce *(FP)*	$FP=FFP+LFP$	262,844	312,327
	External Input *(EI)*	$EI=FEI+LEI$	23,922	1,253,660

Table 3.2. Agroecosystem energy coefficients, complexity of internal energy loops (*E*), information held by energy flows (*I*), and their values in the Valles case study (1860s, 1999). Source: Our own.

Energy coefficients		Formula	Case study values 1860	1999
Incoming or outgoing flows	β_1	$\beta_1=NPP_h/NPP_{act}$	0.630	0.274
	β_2	$\beta_2=UB/NPP_{act}$	0.370	0.712
	β_3	$\beta_3=FTI/ATT$	0.391	0.302
	β_4	$\beta_4=UB/ATT$	0.609	0.698
	β_5	$\beta_5=FFP/NPP_h$	0.517	0.341
	β_6	$\beta_6=BR/NPP_h$	0.483	0.659
	β_7	$\beta_7=FEI/FTI$	0.029	0.796
	β_8	$\beta_8=FII/FTI$	0.971	0.204
	β_9	$\beta_9=LEI/LTI$	0.160	0.891
	β_{10}	$\beta_{10}=LBR/LTI$	0.840	0.109
	β_{11}	$\beta_{11}=LP/LPS$	0.074	0.449
	β_{12}	$\beta_{12}=LS/LPS$	0.926	0.070
Information – Loss	γ_L	$\gamma_L =(UB+NPP_h)/2NPP_{act}$	0.500	0.493
	γ_B	$\gamma_B =(LS+LP)/2LPS$	0.500	0.259
Subsystem – contribution	k_1	$k_1=UB/(UB+BR+LS)$	0.513	0.758
	k_2	$k_2=BR/(UB+BR+LS)$	0.423	0.192
	k_3	$k_3=LS/(UB+BR+LS)$	0.064	0.050
	k_2'	$k_2'=BR/(BR+LS)$	0.868	0.794
	k_3'	$k_3'=LS/(BR+LS)$	0.132	0.206
Energy Storage	***E***	$E=\frac{\beta_2+\beta_4}{2}k_1+\frac{\beta_6+\beta_8}{2}k_2+\frac{\beta_{10}+\beta_{12}}{2}k_3$	**0.618**	**0.622**
Energy Reinvestment Effort	***Ee***	$E_e=\frac{\beta_6+\beta_8}{2}k_2'+\frac{\beta_{10}+\beta_{12}}{2}k_3'$	**0.754**	**0.361**
Energy Information	***I***	$I=-\frac{1}{6}\left(\sum_{i=1}^{12}\beta_i\log_2\beta_i\right)(\gamma_L+\gamma_B)$	**0.639**	**0.587**

According to Ho and Ulanowicz (2005), the most relevant fluxes are the loop producers that have to be detached from the entropy producing flows. For this reason we will use as a first variable β_i^j defined as the quotient of the energy flow relation i associated with the land-use j (Eq.13-24).

$$\beta_1^j = \frac{npp_{h_j}}{npp_{act_j}}, \quad \beta_2^j = \frac{ub_j}{npp_{act_j}}, \quad \beta_3^j = \frac{fti_j}{att_j}, \quad \beta_4^j = \frac{ub_j}{att_j},$$
$$\beta_5^j = \frac{ffp_j}{npp_{h_j}}, \quad \beta_6^j = \frac{br_j}{npp_{h_j}}, \quad \beta_7^j = \frac{fei_j}{fti_j}, \quad \beta_8^j = \frac{fii_j}{fti_j},$$
$$\beta_9^j = \frac{fei_j}{lti_j}, \quad \beta_{10}^j = \frac{lbr_j}{lti_j}, \quad \beta_{11}^j = \frac{lfp_j}{lps_j}, \quad \beta_{12}^j = \frac{ls_j}{lps_j}$$

(Eq.13-24)

Here lowercase letters indicate we refer to coefficients, not to variables like was done previously. All the variables of the energy flow graph (Figure 3.2) are expressed for each land-use j. Thus, for each sample cell we have β_i (Eq.25).

$$\beta_i = \sum_{j=1}^{k} \beta_i^j p_j \quad \text{(Eq.25)}$$

Where p_j is the proportion of the land-use j in the corresponding sample cell, and k is the number of different land-uses. Starting from this spatially-explicit β_i's we can then calculate the complexity and information carried with energy flows, so as to analyse its relationship with landscape patterns.

3.4. From the complexity of energy flows to landscape patterns through information

Once we have defined how to account for spatially-explicit energy flows, we can introduce the three indicators that we are going to use in *ELIA*. They are ordered hierarchically, according to the logical string that goes from the interplay between energy and information to landscape patterns. Energy storage can be seen as the harnessing of dissipation thanks to the farmers' efforts to generate and enhance energy loops (Ulanowicz, 2003). The intervention of farmers' labour also means that the looping of these biomass reuses is not produced randomly through space, because it is driven by information. Owing to the information delivered by farmers' labour the energy fluxes are directed in one or another way across the land-matrix with different intensities. It is precisely because energy carriers flow across different land-covers following a deliberate pattern that they imprint a specific mosaic that we recognize as a cultural landscape.

Therefore, energy reinvestement and storage driven by farmers' knowledge produces an effect on landscape patterns and processes. *ELIA* correlates the following three indicators: i) the complexity attained through the energy storage of loops (*E*); ii) the information embedded in the energy network of flows (*I*); and iii) the landscape functional structure (*L*). Acknowledging from the onset that to collect all the necessary data to analyse the whole environmental impact of the agroecosystem's energy cycles is not possible, we think that the use of the previously explained β_i's is a valuable proxy to give account of a looping rather than a linear set of energy transformations (Giampietro et al., 2011).

The 'loopiness' of energy carriers driven by farmers through *UB*, *BR* and *LS* flows (Figure 3.2) can be adopted as a measure of *E* that expresses the energy potentially available for all food chains taking place in the agroecosystem. We deem this will be something relevant for the conditions to farm-associated biodiversity, as we will see later. We are going to start measuring *E* as the quantity of energy remaining in the system, and then we will measure *I* that allows the farmers to reproduce the agricultural metabolism thanks to the information embedded in the system. *I* can be measured taking into account how evenly distributed the set of pairwise incoming-outgoing fluxes of the graph are. These variables, both *E* and *I* can then be related with *L*, considering them as the landscape 'imprint' of social metabolism.

3.5. Measuring Energy Storage (E) as the complexity of internal energy loops

We understand agroecosystem complexity as the differentiation of dissipative structures that allows for diverse potential ranges in their behaviour (Tainter, 1990). At the same time, the more complex the space-time differentiation is, the more coherent energy is stored within a system (Ho and Ulanowicz, 2005). Hence, higher mean values of even β_i's entail that agroecosystems are increasing in complexity because the different cycles are all coupled together and the residence time of the stored energy is enlarged thanks to a greater interlinked number of transformations looping inside. Accordingly, our way of calculating complexity is as follows in Eq.26-27.

$$E = \frac{\beta_2+\beta_4}{2}k_1 + \frac{\beta_6+\beta_8}{2}k_2 + \frac{\beta_{10}+\beta_{12}}{2}k_3 \text{ (Eq.26)}$$

$$k_1 = \frac{UB}{UB+BR+LS}, k_2 = \frac{BR}{UB+BR+LS}, k_3 = \frac{LS}{UB+BR+LS} \text{ (Eq.27)}$$

Where the coefficients k_1, k_2, k_3 account for the share of reusing energy carriers that are looping through each of the three subsystems (Figure 3.2).

The formula used implies that E remains within the range $[0,1]$. E close to 0 implies low reusing of energy carriers—a behaviour that usually corresponds to an agro-industrial management highly dependent on external inputs and with maximum levels of *Human Appropriation of Net Primary Production* (*HANPP*). *E* close to 1 implies more internal energy loops, meaning that a high share of energy carriers harvested are reused within the agroecosystem—a behaviour usually associated with organic farming with lower dependence on external inputs, lower biomass extraction as *FP*, and also moderate levels of *HANPP*.

E assesses the amount of energy flows that go inside, relative to the whole energy flowing across each one of the three subsystems of the network structure of an agroecosystem. Hence *E* measures the proportion of energy stored on the land coming from each loop considered sequentially. That is, taking into account that a share of the flow stemming from the first loop can still be redirected inside again when flowing across the two subsequent loops. When we account for the three loops nested within one another, we are adopting a landscape standpoint that is focused on what happens with the energy flowing across different land units driven by farmers, and we name this value *Energy Storage (E).*

Note that this *E* will account for all the share of biomass devoted to heterotrophs within the agroecosystem. Despite inside the indicator we also include the effect of storage for livestock, after the bioconversion processes, a relevant part of the flux loops again into farmland through *LS*. Therefore, we deem that this *E* can also be a good proxy for total food chains in the agroecosystem available for farm-associated biodiversity.

For some purposes it is also useful focusing the standpoint on what driving these energy throughputs means in terms of human labour allocation. Notice that from a labour cost point of view the ingoing flow of *UB* is the result of *not* doing anything (Tello et al., 2015), whereas *BR* and *LS* always require investing a farmer's labour. If we calculate this process of energy harnessing by adopting a labour-cost standpoint, we obtain *Ee* as stated in Eq. 28-30.

$$Ee = \frac{\beta_6+\beta_8}{2}k'_2 + \frac{\beta_{10}+\beta_{12}}{2}k'_3 \text{ (Eq. 28)}$$

$$k_2' = \frac{BR}{BR+LS}, k_3' = \frac{LS}{BR+LS}, \text{ (Eq. 29-30)}$$

Indeed, what *Ee* accounts is only that part of the agroecosystem's energy throughput that involves a labour investment, leaving UB aside. Thus Ee expresses as a coefficient the reinvestment effort made by farmers relative to the energy flowing only across the agricultural and livestock subsystems (Figure 3.2), and we name this value *Energy Reinvestment Effort* (*Ee*).

3.6. Measuring Energy Information (I) as shown in the energy flow pattern

The measuring of the information held in the network of energy flows draws on Information Theory (IT)—despite some common misunderstandings that we will try to avoid (Georgescu-Roegen, 1971; Ulanowicz, 2001; Vranken et al., 2014; Cushman 2014). In *ELIA*, IT is applied to the graph model of the network of energy fluxes that cross an agroecosystem (Figs. 1 and 2). The equidistribution of the energy carriers flowing across the binary strings that link the nodes of this graph assumes that the information they carry cannot be known beforehand. In this vein information can be seen as a measure of uncertainty, or the degree of freedom for the system to evolve (Prigogine, 1996). When energy flows concentrate in a specific sector of our graph model, the defined pattern tends to vanish. Conversely, the information embedded is the highest in an equidistributed pattern of energy fluxes.

This kind of 'information' is often called *message-information* that only registers the likelihood of the occurrence of a pair of events (Passet, 1996; Ulanowicz, 2001). It differs from the meaningful content of the information farmers use to direct the fluxes of energy carriers according to a defined purpose, and also from the spatially organized information that can be measured in the land-cover diversity of a farmland mosaic—or even from the auto-reflexive information loop of considering the latter as an imprint of the former.

The information quantified in *I* has an important feature, though: It is always site-specific for the unit of analysis observed, which is a very important trait from a bio-cultural standpoint (Cocks, M., 2004; Robson and Berkes, 2011; Jackson et al., 2011; Gómez-Baggethun et al., 2012; Barthel et al., 2013; Agnoletti, 2014). When *ELIA* registers a decrease on *I*, we wonder to what extent the information running the system has been lost or transferred from the traditional agroecological knowledge of farmers located at landscape level towards higher hierarchical scales, where other people outside the place have taken control over some important parts of the agroecosystem functioning after being linked to increasingly globalized food chains (Johns and Sthapit, 2004; McMichael, 2011; Muradian et al., 2012).

Accordingly, we use a Shannon index (Shannon, 1948) adapted to be applied over each pair of β_i's, so that this indicator shows whether the β_i's pairs are evenly distributed or not. This measure of energy information (*I*) accounts for the equi-proportionality of pairwise energy flows that exit from each node in every sub-process (Eq.31-33).

$$I = -\frac{1}{6}\left(\sum_{i=1}^{12} \beta_i \log_2 \beta_i\right)(\gamma_F + \gamma_L) \text{ (Eq.31)}$$

$$\gamma_F = \frac{NPP_{act} - FW}{NPP_{act}} = \frac{UB + NPP_h}{UB + NPP_h + FW} \text{ (Eq.32)}$$

$$\gamma_L = \frac{LTP - LW}{LTP} = \frac{LS + LP}{LS + LP + LW} \text{ (Eq.33)}$$

Base 2 logarithms are applied as probability is dichotomous. Keeping in mind the definition of β_i's, we know that the pairs $\beta_1 - \beta_2$ and $\beta_{11} - \beta_{12}$ don't sum 1, as the rest of the pairs of β_i's do. This is because waste (FW and LW) can also be understood as a lack of information of the system. The introduction of γ_F, γ_L ensures that I remains lower than 1 when the system presents this information loss.

I values close to 1 are those with an equidistribution of incoming or outgoing flows of the agroecosystem's network structure where the *message-information* is high, whereas values close to 0 means patterns of probability far from equidistribution. We deem *I* values close to 0 correspond to a low site-specific information content in agroecosystem functioning, which may be related to an industrialized farm system with high *HANPP* and low relevance of traditional peasant knowledge; or, by contrast, to an almost 'natural' turnover with slight *HANPP* that may also correspond to rural abandoned forest or pastoral areas at present. Conversely, agroecosystems with *I* equal to 1 are the ones with equidistributed incoming and outgoing energy flows in each sub-process, as well as with intermediate levels of *HANPP* (Marull et al., 2015a), that correspond to an organic mixed farming.

3.7. Measuring Energy Imprint (L) in the landscape functional structure

In order to correlate the above explained energy-information interplay with landscape functional structure we need to introduce a landscape metric (L) as proxy of land-cover diversity. A focus on landscape functionality stresses the spatial dimension of biodiversity, focuses on the interplay between disturbances and land-cover heterogeneity, and the role of agroecological land management in ecosystem service provision (Tscharntke et al., 2005). This perspective relies on the interplay between patch disturbance and land-cover diversity as the key mechanism that actually matters in biodiversity maintenance (Loreau et al., 2010). This also brings to light the capacity of agro-forest mosaics to offer a range of habitats that sustain many species (Harper et al., 2005). Much of this biological diversity is apparent at scales larger than plot or farm level, and depends on landscape-wide heterogeneity of land covers. We are assessing here then, the material conditions of habitat diversity for these farm-associated biodiversity at a landscape level.

We use a modification of the Shannon index commonly used in ecology to account for landscape heterogeneity (Vranken et al., 2014). In this land-cover dimension, Shannon index is not used for looking at agroecosystems as dissipative structures, but as the spatial 'imprint' of their social metabolism—therefore, without any thermodynamic meaning. We calculate L to capture the equidiversity of land-covers into sample cells (Eq.34)

$$L = \left(-\sum_{i=1}^{k} p_i \log_k p_i\right)(1 - p_u) \text{ (Eq.34)}$$

Where *k* is the number of different land-covers (Figure 3.1). We consider that the existence of urban land-cover $p_u$results in a loss of potential habitats. Thus, p_i is the proportion of non-urban land-covers *i* into every cell. An important issue to consider here is that we are only accounting for the forest cover as a whole, without considering internal differences. This is because historical sources did not allow for that, but it is something that could be improved in further analysis with current data. That would be probably very relevant in terms of the conditions for farm-associated biodiversity.

After having defined all the *ELIA* indicators (*E*, *I* and *L*), we surmise that the interplay between *E* and *I* jointly leads to complexity, understood as a balanced level of intermediate self-organization (Gershenson and Fernández, 2012). Finally, we assume that the complexity of socio-metabolic fluxes and *L* are related to landscape ecological processes and biodiversity (Giampietro, 1997; Marull et al., 2015a). Therefore, regarding farm-associated biodiversity, we hypothesize two indicators of this ELIA are relevant: *E*, which accounts for the amount of internal food chains; and *L*, which accounts for the amount of habitat diversity. We will call them 'material conditions for farm-associated biodiversity', as we infer they are relevant but we do not match them with empirical data that allow for accepting or rejecting this hypothesis.

3.8. Case study application

Many traditional Mediterranean agroecosystems had kept complex land-use mosaics, which were later turned into homogeneous land-covers –increasingly polarized between intensive monocultures and spontaneous afforestation of abandoned lands— as a result of the industrialization of farm systems fuelled by cheap fossil fuels that began in the 1960s (Gerard et al., 2010; Parcerisas et al., 2012; Marull et al., 2014). This historical process can be taken as a natural experiment for comparative analysis (Odum, 1984; Gliessman, 1990; Tscharntke et al., 2005). At the same time, the conservation of cultural landscapes has to take into account the human role in shaping their present ecological features (Gustavsson et al., 2007; Henle et al., 2008). *ELIA* looks at these landscape changes as the 'imprint' of the energy carriers driven by farmers, and highlights the bio-cultural role performed by the changing complexity-information interplay in the energy profiles of agroecosystems.

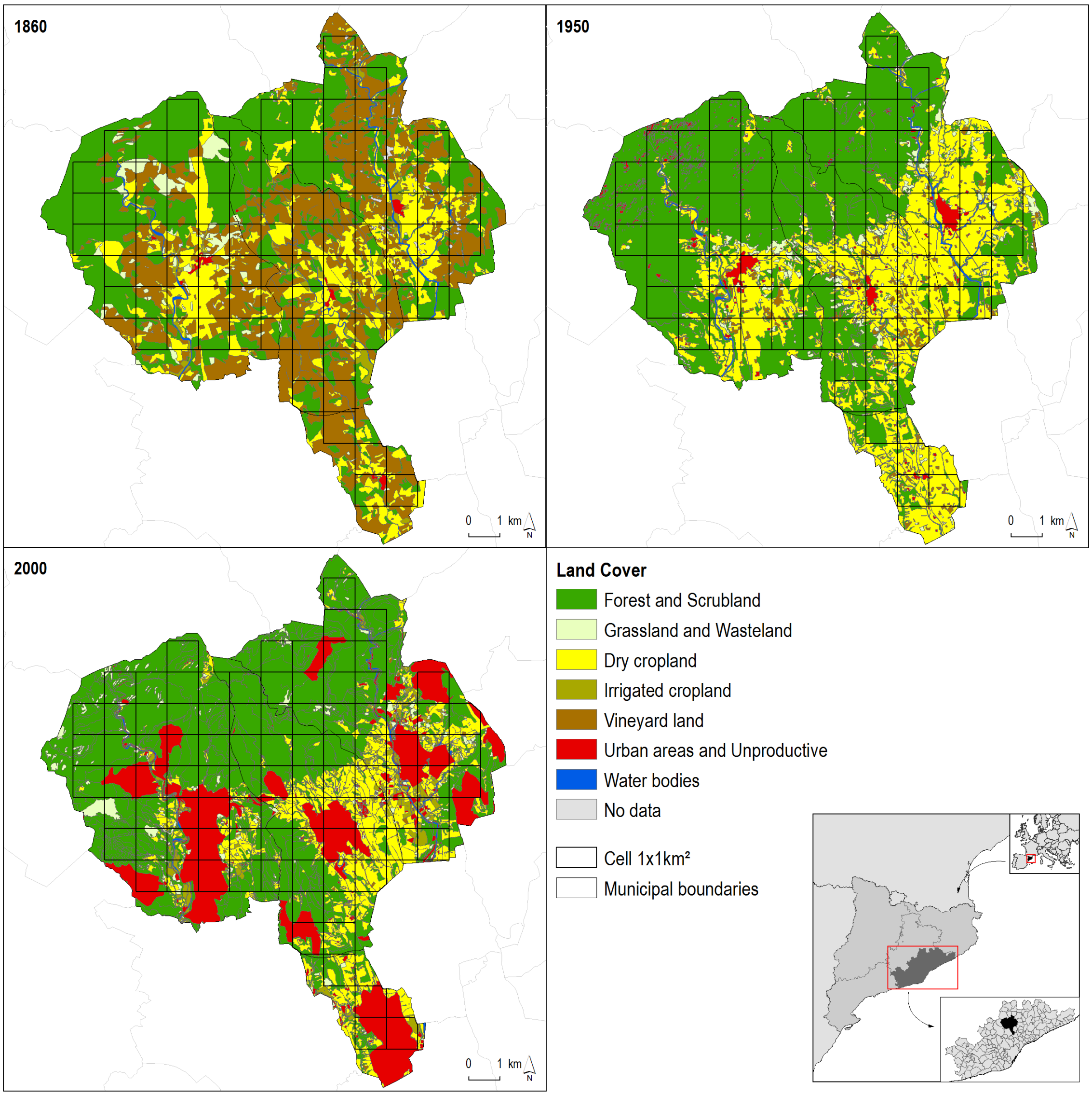

Figure 3.3. Land-cover maps of the Vallès case study (1860s, 1950s and 1999). Source: Our own.

We apply *ELIA* to our case study in the Vallès County that comprises four municipalities (Caldes de Montbui, Castellar del Vallès, Polinyà and Sentmenat; Figure 3.3[8]), located westward in the Mediterranean biodiversity hotspot (Myers et al., 2000). We have been studying this site from a long-term socio-ecological perspective (from c.1860 to the 1999), by reconstructing the energy balances of farm systems (chapter 2), while others studied the ecological functioning of cultural landscapes (Marull et al., 2010). This led us to integrate the study of sociometabolic profiles of energy flows with the landscape ecology performance that existed in past organic farming, or characterize agro-industrial systems at present.

In mid-nineteenth century the Vallès County reached a population density of 65 inhab./km^2. This challenge drove peasants to combine as a response an export-led winegrowing specialization with traditional agro-silvo-pastoral mosaics (Garrabou et al., 2010; Badia-Miró and Tello, 2014). Maintaining and reproducing this poly-cultural landscape entailed a tight integration between cropland and livestock breeding, by means of a labour-intensive mixed farming (Olarieta et al., 2008, 2011; Tello et. al., 2012). Fodder and feed crops occupied 14% of cropland area in the organic case study c.1860, while livestock was also grazing pastures in 7% of farmland area, or in the grass layers below open forests and other uncultivated land. While all these links between diverse land-covers through livestock feeding helped to maintain mosaics, the energy flows of draught power and manure provided by these animals returned again to cropland. Especially in solar-based agroecosystems that practically only depend on a single type of external inputs (labour), this integration among cycles involves the well-known stiffness in societal land-use patterns due to the simultaneous need for food (cropland), firewood (forest) and animal feeding (pasture) (Guzmán and González de Molina, 2009). These were common features of late organic farm systems at the eve of the socio-ecological transition towards industrial agricultures in Europe (Krausmann, 2004).

4. Results

4.1. Land-use changes and landscape patterns from the 1860s to 1999

Between the 1860s and 1950s the area allocated to vineyards was reduced in favour of cereals, hazelnut trees, irrigated orchards, woodland and pasture (Figure 3.3). Cropland acreage fell from 56% to 34% of the total area, while urban expansion remained modest and the agrarian landscape mosaic was kept on the lowlands. Then, from the 1950s to the 1999, cropland area shrunk to 19% due to a wide-scale adoption of the Green Revolution. On the one hand 1,947 ha were devoted to urban expansion (16% of the useful area, two thirds at the expense of arable land and the rest of woodland and pastures). On the other hand, 646 ha of abandoned cropland were reforested (5%). The former agro-silvo-pastoral mosaics tended to vanish, which led to a significant decrease of spatially organized heterogeneity: Land-cover diversity fell from L = 0.72 in the 1860s, to L = 0.38 in 1999 (Table 3.3). Hence, our study area underwent an important reduction in the kind of landscape hetrogeneity that it is increasingly related to farm-associated biodiversity worldwide (Perfecto and Vandermeer, 2010).

[8] Source: Cadastral maps of mid-19th century from the Old collections of the Map Library at the Institut Cartogràfic i Geològic de Catalunya (ICGC); cadastral maps of mid-20th century from the Regional Office of Catalonia, in Barcelona, of the General Directorate of Cadastral Registry of the Spanish Ministry of Treasure and Public Administration; and for the beginning of the 21st century, the third edition of the Land Cover Map of Catalonia generated by photointerpretation made in the Research Center in Terrestrial Ecology (CREAF) from the colour orthophoto map provided by the ICGC.

Table 3.3. Land-cover and landscape functional structure (*L*) in the Vallès case study (1860s, 1950s and 2000s). Source: Our own.

Land-covers		ha			%		
		1860s	1950s	1999	1860s	1950s	1999
Forest and Scrubland		4,675.7	7,088.7	6,801.1	39.0%	59.1%	56.7%
Grassland and Pastureland		299.2	350.0	340.4	2.5%	2.9%	2.8%
Dry cropland		2,240.3	3,773.3	1,869.7	18.7%	31.5%	15.6%
Irrigated cropland		202.2	0	289.4	1.7%	0.0%	2.4%
Vineyard land		4,309.9	266.9	22.3	35.9%	2.2%	0.2%
Water bodies		165.2	142.1	110.6	1.4%	1.2%	0.9%
Urban areas and Unproductive		55.0	374.7	2,562.2	0.5%	3.1%	21.4%
No data		48.2	0	0	0.4%	0.0%	0.0%
Landscape Structure	***L***	**0.72**	**0.50**	**0.38**	–	–	–

4.2. Energy transition of agroecosystems from the 1860s to 1999

The metabolic profile of the case study in the 1860s shows a solar-based agriculture that followed the strategy currently known as Low External Inputs Technology (LEIT) with strong reuse of biomass addressed to maintain the underlying funds. Conversely, in the 1999 chemical fertilizers and tillage mechanization following the massive spread of the green revolution allowed land and labour productivity to increase, rendering the effort of keeping internal reuses unnecessary. This combined with huge imports of animal feed consumed in industrial livestock

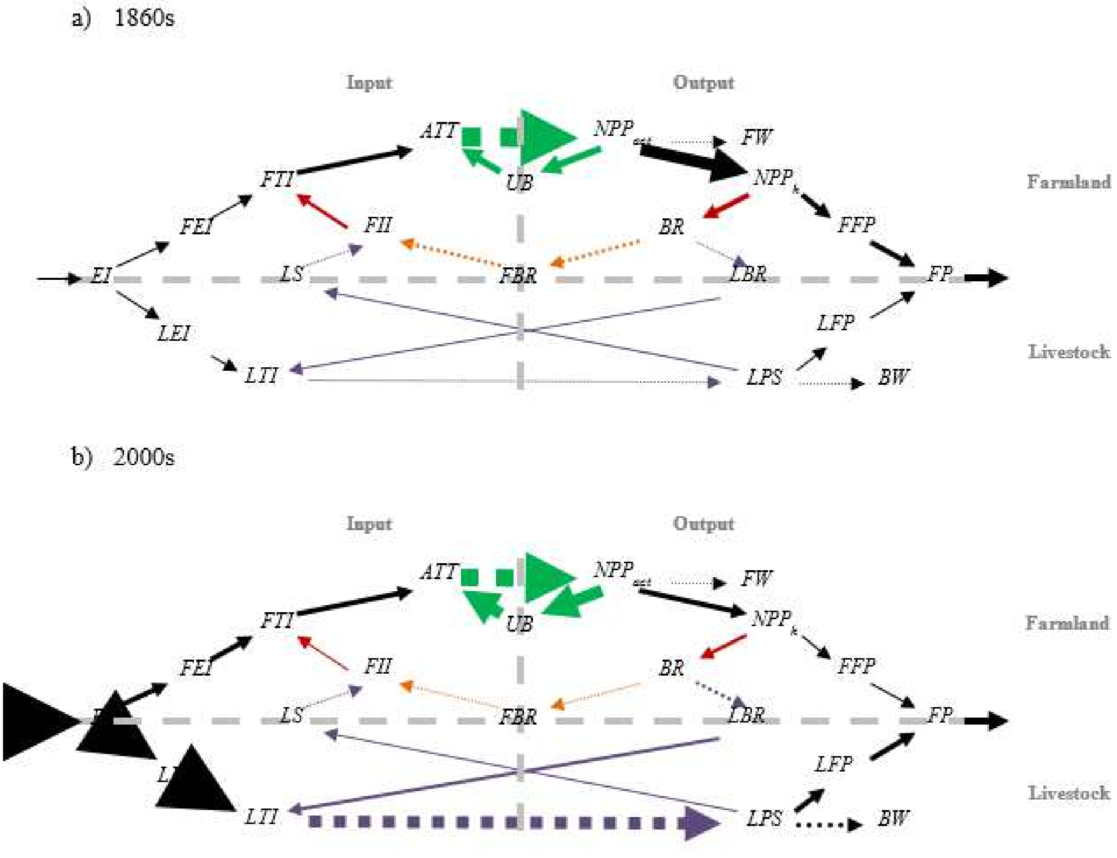

Figure 3.4. Graph model of energy carriers flowing in the farm systems of the *Vallès* case study in the 1860s (a) and 1999 (b). Source: Our own.

breeding. Meat became the main component of *FP*, and relegated arable land to the role of provider of fodder, feed and straw to feedlots. At the same time woodland grew with the withdrawal of farming and grazing in the steepest areas, while its human use shrunk due to the ongoing rural abandonment (Cussó et al., 2006).

The use of graph modelling as an analytical tool (Figure 3.4) [9] allows us to reveal how the agroecosystem c.1860 was indeed highly dependent on internal energy loops and relied on a low amount of external energy fluxes. To obtain *FP* with very few *EI* (a LEIT strategy), it had to bear a high 'sustainability cost' of *BR* while a significant amount of *UB* available for farm-associated biodiversity was still kept (Guzmán and González de Molina, 2009). In turn, the graph model for the 1999 also reveals the deep transformation that has taken place in farming strategy, currently addressed to industrial livestock breeding as shown by the enormous amount of *LTI*, combined with a subsidiary monoculture of animal feeding crops.

A key component in agroecosystem analysis is to determine which part of the energy flowing is redirected again towards the land matrix, in order to keep the underlying renewable funds. Accordingly, we propose three indicators calculated from the graph modelling (*E*, *Ee* and *I*): *E* assesses the entire proportion of energy stored in the agroecosystem throughout the successive nested loops, either by means of farming activity or not, relative to its whole energy turnover ($E = 0.618$ in 1860 and $E = 0.622$ in 1999). *Ee* expresses as a coefficient, relative only to the agricultural and livestock turnover, the labour investment made by farmers to maintain the farm system ($Ee = 0.754$ in 1860 and $Ee = 0.361$ in 1999; Table 2). In turn, the network structure of these energy flows and loops provides us with a measure of the information (*I*) they contain ($I = 0.639$ in 1860 and $I = 0.587$; Table 3.2).

4.3. <u>Complexity and information of energy flows in the 1860s and 1999</u>

We calculated *E* and *I* over energy carriers of agroecosystems' flows, and their specific coefficients (Tables 3.1 and 3.2). These results are consistent with what has been discussed in previous sections. Circa 1860 a traditional organic farm system was closer to what we have considered a 'balanced' agroecosystem typology than to the agro-industrial management adopted in the 1999, which fits with what we have considered as 'industrialized-intensive' farm systems. We also expected that a LEIT strategy would have scored higher information (*I*) values combined with moderately high energy reinvestment (*Ee*) and storage (*E*) indices, as shown by the results. Conversely, resorting to industrial feedlots and cereal monocultures has led to a slight decrease of the information embedded in the local agroecosystem in the 1999. However, as we see, it seem that this selected indicator for information is not as sensitive to the experienced changes on an aggregate scale.

Seen at aggregate level the results show comparable energy storages for the two time-points, although these similar *E* values conceal that those ingoing energy flows followed very different paths across the three subsystems interlinked in the corresponding graph models (Fig 3.4): c.1860 a great deal of them were biomass reused into farmland in a way that entailed many interconnections between cropland, forest and livestock, and showing an even distribution of

[9] Variables: Actual Net Primary Production (NPP_{act}); Unharvested Biomass (*UB*); Harvested Net Primary Production (NPP_h); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input (*FEI*); Livestock External Input (*LEI*); Livestock Total Input (*LTI*); Livestock Produce and Services (*LPS*); Livestock Final Produce (*LFP*); Livestock Services (*LS*); Final Produce (*FP*); Agro-ecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*).

Note: The width of the arrows in both graphs is proportional to the magnitude of energy fluxes in the agro-ecosystem. The colours of the arrows represent the 'natural' (green), 'farmland' (red) or 'livestock' (purple) subsystems.

energy flows among them; conversely, in 1999 these incoming energy flows turned out to be mainly unharvested biomass left in abandoned woodlands after forest transition. *Ee* values highlight these differences by showing that c.1860 the efforts that farmers made in energy reinvestment were much higher than in 1999, while the energy storage that takes place in current industrial farm systems is an unintended result of the withdrawal of farmer's activity ensuing rural abandonment. Indeed, it concentrates in woodlands kept unexploited which have no bonds with cropland tillage and animal husbandry. Whereas in traditional organic farm systems the incoming flows were nesting all the three loops of the agroecosystem, in current industrial farm systems they stay either accumulated in forests, or they appear as dung slurry stemming from feedlots where animal intake comes from abroad (chapter 2). The splitting among subsystems that we observe in 1999, and the disconnection between energy flows crossing land covers, is coherent with the decrease of the average farmers' energy reinvestment (*Ee*) and with the lower values of information (*I*) found in the agroecosystem's network structure compared with c.1860.

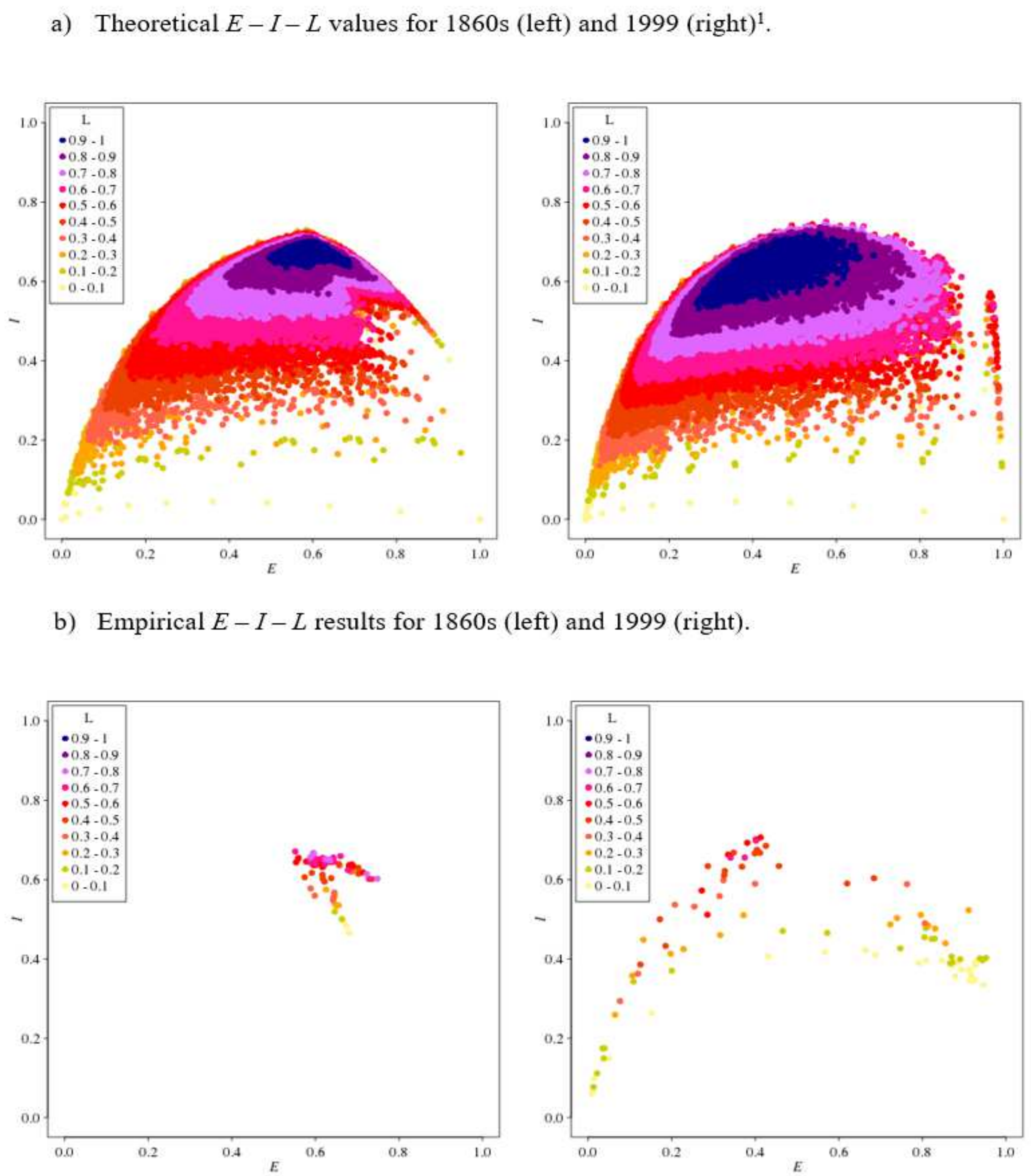

Figure 3.5. Relationship between complexity of internal energy loops (*E*), information held in the network of energy flows (*I*) and landscape functional structure (*L*). Theoretical values (a), and empirical results (b) in the Vallès case study (1860s and 1999). Source: Our own.

The disaggregated results in Table 3.1 also show a noteworthy decrease in NPP_h from 506.000 GJ in the 1860s to 216.000 GJ in the 1999 driven by rural abandonment and spontaneous reforestation of the study area (Table 3.4). Although this entailed an increase of *UB*, from 295.000 GJ to 561.000 GJ respectively, wee deem, probably,this did not translate into a potentially higher farm-associated biodiversity due to the simultaneous decrease in land-use complexity (Marull et al., 2015a; Tello et al., 2015). Just making more biomass available to ecological food chains, while the number of habitats is reduced in a more homogeneous landscape, instead of enhancing biodiversity probably only increases the populations of some better adapted species (Tello et al., 2014; Marull et al., 2014).

4.4. Energy-landscape modelling applied in the 1860s and 1999

To run the *ELIA* model we have to work with spatially-explicit energy carriers and coefficients (as measured in 1x1 km^2 sample cells, Figure 3.3). Figure 3.6 shows both the theoretical and the empirical *E – I – L* relationships in the Vallès County in a two dimensional projection of a three dimensional figure. Lowest theoretical values of *L* correspond to lowest values of *I* for each *E*; furthermore, for intermediate values of *E*, *I* attains its maximum (Figure 3.5a). This phenomenon is less evident in the empirical case of the 1860s, where points are closer than in 1999 (Figure 3.5b). This is due to the fact that in the 1860s the cells' land-cover distribution is similar, being tightly integrated to one another and having all of them higher energy complexity and higher information embedded. Conversely, in the 1999 there is more diversity among the cells' land-cover distribution, owing to the simultaneous loss of landscape functional structure, energy complexity and site-specific information. This means that by applying *ELIA* to the selected size of cells we are capturing the socio-ecological role of the typical Mediterranean agro-silvo-pastoral mosaics that existed c.1860, and tended to vanish in the 1999.

To sum up, the higher values found in 'energy storage-reuse' (*E*) and 'energy message-information' (*I*) in the 1860s (Figure 3.5b) correspond to a lower dissipative structure, which was imprinted in the agroecological landscape (*L*) according to the typical mosaic shape of a 'mixed-farming' system. Instead of that, cells in the 1999 show a more polarized pattern, where some 'natural' landscapes (involved in forest transition) have low dissipative structures, while most 'industrial-intensive' landscapes (intensified cropland, feedlots that rely on imported feed and urbanized areas) are highly dissipative structures. These results highlight the bio-cultural role that the information embedded in the land matrix (*I*) plays as a crucial link between socio-metabolic energy looping fluxes (*E*) and landscape functioning (*L*) in agroecosystems (Marull et al., 2015c).

This also has an impact in terms of material conditions for farm-associated biodiversity. While c.1860 most points matched high levels of *E* and *L* at the same time (with ranges of 0.6-0.8 of *E* and the most part of them over 0.5 of *L*), in 1999 the contrary was true. There, we find how cells with higher values of *E* (more than 0.6) had low values of *L* (lower than 0.3), while the higher land cover heterogeneity and habitat differentiation (values over 0.5) coincided with values of energy storage lower than 0.4. Therefore, we observe in current agroecosystems a *land sparing* dynamics, where the latest areas with agro-silvo-pastoral mosaics coincided with the most perturbed ones. As a result, we deem that the most likely outcome has been a worsening of the material conditions for farm-associated biodiversity in 1999 compared to c.1860.

5. Discussion and conclusions

The main aim of this chapter has been to test the hypothesis that what lies behind the deterioration in the energy yield of agroecosystems, as a result of the current crisis of the rural world that is losing its age-old capacity to keep an integrated land-use management, is a considerable decrease of landscape efficiency, related to a misplacing of information held by energy fluxes (local farmers' knowledge) and its mutual interplay with energy-loop complexity.

We have built an *Energy-Landscape Integrated Analysis* (*ELIA*) that allows us to measure both the energy storage as the complexity of internal energy loops, and the energy information held in the whole network of sociometabolic energy fluxes, in order to correlate both with the energy imprint in the landscape functional structure. The case study shows how landscape heterogeneity of Mediterranean land-use mosaics, created by traditional organic mixed-farming, tended to vanish as a result of simultaneous reduction in the complexity of the interlinking pattern of energy carriers flowing across the land-matrix and the quantity of information carried by them. From this case study we draw two main provisory conclusions, and a future research agenda:

Firstly, that the path followed by 'industrialized-intensive' agroecosystems which get rid of internal reuses to rely on increasing external fossil inputs has led to a loss of habitats in a simplified and monotonous landscape, in spite of the simultaneous 'land sparing' effect of steep land abandonment and forest transition that has taken place in the meantime. Land-use intensification and abandonment have been the joint outcome of giving up the former integrated multiple-use of farm systems. Both have entailed a reduction in land-cover diversity and ecotones. Even if the amount of unharvested biomass free to feed ecological food chains has increased as a result of land abandonment, this has probably only enlarged the population of some species because of the lack of habitat differentiation in the land-matrix. Recent studies in Mediterranean cultural landscapes reveal that the conservation of a heterogeneous and well-connected land matrix with a positive interplay between human disturbances and land-cover/land-use complexity are able to hold high species richness at regional scale (i.e. birds; Marull et al. 2015a), landscape scale (i.e. orchids; Marull et al. 2014) and local scale (i.e. butterflies; Marull et al. 2015b). Hence, the apparent land-use polarization experienced in the 1999 (Fig 3.5b) has entailed an interlinked decrease in energy complexity, site-specific information held and land-cover richness, leading to a likely loss of landscape capacity to host biodiversity.

Secondly, we infer that the opposite strategy of more 'sustainable' agroecosystems, which consists of saving external inputs by replacing them with internal reuses, also requires achieving a balance between human appropriation of net primary production and keeping high biodiversity in the landscape. By reinvesting as reuses a relevant share of the harvested biomass, and maintaining an integrated land-use management, organic farmers seek to balance human pressure on the land with the increasing complexity, information and resilience of agroecosystems. This strategy will also have an upper limit though, given that up to a point increasing harvested phytomass, either reused by farmers or consumed outside, will decrease the unharvested share let free for farm-associated biodiversity. We deem that beyond a threshold land-use intensification will no longer be 'sustainable' even in organic agriculture.

In the same vein, the capacity provided by organic agroecosystems able to shelter a high farm-associated biodiversity needs to be supplemented by natural protected spaces which offer refuge for the surviving populations of many species that recolonize the land matrix after each farming disturbance, as well as of sanctuaries for some rare highly-specialist species unable to withstand recurring disturbances, thus complementing both strategies (Tscharntke et al. 2012). By linking these protected sites one another, the heterogeneous cultural landscapes which host a rich *alpha* and *beta* biodiversity may also provide suitable ecological connectors to ensure *gamma* biodiversity at the regional level—as argued by a land-sharing approach (Gabriel et al. 2006). We deem that by combining landscape ecology metrics with a measure of the site-specific energy-information interplay exerted by farming, a useful assessment can be made to capture the underlying dynamics between land-use patterns and species richness. However, we deem more improvements could be done for information indicator in order to better capture the role of social metabolism on structuring the agroecosystems in the interplay between farmers' decisions and the capabilities of the territory.

Confirming or rejecting these provisory hypotheses requires further research applying *ELIA* to more locations and time periods, and using large biodiversity datasets in order to find out where the abovementioned critical thresholds in energy throughputs and the information-complexity interplay are placed. This research agenda would help to reveal how and why different agroecosystem managements lead to key turning points in the relationship of the pattern of energy flows with landscape ecological functioning and biodiversity.

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CHAPTER 4. DOES YOUR LANDSCAPE MIRROR WHAT YOU EAT? LOCAL FOOD SYSTEM ANALYSIS [10]

1. Introduction

As we explained in chapter 1, farm systems are currently experiencing the effects of the prevailing food regime (McMichael, 2016). Global changes in food trade, along with new dietary patterns and food demands from consumers, have shaped the regional specialization of farm producers. Purchasers of these globalised food baskets have become increasingly alienated from foodscapes that farmers cultivate in ever more distant locations, and vice versa (Leguizamón 2016).

Under this prevailing globalized system, cheap agro-industrial food has been transformed into a highly branded, packaged and de-spatialized commodity severed from time (e.g. season), space (e.g. landscape) and culture (e.g. meaning) (Weis 2010). Indeed, cheap oil subsidizes the huge amount of biomass globally traded that experienced a 5-fold increase from 1962 to 2010 (Mayer et al. 2015). Most people in the Global North buy their food in supermarkets, often without knowing anything about where it comes from or which social and ecological impacts it entails. Meanwhile, most of the information and the decision-making power is kept at the headquarters of transnational agribusiness, far away from the actual labour needed to produce this food and far from its consumption (Friedmann 2016). For these corporations, the only relevant link between both extremes of the food chain is the price paid to the producer, and the one received from the consumer.

New social movements, like La Via Campesina, have brought this issue to the forefront, putting food sovereignty in research programmes and decision-making agendas worldwide (Edelman et al. 2014). They want a relocation of agri-food chains, so as to empower peasant producers as well as urban and rural consumers, and to raise collective awareness about the socio-ecological consequences that the prevailing food regime carries. From a research standpoint, this emerging social demand can be met with the study of social metabolism, a way to overcome current cultural alienation by carefully accounting the material and energy flows moved across food chains, from farmers working in agroecosystems to the tables of consumers and their kitchens' dustbins (Gliessmann 1998; González de Molina and Toledo 2014). This socio-metabolic scanning may help us realize that what we eat, wear, and burn is always generating socio-ecological imprints on the environment (Infante-Amate et al. 2014). Given that agroecosystems are the result of the complexity of both ecological and social systems interacting (Kay and Schneider 1994), a socio-metabolic analysis of food regimes cannot be generated from a single dimension. The multiscale character of food chains (Tello and González de Molina, 2017) demands a new holistic approach in natural and social sciences (Tilman and Clark 2014).

Food sovereignty is aimed not only at criticizing current agri-food systems, but also to open the way for other, more sustainable ones. This chapter has a unique approach to show this, as it offers a historical perspective from which we can learn for the future. We will incorporate

[10] I carried out this research as corresponding author together with Inés Marco, Claudio Cattaneo, Jonathan Caravaca and Enric Tello. While my main contributions were on building the socio-metabolic analysis together with Inés Marco for c.1860 and 1999, Claudio Cattaneo and Jonathan Caravaca were responsible for the 1956's one. I also contributed designing the methodological proposal made in sections 3.2 to 3.4, as well as linking results with current debates. We discussed the results altogether among all co-authors, but I was responsible for writing the main part of the text, except for section 3.1 that was mainly done by Inés Marco. I want to thank Francesc Coll as well for calculating the *EMS* for the case study. The research is currently in press by Springer, in a book on *Socio-metabolic Perspectives on the Sustainability of Local Food Systems* edited by Eva Frankova, Willi Haas and Simron J. Singh (Padró, Marco, Cattaneo, Caravaca, & Tello, in press).

the food system analysis to observe how changes are also driven by transformations in diets by introducing the consumption analysis into the production one that we have already been carrying so far. Studying the socio-ecological transition from a past organic agri-food system to the current industrial ones is an opportunity to perform a natural experiment aimed at identifying crucial points, linkages and limits from a systemic point of view (González de Molina and Guzman 2006).

We are going to use the same case study located in Vallès County (Barcelona Metropolitan Region, Catalonia) as in previous chapters, but including a new time point for 1956. Starting from an organic local food system with a vineyard specialization, we study the evolution into a highly globalized industrial one. We are going to analyse the agroecosystems of these four municipalities c.1860, and in 1956 and 1999, from a multidimensional and multi-scalar perspective to draw some general conclusions from the socio-ecological transition carried out in food production and consumption. The socio-metabolic patterns at the start and the end of this period were extremely different. In 1860, winegrowing specialization coexisted with a subsistence-oriented organic farming that kept a significant level of self-reliance (Garrabou et al. 2007). In 1956, the resumption of grain growing, combined with an incipient use of industrial fertilizers, led to a more diversified agroecosystem where greater dependence on external inputs was countered by increased productivity; this provided a more balanced diet, and produced lesser impacts on the local landscape ecology. In 1999, a specialization in feedlots disconnected local diets from a linear agro-industrial feed-meat chain, based on huge feed imports from the Global South which entail strong socio-ecological impacts both locally and worldwide.

By comparing these very different agri-food systems four key dimensions are brought to light: 1) the evolution of agricultural labour productivity and its connection or disconnection with regional diets; 2) the importance and increasing loss of multi-functionality in agroecosystems; 3) a significant loss of landscape ability to host biodiversity; and 4) the strong socio-ecological impacts of the current food regime at global and local scales. Combining them, we gain a multidimensional perspective of the socio-ecological functioning that links production and consumption with the satisfaction or dissatisfaction of human needs, and with socio-ecological patterns and processes at different scales. Throughout the period studied all these factors were modified following nutritional transition and agroecological change from organic to industrial farm systems. Behind them there lay the overall energy transition to fossil fuels, a growing socio-metabolic rift in the circulation of nutrients in and out of soils (Clark and Foster 2009), and a vanishing of former landscape mosaics (González-Bernáldez 1981; Levers et al. 2015) which kept a great deal of farm-associated biodiversity (Altieri 1999).

2. Materials and methods

By using material-energy-flow accounting (MEFA), we develop an analysis of the Vallés agroecosystem over three time periods in order to profile the socio-metabolic transition from organic to industrial agriculture. This allows us to identify different patterns and drivers of transformation along the socio-metabolic transition from traditional organic to industrial farming. Therefore, we will again make use of the former energy balances from Chapter 2.

In this chapter, we propose a step forward towards a multi-scalar analysis (Giampietro et al. 2008) considering the local food system embedded in the global food systems. As this chapter focuses on the dimension of local food systems, and how socio-ecological transition shaped the external links and internal synergies of the agroecosystems, we perform an analysis through four different perspectives: population, land-uses, landscape, and the global food system. In doing so, we refer to three theoretical frameworks: analysis of social metabolism, landscape ecology, and political ecology.

2.1 Social metabolism in agroecosystems: population and land-use perspectives

Our analysis regarding social metabolism in agroecosystems takes two different elements into account: on the one hand, satisfaction of human needs; on the other hand, we acknowledge the multifunctional role that different land-uses and livestock may or may not have. We consider the agricultural active population as the main fund of an agroecosystem, together with other basic funds such as the farmland, the livestock, and the farm-associated biodiversity.

In order to get an adequate profile of the agroecosystem functioning, the analysis has to take into consideration that the labour cost to provide food to society is as important as the ability of the agroecosystem to keep providing the required biotic materials over time. Section 3.1 assesses the evolution of the agricultural labour energy productivity (ALEP), i.e. agricultural produce obtained per unit of labour, and its linkages with the potential capability of the agroecosystem to cover local human needs of subsistence through food and fuel '*satisfiers*'. This potential capacity would depend on (i) the composition of agricultural produce, (ii) food and fuel requirements per capita according to the prevailing diet, (iii) the percentage of the workforce engaged in agriculture, and (iv) population density. Following these steps, we first compare agricultural labour productivity with food and fuel biomass requirements per capita, thus assessing which was the surplus or deficit per farm worker at different levels of aggregation. We then compare if this fits the ratio of non-agricultural population per farm worker, observing whether local food and fuel produce was adapted to local food and fuel demand.

In order to assess the energy performance of these contrasting farm systems in a way that does not conceal their internal agroecological reproduction. We will use the accountancy methodology explained in Chapter 2 and furtherly developed in Annex I. Agricultural labour productivity is estimated through the agricultural produce per farm worker, thus dividing the agricultural produce by the total number of farm workers at each time point. Units of labour are defined as full-time Agricultural Working Units (AWU) a year. Diet composition for the mid-19th century is based on a thorough research made by Cussó and Garrabou (2001) supplemented by contemporary historical sources such as the *Estudio Agrícola del Vallès* (1874) (Garrabou and Planas 1998). For the 1954 and 1999 diets, we have used Catalan averages gathered in the Household Budget Survey made in 1963-1966 (INE, 1969), and statistics of consumption (DARP, 1999).

In order to avoid a bias in our results due to the effect of winegrowing specialization c.1860, given its very low energy content, and considering it a cash crop linked to its exchange value more than to its use value, we propose a slightly different approach to assess it. We transform wine surplus into an equivalent of food (such as bread or legumes) through market prices taken from regional cadastres (*amillaramientos*).

Regarding household fuelwood consumption patterns, we have reviewed historical and current data (Sancho et al., 1885; FAO, 1983; Reddy, 1981; Wijesinghe, 1984). Based on these references, we propose an average daily consumption of 1.56 kg of firewood for heating and cooking, adapting the estimation to climate and seasonality (Giampietro and Pimentel, 1990; Colomé, 1996; Bhatt and Sachan, 2004).

In section 3.2 we evaluate the loss of multifunctionality through energy accounting. Going beyond a purely efficiency analysis, the methodology followed in this chapter also allows us to show how the energy flows from a specific fund contribute to different types of services. As has already been assessed, either from a physiological or from a socio-metabolic perspective (Krausmann, 2004), the metabolizable energy incorporated by livestock is distributed into different energy carriers of different qualities (e.g. it can produce milk, but also manure, draft power as well as heat). We will then take these different services of the agroecosystem (fertilization, food, power for tillage) to analyse the share of them that are provided by livestock at the three time points.

2.2 Landscape Ecology Indicators as a proxy for material conditions to host farm-associated biodiversity

A further dimension analysis refers to landscape ecology. We adopt a *land-sharing* approach and assume that intermediate levels of human intervention in agroecosystems can benefit *beta* biodiversity – related to differentiation among habitats – compared to non-intervention (Gliessmann 1998; Marull et al. 2015). We define farm-associated biodiversity as communities of non-domesticated species that are a part of, and play a relevant role in, the reproduction of an agroecosystem (Altieri, 1999). They provide ecosystem services, but are not the focus of farming activity, and depend on the dispersal ability of a landscape to provide proper material conditions for the survival of these and other non-farm related communities (Loreau et al. 2003; Tscharntke et al. 2012).

In order to assess these conditions for farm-associated biodiversity, we will take into account the interaction among social metabolism and landscape patterns, by using six indicators: the amount of biomass left to non-domesticated food chains *(UB+FBR+LS*); the ecological disturbance exerted by the flows of social metabolism (*EI; NPP_{act}EROI; and AFEROI*); habitat differentiation (*L*); and landscape fragmentation (*EMS*). We add a measurement of the barrier effect to the landscape material conditions for farm-associated biodiversity, a crucial issue regarding the dispersal capability of many species to withstand human disturbances exerted at plot level. However, while in the previous chapter we were laying the foundations for a new methodological proposal, here we only want to evaluate at an aggregate scale the trends in those indicators that we deem could be relevant for farm-associated biodiversity maintenance.

The first indicator is the energy left for farm-associated biodiversity. Based on the progress made in *ELIA*, here we consider only the flows that are directly devoted to non-domesticated heterotrophic chains. That is: the *Unharvested Biomass*, the biomass aimed to restore soil fertility (*Farmland Biomass Reused*), and the flux of manure from livestock (which is most of the *Livestock Services*). All these fluxes are relevant for ecological food chains, considering that biodiversity is not only the biota found aboveground in the habitats offered by different land covers that exist on a landscape, but also belowground into the soil biota.[11]

Therefore, we include three indicators, developed from the *EROI*, which account for the disturbance exerted by human activity. We start with *External Inputs*. Then, we calculate the methodological proposal on *NPP_{act}EROI* (Galán et al. 2016), which is the ratio of the *Actual Net Primary Production* (*NPP_{act}* as defined in Vitousek et al 1986) to the *External Inputs* and *Biomass Reused* (as a proxy of human ecological disturbance)[12]. We are also interested in the Agroecological *FEROI* proposed by Guzmán and González de Molina (2015), which accounts for the land cost of producing an amount of final produce regarding the total investment made, which also includes the *Unharvested Biomass*.

The fourth indicator relies on the Shannon index to account for landscape heterogeneity (Vranken et al. 2014), a key mechanism for biodiversity's habitat maintenance (Loreau et al. 2003). Spatial habitat differentiation is also associated to margins management, which reinforces

[11] Here we want to notice that we have not considered belowground biomass flows in any of the balances. True, we know that belowground food chains are highly relevant for the whole functioning of the agroecosystem. However, in order to carry out a comparative approach we consider it does not invalidate the whole analysis. We are aware this is something missing that has to be improved when dealing with further approaches that would aim to capture biodiversity.

[12] We make notice these indicators are derived from the *Energy Return on Investment* (*EROI*) that is calculated through energy analysis: *External Inputs* mean those flows coming from outside the agroecosystem boundaries; *Biomass Reused* is the share of *NPP_{act}* devoted to maintain the livestock, or farmland soil fertility; *Unharvested Biomass* is the share of *NPP_{act}* that remains available for the associated biodiversity; *Final Produce* is the total amount of *NPP_{act}* that is available to be consumed by the farming community or that goes outside the agro-ecosystem. For a deeper definition of these concepts, see Tello et al. (2016). Once the flows have been calculated, the indicators are the following: $NPPEROI = \frac{NPP_{act}}{BR+EI}$ where *BR* is the *Biomass Reused* and *EI* the *External Inputs*; $AFEROI = \frac{FP}{BR+EI+UB}$ where *FP* is the *Final Produce* and *UB* the *Unharvested Biomass*.

ecosystem services such as plague and disease control, in turn enhancing the farm-associated biodiversity (Holland et al. 2012). Finally, we also account for other aspects of social metabolism that are beyond agrarian activity, such as fragmentation of habitats due to linear transport infrastructures as well as patch dimension, using the *Effective Mesh Size* (*EMS*; Jaeger 2000). This latter indicator accounts for the probability that any two random points in a region may be connected, i.e. not separated by barriers. Both indicators are landscape metrics that can be calculated through GIS analysis of digital land cover maps. To this aim, we divided the whole surface of the four municipalities into 95 squared cells of 1 x 1 km^2. Calculating the *Shannon Index* requires assessment of the ratio of land-uses in the total surface, while for the *Effective Mesh Size* only the surface of each patch is needed[13].Then, using these six indicators, we can gauge trens on how socio-metabolic transition has affected the material conditions for farm-associated biodiversity.

2.3 Global and local effects, political ecology

The interpretation of our results is based on a political ecology perspective, assessed in terms of who gets the environmental benefits of a foodscape and who has to bear the environmental costs. As we have outlined in previous sections, current regional specialization in Vallès County in industrial livestock fattening is supported by the global food regime via massive feed imports (McMichael 2016). We therefore focus on the agroecosystem's ability to host livestock density, and its political ecological implications. Our aim is to assess to what extent an unequal exchange of environmental benefits and impacts might be at stake. Thus, to implement this approach, we estimate the carrying capacity of the agroecosystem studied to host different livestock densities, taking into account local productivities and the total metabolizable energy required by current animal diets (Church 1984; FEDNA, 2010; Flores and Rodríguez-Ventura 2014; Instituto Nacional de Estadística 1999). Then, imports have to be considered for all the animal feed not supplied from local sources. In order to identify the source of the different feed imported, we use international trade statistics at regional and State level to calculate the apparent consumption, that is, the share that is produced in the area (Catalonia or Spain), the non-consumed part, and the imports from any other countries (SEC 1999)[14]. To approach the virtual land cost of industrial livestock fattening with feed imports, we calculate the hectares required using FAO's average land yields of each crop. This allows us to identify hot spots in countries specialized in supplying this feed and then, through a bibliography review, to refer to the ensuing impacts in their landscapes.

Obviously, we are aware this is a strong assumption. Despite the vertical integration that exists in Catalonia, we cannot know at the municipality level where the imports really come from. However, we presume a similar behaviour of farmers along the State regarding the origin of their feed. Therefore, the average consumption pattern can be inferred, cautiously, to the local level, always keeping in mind that patterns are from State and regional level and not local. While assuming the probable uncertainties, we deem this still has explanatory effect on current trends.

Finally, we focus on the internal impacts on the local agroecosystem functioning that these feed imports generate. We gauge how livestock breeding specialization is overproducing dung that exceeds the requirements and, again by reviewing bibliography, how this pollution

[13] The mathematical expression of the Shannon Index, modified for agrarian metabolism, is shown in chapter 3 as $L = \left(-\sum_{i=1}^{k} p_i log_k p_i\right)(1 - p_u)$ where p is the share of surface for each land-use, k is the number of land covers not considering the urban ones, and p_u the share of urban area over the total. On the other hand, the formula for the Effective Mesh Size, using the definition given by Jaeger (2000), is $EMS = \frac{1}{A_t}\sum_{i=1}^{n} A_i^2$ being A_t the total surface, n the number of patches, and A_i the surface of each patch.

[14] In Catalonia, vertical integration on pig feeding accounts for around 75 % of the feedlots, and the greatest share of livestock measuring it in total weight. So it seems reasonable to estimate that its' consumption of feed will have a similar pattern in international sources as the Spanish and Catalan one, regarding data used (Observatori del Porcí 2009).

raises concerns that require new researches and policies addressed to relocate and downsize the sources of these impacts.

3. Results and discussion

3.1 Agroecosystem as a human needs satisfier

3.1.1 Modern nutritional transition in Vallès County

We assume that, either historically or at present, the main aim of society-nature interaction by means of agroecosystems is to satisfy *subsistence* needs, mainly through food and fuel. No doubt these *satisfiers* are not static, but shift over time. Although dietary needs have not changed throughout time, as endosomatic energy requirements are fairly constant (Lotka 1956), dietary composition have changed dramatically between 1860 and the present. A modern nutrition transition (Popkin 1993; Smil 2000; Cussó and Garrabou 2007) took place in Europe from the beginning of the 19th century to the end of the 20th century, with different paths between Northern and Southern Europe. This process entailed a change from a local, seasonal, eminently vegetarian and often monotonous diet, to a diversified, excessive, unbalanced and globalized diet (Cussó and Garrabou 2010).

However, at the same time, the substitution of traditional renewable energy carriers (manpower, firewood, wind and water) by modern fossil-fuel ones (coal, gas and oil) has occurred. Gales et al. (2007) found that the contribution of traditional biomass energy carriers to total energy input was less than 50 per cent in the Netherlands and the United Kingdom in 1864, but not at this level in Italy and Spain until the 1940's. Both nutritional and energy transitions involved a disconnection of food and fuel consumption from farming communities and their agroecosystems (Kander, Warde and Malanima 2013).

Table 4.1. Change in diet composition for Vallès case study c.1860, 1956 and 1999. Source: Our own from sources detailed in text.

Products	1860		1956			1999		
	Fresh Weight	Metabolizable Energy	Fresh Weight		Metabolizable Energy	Fresh Weight		Metabolizable Energy
	gr·day⁻¹·cap⁻¹	kcal·day⁻¹·cap⁻¹	gr·day⁻¹·cap⁻¹	Variation Rate (%)	kcal·day⁻¹·cap⁻¹	gr·day⁻¹·cap⁻¹	Variation Rate (%)	kcal·day⁻¹·cap⁻¹
Bread	437	1,149	302	-31	793	192	-36	504
Olive oil	15	135	72	380	643	59	-18	425
Wine	214	130	165	-23	100	287	74	167
Other cereals	92	325	32	-65	112	19	-41	69
Pasta	-	-	15	-	55	15	0	54
Legumes	74	41	33	-55	18	15	-55	54
Potatoes	460	327	238	-48	170	119	-50	86
Vegetables	293	75	223	-24	57	300	35	107
Fesh fruits and nuts	52	83	225	333	239	200	-11	72
Fish	30	34	66	120	76	90	36	103
Meat	88	306	83	-6	258	192	131	580
Eggs, milk and cheese	-	-	223	-	179	394	77	265
Others	10	5	30	200	119	524	1,647	382
Total	**1,765**	**2,610**	**1,707**	**-3**	**2,820**	**2,406**	**41**	**2,869**

Changes in Catalan diet (Table 4.1) are in line with the Spanish nutritional transition (Cussó and Garrabou, 2010). From a Mediterranean diet, based on a great consumption of bread, potatoes and legumes accompanied by vegetables, fruits and fresh or salted fish, including some pork and mutton as main contributions of animal origin; to an increasingly globalized diet with a greater prominence of animal products (Nicolau and Pujol, 2005). Circa 1860, 70 % of the total dietary intake in ME were cereals, legumes and potatoes. This percentage was reduced to 40 % in 1956 and 25 % in 1999. Consumption of animal products has experienced a 4-fold increase, from 12 % of total intake c.1860 to 15 % and 30 % in 1999, which equals the peak reached at Spanish scale (Marrodán et al. 2012; Infante-Amate and González de Molina 2013; Infante-Amate et al. 2015; Soto et al. 2016). Whereas in the first interval, from 1860 to 1956, dairy products and eggs were the items that increased the most, from the 1950s it was meat, as happened in other European countries (Teuteberg et al. 1999). Current protein intake comes from animal products which have replaced legumes, despite the fact that the latter are much more energy efficient to produce. On average 6 kg plant protein is required to yield 1 kg meat protein (Pimentel and Pimentel 2003; Smil 2000).

Moreover, population growth in the Vallès adds pressure on local agroecosystems. If meat produce per person and year has increased 4-fold throughout the period studied, increase of total meat requirements has grown by a factor of 19 when we include the effect of an increased population density. Given the lower bioconversion efficiency, and the astonishing land requirements to feed this huge livestock increase, strong environmental pressures have ensued due to this dietary change (Smil 2002; de Boer et al. 2005), as discussed in greater detail in section 3.4. Finally, processed food, which involves high levels of embodied energy through its industrial transformation (Infante Amate et al. 2014), has also boomed during this period, from 0.2 % to 13 %. All this points to the fact that globalized diets are clearly no longer linked to natural resource endowments at local and regional scales, as age-old practices were.

3.1.2 *Evolution of labour productivity, agricultural surplus, agricultural population and total population*

From the beginning of the 20th century, but particularly in the second half of the century, the introduction of chemical fertilizers has increased yields. Rainfed wheat yields rose from 1,135 kg/hectare (fresh weight) to 1,231 in 1956 and 2,795 in 1999. Mechanization boosted total power capacity from 449 kW (only human and animal power) to 780 kW in 1956 and to 12,065 kW in 1999.

Labour productivity increased, on the one hand due to the abandonment of traditional fertilizing techniques, but on the other because machinery replaced human and animal labour. *Final Produce* (*FP*)[15] per farm worker and year rose from 128 GJ to 204 GJ, and then to 1,249 GJ in 1999 (Table 4.2), that is, 67, 106 and 650 MJ/h respectively. This increase has more to do with the decrease in the total number of farm workers (-87%) than to an increase of *FP* as such (this only grew by 19%). In turn, farm workers were substituted by capital, with a dramatic growth in external inputs and consequent decrease in *EFEROI*[16]. At the same time *FP* in Vallès County shifted through the whole period, from a pretty balanced composition between cropland (34 %) and woodland produce (65 %), and a residual share of animal *FP* (1%), to an animal-produce specialized system (76 % of FP) (chapter 2). But how have these changes in agricultural production, in terms of size and composition, and agricultural productivity been related to local food and fuel consumption, agricultural labour and demographic dynamics?

In the mid-19th century, we estimate that FP per farm worker and year was 22 GJ of food and wine, equivalent to the dietary needs of more than 5 male adults, and 108 GJ of woody biomass, equivalent to the fuel needs of nearly 10 people: with a farmer every 4 people, local food and fuel needs could be more than satisfied. Notwithstanding, if we distinguish between different food typologies, unbalances emerge: winegrowing specialization (64 % of cropland area) implied a shortage of cereals, which were imported from inner Spain (Garrabou et al. 2007; Garrabou and Tello 2008). Therefore, although farmers' surplus was just enough to satisfy the dietary needs of the local population, a balanced diet could only be achieved through commercial exchange, thus c.1860 the Vallès was not entirely a local food system. We estimate at that time that at the aggregate level, 69% of food requirements were locally produced.

In 1956, food and fuel requirements had not changed a great deal from the 19th century. Particularly, regarding household fuel consumption, modern energy carriers had not yet spread broadly, and less so in rural areas. Arroyo (2006) estimates that in 1956 only 13 % of households in Barcelona used gas for cooking and heating; this percentage drops to 11.4 % and 8 % for the nearby industrial towns of Sabadell and Terrassa. Gas cylinders only started to be widely used from the 1960s onwards. The increase in labour productivity – food surplus grew by 60 %, allowing each farm worker to supply produce to nearly 9 male adults — was more than offset by an increase in the total population density (+51.7 %), and a decrease in agricultural workers (-43.9%). In contrast to both 1860 and 1999, in 1956 there is no evidence of any outstanding specialization, and agroecosystem produce was sufficient in quantity and diverse enough to supply practically the whole population's requirements, including cereals and vegetables. The end of winegrowing specialization, after the *Phylloxera* plague (Badia-Miró et al. 2010) and the partial substitution by herbaceous and vegetable crops, along with the beginning of livestock dairy specialization in the Vallès, may explain this change. It still appears a very tight, albeit reduced, adjustment between farmers produce and population needs, with no need to import. Indeed Spain was just leaving behind the autarchic period imposed by Franco's dictatorship.

[15] This flow refers to that part of an agroecosystem's products and services (from agriculture, livestock and forestry) that is destined to final use or consumption, as explained in Tello et al (2016).

[16] The External Final EROI (EFEROI) is calculated as follows: $EFEROI = \frac{FP}{EI}$ where FP is the Final Produce and EI the External Inputs (Tello et al. 2016); Biomass Reused is not included.

Table 4.2. Comparison between Final Produce per farm worker and adult food and fuel requirements for Vallès study area c.1860, 1956 and 1999. Source: Our own.

Products		1860 Produced	1860 Required	1860 Self-sufficiency[b]	1956 Produced	1956 Required	1956 Self-sufficiency	1999 Produced	1999 Required	1999 Self-sufficiency
		GJ/L·farm worker^{-1}·year^{-1}		%	GJ/L·farm worker^{-1}·year^{-1}		%	GJ/L·farm worker^{-1}·year^{-1}		%
Vegetables, Fresh fruits, Nuts		2.1	0.9	60%	10.7	0.8	130%	28.9	0.6	31%
Cereals		6.1	2.5	65%	16.7	1.7	96%	19.0	0.9	13%
Livestock Food Produce		1.3	1.0	35%	6.0	0.8	74%	666.6	1.4	295%
Wine		11.0	0.2	1,239%[c]	5.0	0.2	281%	1.5	0.3	3%
Olive Oil		1.8	0.2	212%	0.3	1.0	3%	2.5	0.8	2%
Total Food, Wine and Olive Oil		**22.4**	**4.2[d]**	**137%**	**38.7**	**4.5**	**83%**	**718.4**	**4.0**	**114%**
Woody biomass	**Fresh Fruits and Nuts**	1.1	11.0	253%	8.9	11.0	109%	24.6	-	-
	Vineyard	19.1			1.1			6.1		
	Olive Trees	6.8			3.1			15.3		
	Woodland	80.6			111.6			87.1		
Total Woody biomass		**107.6**	**11.0**	**253%**	**124.7**	**11.0**	**109%**	**133.3**	**-**	**-**
Total Food and Woody biomass		**129.9**	**15.2**	**221%**	**163.4**	**15.5**	**101%**	**851.7**	**-**	**-**
Population data		**Inhabitants**		**Ratio[a]**	**Inhabitants**		**Ratio**	**Inhabitants**		**Ratio**
Farm workers		2,057		3.9	1,154		10.4	250		156.8
Total Population		7,941			12,047			39,189		

[a] Inhabitants per farm worker, which includes non-agricultural population and also non-working agricultural population (mainly children). [b] Self-sufficiency refers to the percentage of the total requirements covered with total produce [c] Note that as we transformed wine surplus into food equivalents (see methodological section), this ratio would be lower in terms of wine surplus over wine requirements per capita. Without this transformation, wine produce per farm worker would be 7.3, thus the ratio would be reduced to 32. [d] Note that total GJ do not coincide with those appearing in Table 4.1, as here we are not including the item Others, and we are referring to Gross Calorific Value while in Table 4.1 we account for Metabolizable Energy .

In 1999, we observe an increase on per farmer productivity – food produce per farm worker was multiplied by 18 – going hand in hand with the combined effect of less farm workers and an even higher population. This implies that at aggregate level more than enough food calories were produced for the local population, however, 78 % of this was animal produce. On the one hand, local animal produce per farm worker could supply the dietary requirement of 463 male adults, and with a farmer every 157 inhabitants, we can expect that Vallès is exporting most of its meat; on the other hand, this huge increase is offset by a fall in the agroecosystem's capacity to supply enough food for the local population. Wood biomass comparison makes no sense in this period due to the diffusion of heat obtained from fossil sources. New consumption patterns linked to supermarket chains and large groceries broke the link with local vegetable and cereal produce. The main purpose of *FP* in 1999 was not to cover local food needs, but to provide livestock produce to markets. This pork, once slaughtered, and some parts processed as inlay, was mainly distributed in Spain and only around 11 % went to consumers abroad, mostly in France, Portugal and Germany (SEC 1999).

Finally, some limitations of this approach need to be highlighted as the results are aggregated and averaged. First, we are accounting for production without considering that land

and livestock distribution was strongly influenced by inequality. Second, labour productivities differ slightly, depending on the kind of agricultural work (e.g. cropland, woodland and livestock). Third, individual requirements refer to an adult male, not to average requirements that would depend on demographic structure. And fourth, we did not include here the need to generate a surplus to cover the local population's other needs, such as clothing, housing, the building of infrastructures and tool repairs.

3.2 The loss of multifunctionality

By assessing the energy balances of these very different farm systems and activities, we capture the loss of their original multifunctionality. In turn, we also identify the unsustainable processes of land-use specialization, as well as the ensuing impacts on emergent properties such as conditions for farm-associated biodiversity at a landscape scale. Below we detail the effects of this loss of multifunctionality on two different agroecosystem funds (land and livestock).

3.2.1 Disturbed fields, silent forests: Land-use polarization

Before the socio-metabolic transition to industrial farming, food and fuel produce had to be in balance with feed production and the maintenance of ecosystem services. In advanced organic agricultures, only some valuable cash crops were profitable enough to allow for imports of nutrients from outside agroecosystems[17]. In turn, land productivity was maintained in these traditional organic farm systems by local nutrient transfers from forests and livestock: fertilization was one of the main drivers of biophysical internal loops, which required a high labour intensity and tight land-use integration. The progressive introduction of synthetic fertilizers, which occurred throughout the 20th century, broke the integration between the basic funds of agroecosystems through these internal loops, and fostered the functional disconnection of agrarian activities. The use and abuse of industrial fertilizers also contributed to the fall in Final and External EROI[18] for the high energy cost of their production (Aguilera et al. 2015; Chapter 2).

In addition to cropland intensification, crop homogenization also occurred. If we measure land cover diversity only for crops with the Shannon Index, we first observe an increase of spatial heterogeneity from 0.59 c.1860 to 0.84 in 1956, mainly because vineyards ceased to dominate the cultural landscape following the Phylloxera plague in the 1880s and 1890s. Afterwards, as a result of the new specialization in livestock fattening in industrial feedlots, heterogeneity was reduced again, to 0.65 in 1999.

At the same time, landscape homogenization probably has given rise to a reduction in the ecosystem services of plague and disease regulation and led to a greater consumption of biocides, from 3.47 kg/ha in the 1960s up to 4.66 kg/ha currently on average. As shown in other case studies, loss of land cover heterogeneity increases consumption of pesticides (Jonason et al. 2013; Landis et al. 2000). Therefore getting rid of biocides requires the restoration of ecosystem services, which in turn means recovering the multifunctionality of integrated land-use management and animal husbandry (Foley et al. 2005).

Synthetic fertilizers and cropland homogenization explain the process of linearization of agricultural and livestock energy flows, where external inputs have replaced internal recirculation

[17] A good example could be the case of biomass imports of *toxo* (*Ulex europaeus*) for vineyard fertilization; these were imported in carts during the 19th century from the interior to the coast in Galiza (North-West of Iberia), as described in Corbacho-González (2015).

[18] Again, this indicator emerges from the proposal of the so-called Energy Return of Investment (Tello et al., 2016). The Final EROI (FEROI) accounts for the energy efficiency of the whole agroecosystem and is calculated with the following formula: $FEROI = \frac{FP}{BR+EI}$, where FP is the Final Product, BR the Biomass Reused, and EI the External Inputs.

of biomass and services. In the same vein, biocides have decreased the rate of Unharvested Biomass with weed management and the ecological services it can provide. Complex agroecosystems have been converted into a simplified soil (Pollan 2008).

In 1860, 18.4 % of the Actual Net Primary Production grown in the whole agroecosystem was needed as Biomass Reused to maintain soil fertility, an energy loop that entailed high labour requirements. By 1956 this share had decreased to 2.0%, and then to 1.6% in 1999 (see also in chapter 2). This is an example of substitution among productive factors, where labour and land – in their mainstream economic meaning – seem to be replaced by external biophysical inputs, which in turn hide embodied labour and natural resources. Thus, the stronger the functional disconnection among agroecological funds is, the higher the required external inputs are, and as we will see in section 3.4, the deeper the socio-ecological impacts on other agroecosystems will be.

Paradoxically, while human disturbance on agricultural land increased with the advance of an agro-industrial system, the transition in household energy carriers to fossil fuels which boomed in the 1960s (Soto et al. 2016) relegated forests to practically providing only aesthetic and conservational functions. The effects of this no-management strategy provided forests with a low quality endorsement and lower internal diversity (Cervera et al. 2017). While woodland area has increased from 35.5 to 56.7 %, mainly in the steepest marginal areas, where agriculture could not be industrialized, its contribution to Final Produce has decreased from 65 to 8 % of FP due to the collapse of charcoal making and wood extraction.

Forests have been the greatest source of final product per unit of labour spent thanks to the lower human intervention required in comparison to agriculture. In 1860, FP per farm worker was 59 GJ in cropland, 968 GJ in woodland and 9 GJ in livestock, respectively. The widespread access of households to gas cylinders, natural gas and oil fuel tanks, which began in the 1950s (Tello et al. 2014), resulted in forest extraction rates dropping from 41.1 GJ/ha in 1860 to 21 GJ/ha in 1956, and to only 3.5 GJ/ha in 1999. Although historically woodland has offered the greatest amount of Final Produce per unit of labour, market prices do not incorporate the positive environmental externalities of sustainable woodland management, or the negative externalities of fossil fuel consumption. Market signals have cancelled society’s ability to supply cooking and heating fuel from local renewable sources. The process of forest transition was reinforced by the collapse of extensive livestock grazing in meadows and wood pastures, a source of animal feeding that covered 16 % of the total animal feed intake circa 1860 and an insignificant 0.1 % in 1999.

3.2.2 Pork is no longer the greater profiteer: losing the functions of livestock

Despite the low energy efficiency of feed-meat animal bioconversion, in traditional organic agroecosystems livestock had been a key factor in closing the greatest part of metabolic cycles: draught power, fertilization, heat emanating from stables, by-products revalorization and, as a complementary source, food. Traditional organic farming kept livestock breeding carefully integrated with cropland, pasture and forestland (Krausmann 2004) – as well as with peasant housing. The multifunctionality of livestock husbandry in the mid-19th century was lost during the 20th century. Mechanization and synthetic fertilizers on the one hand, and nutritional transition and agribusiness on the other, reduced livestock functions in the Vallès to only one: animal food (principally meat, milk and eggs). Livestock densities[19] have increased dramatically from 7 LU500/km2 of farmland in 1860 to 241 in the present, 74% of which are constituted by swine.

[19] We express livestock density with LU500/km^2, meaning the number of equivalent animals of 500 kg per square km.

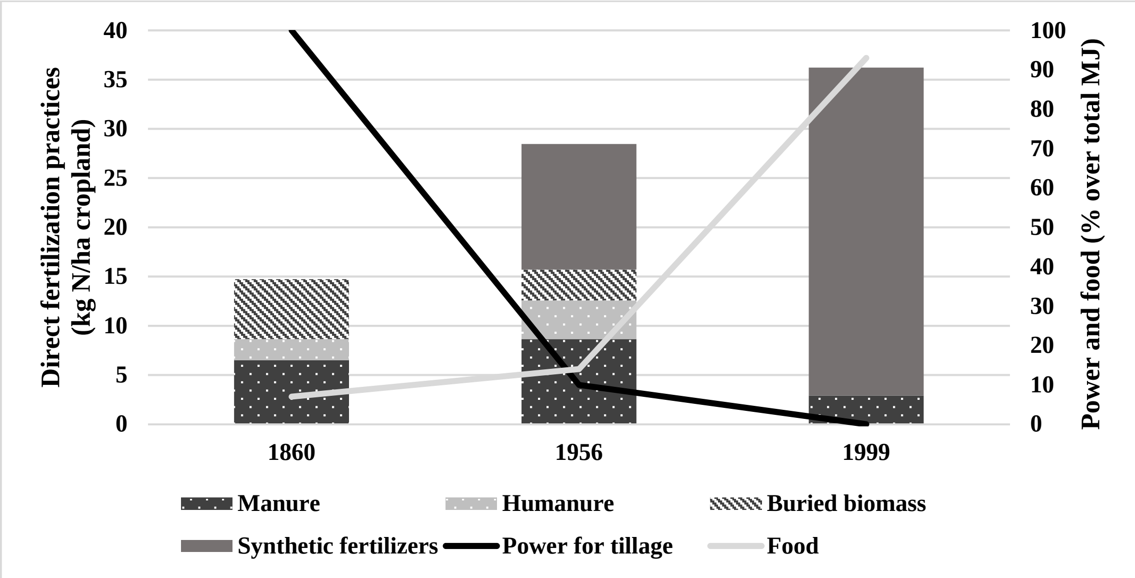

Figure 4.1. Nitrogen supplies for cropping area, share of animal power for tillage and food provided by livestock among the Vallès transition. Source: our own from the sources listed in Chapter 2 and Annex I.

Pigs have also experienced a nutritional transition, from being the best profiteer of residues to becoming responsible for massive grain imports. From being fed with domestic garbage, horticultural and vineyard by-products, to being fed mainly with corn, soybean meal and barley. Today 70 % of swine intake is barley, which entails both a high land cost for its production and a strong competition with human food requirements[20] (Haberl 2015). Not in vain, is the change in livestock density viewed as the main reason for the fall in the whole agroecosystem energy efficiency (Final EROI) from 1.03 to 0.22 (chapter 2). Animal produce constitutes 76 % of Final Produce, and animal intake 73.9% of Total Inputs Consumed. Conversely, c.1860 ruminants were fed in traditional organic farm systems, only one third with grains, because of their ability to degrade fibrous feed that does not compete with human demand of food. This become even more relevant, if we take into account that ruminants were the largest and most diverse source of livestock services in those traditional agroecosystems. Thus, looking at livestock diets can help to understand the role animal husbandry plays in agroecosystems, either integrating energy flows across different funds or contributing to a further linearization of food chains within an input-output, simplified and over-specialized, industrial production system in feedlots.

We can also analyse the different services provided by livestock as a share of the total service in the agroecosystem. As stated before, we consider here the functions of fertilization, the power of tillage, and food provision. Heat obtained from stables – not accounted for in our balances – has been used for centuries for warming farms and houses, thus contributing to minimizing fuelwood demand[21]. Organic fertilization through manure still played an important role in 1956, as can be seen in Figure 4.1, but was almost anecdotal four decades later. Livestock contribution to tillage power was reduced earlier, and in 1956 covered less than 10 % of total installed tillage power despite its high weight in applied tillage power figures. On the contrary, meat production doubled its contribution to the overall production and, as mentioned, had a huge contribution in 1999.

[20] In turn, this entails an associated contradiction: Farmers are giving sodium bicarbonate to ruminants to prevent the acidity produced by the excessive consumption of grains (Ferre & Baucells 2009).

[21] The isolated Catalan farms (*masies*) usually included the stable on the ground floor, where animals stayed during the night, while the chambers were on the upper floor, taking advantage of the animal heat that flowed from downstairs (Closa 2012).

Low livestock densities in the Vallès area c.1860 required integrated land-use management and diversity of fertilizing techniques. As shown in Figure 4.1, at that time the replenishment of nutrients required, besides animal manure, the reintroduction of human dung in the soils and also the burying of biomass which represented one of the most labour-intensive ways to maintain soil fertility as well as an opportunity for nutrient catchment from forestlands. All these diverse biocultural managements were abandoned with the introduction of synthetic fertilizers, which in 1956 accounted for 41 % of total fertilization requirements, increasing to 92 % in 1999. Yet, as we have highlighted in section 3.2.1, current fertilization patterns in most industrialized agroecosystems conceal the new role that pig slurry plays in the feedlots' specialized regions, which is being converted from resource to waste.

3.3 Emergent properties of cultural landscapes: farm-associated biodiversity

The progressive linearization of flows interlinking farmland and livestock funds has implied a partial disconnection of agrarian activities from their endowment of natural resources and an impoverishment in land covers. An emergent property of landscapes rich in land covers is habitat differentiation, enhancing farm-associated biodiversity (Loreau et al. 2003; Tscharntke et al. 2012).

The distribution patterns of farm-associated biodiversity not only depend on the flows that agrarian activity voluntarily or involuntarily devotes to them, but on how land covers are managed by farmers, along with other site-specific physical and biological characteristics. It is, in fact, through habitat heterogeneity at the landscape scale that the best advantage can be taken from ecosystem services for farmers (Power 2010). Therefore, we combine land-use changes with landscape ecology analysis to consider four indicators constituting the landscape – social metabolism interface: *NPPEROI*, *AFEROI*, *L* and *EMS*. We have presented them in section 2.2, and the values found in the study area are shown in Table 4.3. We want to remember we take here those values as proxies in order to identify certain tendencies, as the balance is at aggregated scale.

The measure of biomass left for non-domesticated ecological food chains is a measure of the amount of energy flows left for the associated biodiversity: the higher its amount, the better. On the contrary, External Inputs (EI) can be understood as a measure of anthropic ecological disturbance, so the lower the EI remains, and the lesser the human perturbation is. NPP-*EROI* and A-*FEROI* show how these, and other flows, interact in the whole agroecosystem. Higher values of both are desirable, as the first accounts for the NPP_{act} that an agroecosystem has per unit of farming disturbance exerted, and the second for the amount of final production that goes outside the system boundaries per unit of the overall anthropic effort made to keep the agroecosystem functioning[22]. Finally, higher values of L and EMS show better habitat conditions to host different ecological niches.

[22] It is important to remember that the first motivation of an agroecosystem is to provide biotic materials for a society. Yet the continuous extraction of this final produce involves an ecological disturbance that needs to be kept below a certain level compatible with the reproduction of the agroecosystem funds. Therefore, in order to have sustainable farm systems, production must be balanced to the ecological disturbance exerted through the investment made to keep the agroecosystem functioning (Chapter 3).

Table 4.3. Dynamics of material conditions for farm-associated biodiversity c.1860, 1956 and 1999. Source: our own.

		1860	1956	1999
UB+FBR+LS	$GJ \cdot ha^{-1}$	39.9	34.7	50.9
External inputs	$GJ \cdot ha^{-1}$	1.0	7.8	104.5
NPP_{act}*-EROI*	dimensionless	3.27	3.08	0.55
A-FEROI	dimensionless	0.49	0.25	0.16
L	dimensionless	0.72	0.50	0.38
EMS	Km^2	142.5	135.0	89.0

Our results show an increase in farming disturbance from 1860 to 1956, expressed in the magnitude of *EI* per unit of farmland, together with a slight decrease of biomass devoted to non-domesticated ecological food chains. In the same period, 1860-1956, we observe a decrease in land cover heterogeneity followed by another decline from 1956-1999. This decrease in land cover richness has gone hand in hand with the growing presence of roads and other linear infrastructures whose barrier effects are affecting the ability of wild animals and plants communities to connect with each other.

The most dramatic change occurred during the last time period. From 1956 to 1999, there was a 6-fold drop in $NPP_{act}EROI$, *L* decreased by 24 %, and *EMS* by 34 %. What the $NPP_{act}EROI$ *and Agroecological Final EROI* reveal is to what extent the proportion of *Final Produce* has decreased with respect to the sum of *UB*, *EI* and the *Biomass Reused*. The combined effect of forest abandonment and feed imports have strikingly increased both *UB+FBR+LS* and *EI* with respect to the previous time points. Here, the increase in *UB+FBR+LS* is mainly driven by *UB*, which raised from 30.4 to 46.8 GJ/ha. This socio-metabolic shift has translated into a landscape polarization between abandoned woodlands in the steepest lands, and intensification in flatter ones. This land-use polarization entailed a loss of landscape complexity, and a vanishing of land cover mosaics, which reduced habitat differentiation richness – as the values of their proxy indicators (*L* and *EMS*) show (Marull et al. 2014, 2015; Tello et al. 2014; Otero et al. 2015).

These results reveal that through the time period studied, and particularly in keeping with the Green Revolution from 1956 to 1999, the farming social metabolism gave up its efforts to increase the overall share of biomass harvested, in an unintended land sparing effect, while the disturbance exerted in the remaining cropland increased. Both opposite changes entail agroecosystem degradation, which becomes apparent with the loss of agro-forestry mosaics, and *Unharvested Biomass* accumulation in woodland that make them more fire-prone, and give rise to homogeneous landscapes whose niches grow out of control, leading to plagues – as happens in Catalonia with the wild boar (Bosch et al. 2012). This could explain the lesser variety of ecological niches, and the loss of complexity in ecological food chains, when *UB* is accumulated only in some specific habitats. Besides these agroecosystem metabolism impacts, the barrier effect of linear infrastructures, such as highways, high-speed railway lines, and a significant urban sprawl, have added a strong habitat fragmentation, and a decrease of ecological connectivity between landscape patches that reinforces the loss of the capabilities to host biodiversity.

In short, the role played by agro-forestry mosaics was very important, not only because of the agroecosystem multifunctionality they entailed, but also in terms of the material conditions for farm-associated biodiversity they provided. The socio-metabolic transition towards industrialized farming systems has led to a loss of habitat differentiation, tied to a higher level of disturbance, a greater fragmentation, and a lower ecological connectivity that has grown even deeper in the last decades.

3.4 Expelling socio-environmental unsustainability

3.4.1 Agroecosystems' carrying capacity

Besides the hazard that external inputs represent in terms of linearization of agroecosystems functioning, there are impacts that are hidden when a local scale of analysis is adopted: *External Inputs* (*EI*) are not a cybernetic issue, they imply biophysical flows proceeding from elsewhere with all the energy embodied in their production and transport processes (Tello et al. 2016). In 1999, 74 % of the *EI* energy flow in the Vallès area was animal feeding. In addition to 71 % of local cropland already being devoted to feed products, imports account for 87 % of all the biomass required for livestock maintenance. To put it simply, livestock density in 1999 cannot be supported by the carrying capacity of the local agroecosystem.

Despite the increase of meat consumption per capita, and the higher population densities in Vallès County, this huge livestock density is linked to regional economic specialization in meat production. According to the estimated diets of this area, pork production is 17-fold greater than the requirement for average diet types at present. Considering all types of meat, the study area produces 3 times the dietary requirement of its local population (if they were all male adults; even more if we differentiate by age and gender). Moreover, if all cropland area in 1999 had been devoted to livestock feed, 82% of animal intake would still have to be imported from abroad. In fact, the livestock density that could be carried within agroecosystems boundaries, assuming a complete local specialization of cropland to animal feeding, is 43 LU500/km^2, that is more than 5 times less than the actual one in 1999.

3.4.2 A global land sprawl? The appropriation of the land of others

To gain a better understanding of the footprint of local food systems, it is necessary to expand the scale of analysis. Since social metabolism is no longer closed at local scale, information tends to be hidden at higher scales (González de Molina and Toledo 2014). We have analysed the likely origins of these feed imports, although the limitations of the analysis have to be taken into account. As can be seen in Figure 4.2[23], corn represents the largest feed import item, mainly coming from other Spanish regions, but also probably from France, Argentina and Brazil. Indeed, we estimate nearly 10.000 tons of soybean meal could have to be imported from South America.

Livestock breeding in the four municipalities need an 8.3-fold greater area than the one devoted to cropland within the Vallès study area region. The metabolic rift[24] generated in terms of surfaces of fertile land is enormous, as Lassaletta et al. (2014) have already pointed out in terms of nitrogen flows. Moreover, this estimated food imprint disregards the degradation of agroecosystem funds in feed-supplying countries (Guzman et al. 2011).

The virtual land cost of the intensive meat production performed in the study area is not only associated with local diets being disconnected from their local territory. Actually, only 32 % of the land devoted to agriculture in the mid-19th century in the Vallès is cropped nowadays. This refers to several reasons along the transition but also to a question of the concentration of decision-making power and ejection of unsustainability from the global North to global South; as can be seen in Figure 4.2, the main providers of feed we deem are peripheral countries. Agrarian activities and food consumption baskets in the open economies of the Global North trace impacts

[23] The area of fishmeal is not included as it cames from the ocean. The surface required from the rest of Spain excludes the production inside the Vallès county (which is located in the box). Note that this is an estimation as sources do not allow for local information on feed origin.

[24] We take the definition of metabolic rift from Schneider & McMichael (2010) as "a social, ecological, and historical concept describing the disruption of natural cycles and processes and ruptures in material human-nature relations under capitalism".

on global environment due to market power asymmetry (Garmendia et al. 2016), which underlies unequal economic and ecological exchange (Foster and Holleman 2014).

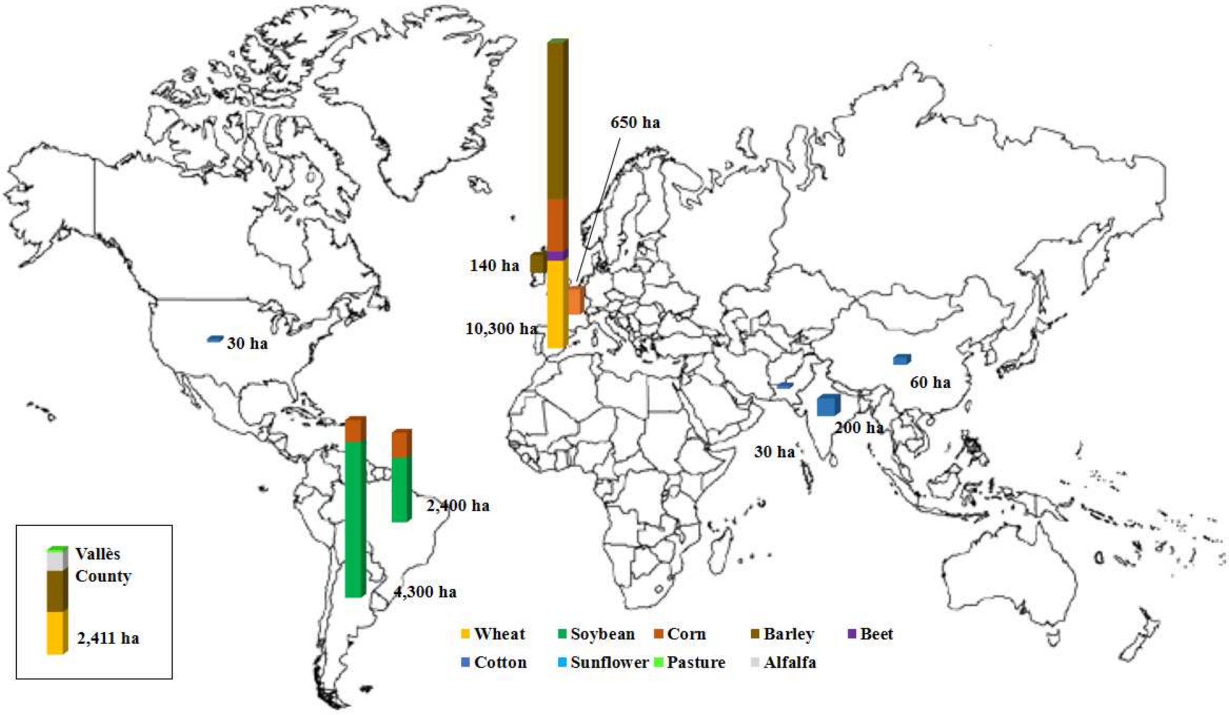

Figure 4.2. Estimated average surface required to maintain the Vallès feed imports for 1999. Source: our own.

For soybean imports, which constitute some 20 % of the total feed imports, we estimate they come mainly from Argentina. Its growth is supplied by an agro-industrial production system whose environmental and social impacts would not be allowed under current Spanish legislation. Agribusiness consolidated in Argentina with the introduction of Roundup Ready^{TM} soybeans in 1996 (Leguizamón 2016). Almost all soya bean produced is GMO, and 90 % is exported. National food security risks, the high volatility of the commodity market, and a handful of large corporations controlling the whole production chain, are only one part of the negative economic and social effects of this food regime. The disappearance of family farms, the displacement of indigenous communities, deforestation, biodiversity loss and health problems associated with the aerial spraying of glyphosate have to be accounted too (Teubal 2008). As Leguizamón (2016) argues, agribusiness chains create a geographic and cultural distance between farmers and consumers that hides its socio-ecological negative impacts. We would also say this socio-ecological distance increases further once this agro-industrial feed is consumed indirectly through livestock bioconversion.

From a farm-associated biodiversity perspective, the impact emerges with the loss of management diversity (Brookfield and Stocking, 1999): in Argentina monoculture is conducted by big estates, larger than 5,000 ha, more than doubling the current agricultural surface of the Vallès (Catacora-Vargas et al. 2012). Obviously, this also entails a landscape homogenization and the ensuing decline of farm-associated biodiversity, as well as deforestation. Moreover, behind these biophysical changes there are also social consequences, such as the impact on the livelihoods of populations affected through the violent process of peasants' expulsion from the land and the loss of subsistence farming (Magdoff 2013). This is what a rough analysis of soybean meal production in Argentina reveals. Similar societal and environmental impacts have been reported with cotton production in India, fish meal in Peru, and soybeans in Brazil (Temper et al. 2015).

3.4.3 *Local socio-ecological costs of global trade*

The importation and bioconversion of such an enormous amount of foreign corn and soybeans is not an inert process for the local territory. From a socio-metabolic perspective, the negative externalities associated to the farming of the imported feed in the producing countries go hand in hand with strong agroecological impacts at local scale. The overall estimated volume of dung produced by animal husbandry in Vallès County is up to 221.700 cubic meters of slurry per year, equivalent to a cubic pool with a 60-metre side. Because of the difference in its concentration of nutrients between grain and dung, the energy cost of returning to the original soils all this biomass, in order to close the nutrient cycles, would be about 5 times the transport cost of feed imports. It is simply entropy that makes it impossible in monetary terms to close such a nutrient cycle.

This animal excreta, which in former historical periods would have been considered a precious resource in a region with a structural scarcity of manure (Galán et al. 2012), is now treated as an economic problem that leads to serious environmental pollution. In other words, within the current globalized food regime it becomes an out of place resource (Odum 1993). This volume of dung, after being composted, could fertilize around 8 times the nitrogen requirements of all the cropping area in the four municipalities of Vallès County. Yet, due to economic decisions adopted in the context of a great atomization of agricultural activities, farmer instead use significant amounts of chemical fertilizers. Pig slurry is thus applied as a pre-planting fertilizer, with rates that even exceed 400 kg N/ha·year (Sisquella et al. 2004), while recommendations are not to trespass a limit of 170 kg N/ha·year on organic amendments (DOGC 2009). Therefore, we calculated only 37 % of all this dung can be actually effective to soil fertility in terms of nitrogen. The rest would produce leaching processes, as well as overconcentration of other nutrients and possible salinization problems (Moral et al., 2008), or wasted if not applied to cropland soil. This nitrogen leaching is polluting local aquifers with a widespread diffuse impact (ACA, 2004). Indeed, over-fertilization is increasing the eutrophication risk in agricultural soils due to the excess of phosphorus and potassium (Penuelas et al. 2009).

Summing up, the metabolic rift driven by cheap fuel prices does not only allow the breaking of nutrient cycles; it also damages the environmental quality of the local aquifers and river streams, as well as being responsible for the opportunity cost of not closing nutrient cycles by recovering multifunctionality of agroecosystem funds both in exporting and importing countries. Not without reason, has part of the scientific community long been calling for a downscaling of livestock densities to the real carrying capacity of soils at a municipal or regional scale, in order to avoid pollution (Teira-Esmatges and Flotats 2003). However, as long as this problem remains a consequence of massive feed imports at global scale, any local assessment will only partially tackle the problem. We deem, the actual solution means devising and implementing agroecological strategies oriented towards local sustainable food systems.

4. Conclusions

During the end of the $19^{th,}$ and the first half of the 20^{th} centuries, the agroecosystem of Vallès County was tightly connected with the food and fuel requirements of the local population. This was so despite the fact that vineyard specialization c.1860 implied a higher dependence on market exchanges. In other words, people were not only living *within* a territory but they lived *of* the territory. Interestingly, in the mid-20^{th} century, increases in labour productivity allowed for a lower share of an agriculturally active population and higher population densities. This could be explained partially by the abandonment of labour-intensive vegetable fertilizing techniques; these were gradually replaced by chemical fertilizers at a time when they were devised to supplement, but never replace, organic manure. During the second half of the 20^{th} century, nutritional and energy transitions, the massive spread of the Green Revolution, and industrial livestock fattening in feedlots, broke all these linkages. Agricultural produce was no longer defined by the local population's food and fuel needs. Labour productivity rose steeply, while the role of agricultural labour within the whole economy shrunk. At the same time, animal produce went on to dominate *Final Produce* composition. New dietary patterns explain both livestock specialization in Vallès County, and the ensuing disconnection between local food requirements and local food produce.

Disconnection with local people went hand in hand with a disconnection of agro-industrial meat produce with the surrounding territory. The abandonment of integrated farmland management during the socio-metabolic transition to industrial farming, and livestock fattening in feedlots, also supposed the atomization and linear behaviour of agroecosystem funds due to the end of many multipurpose farm activities. While production is focused only on maximizing short-term economic profit, disregarding the positive externalities of closing biophysical cycles at local level, the ensuing imbalance among funds (e.g. between livestock and farmland) derived from an ever greater need to rely on external inputs which, in turn, increased anthropic ecological disturbance. Particularly interesting is the case of livestock, whose services have been reduced to only meat production, while their animal diets have lost their former reusing ability and are increasingly competing with human food production. The ensuing disappearance of the former complex agro-forestry mosaics has resulted in a worsening of material conditions for hosting farm-associated biodiversity. Hence, socio-metabolic transition to agro-industrial food systems has led to less variety in food-chains available for non-domesticated species, together with a loss of habitat differentiation. To this, a greater landscape fragmentation has been added as a result of an increasingly polarized land-use pattern between a highly disturbing industrial farming of flatter lands, and the abandonment of steeper ones to forest encroachment.

While in former organic agricultures commercial specializations were adjusted to the local or regional agroecosystem's carrying capacity, in the current industrialized capitalist ones specializations depend on the massive imports of external inputs. We have seen in the Vallès case study that meat produce would have had to be 5 times lower in 1999, if it had been adjusted to the local capacity to grow animal feed. We estimated this disconnection implies a global footprint that appropriates the land yields of a cropland surface 8.3 times greater than agricultural land in the Vallès, mainly from Spain but we estimated also coming from the Global South. These global trade relations involve a power asymmetry of agri-business corporations that entails relevant societal and environmental impacts in the exporting countries which cannot be kept in check by current social and legal constraints in Spain. In turn, this unequal ecological exchange also damages the importing area, where dung accumulation is harming water and soils' environmental quality. These local impacts of a global trading chain cannot be countered with just local analysis and action, but require a changing of the food regime as a whole. To give but one example, the nutrients extracted from export regions in the Global South cannot close their nutrient cycles in an organic, sustainable manner. Agri-food systems can only become sustainable if their biophysical and socio-economic flows are relocated, along with their cultural practices and political decision-making processes.

Our study also teaches us some lessons from a methodological point of view. Carrying out a multi-dimensional and multi-scalar analysis of social metabolism is a useful tool that allows us to comprehend the diffuse impacts of policy making in food regimes at different dimensions: diets, land-uses, landscapes and international trade. Despite limitations in sources for inferring the actual origin of feed at local level, we deem that this allow at least an approach of the socio-environmental costs of current agrarian systems. This permits, on the one hand, going beyond single-sided analysis to enhance the complexity of agrarian systems and food regimes through its social and ecological linkages; from our perspective, this is a good way to face current challenges to global food systems. On the other hand, performing a long-term dynamic analysis of how local food systems have changed over time helps us address an applied history task: to recover peasants' bio-cultural knowledge and expertise that had been employed in managing society-nature relations for such a long time, as a key resource to devise new relocated and resilient agri-food systems for a more sustainable future.

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CHAPTER 5. MODELLING AGROECOSYSTEMS AS A TOOL TO DEFINE AGROECOLOGICAL HORIZONS AND TO UNDERSTAND THE PAST [25]

1. Agricultural systems: deepening the ecological crisis or coping with it?

In Chapters 3 and 4 we have analyzed the current agricultural metabolism for the case study of the Vallès and the changes it has experienced throughout the socioecological transition from organic agriculture to an industrial one. Within this transition, massive introduction of external agricultural inputs has resulted in a linearization of organic processes and a loss of integration among its fund elements. This has also led to a loss of the agro-silvo-pastoral mosaics, in which a polarization of perturbations all over the agroecosystem as well as a simplification of the cultural landscapes can be observed. These go along with a corresponding loss of material conditions required for farm-associated biodiversity – i.e. habitat and biomass available to the trophic chains, landscape fragmentation and anthropic disturbances.

The above-mentioned situation strengthens the thesis that agricultural systems trascend the pursuit of local needs' fulfillment to become a cog in the wheel of a globalized food regime interdependent on other systems abroad. The lower local complexity contends with a higher global one, resulting in an impoverishment in the balance between population, livestock and soil fertility kept in pre-industrial systems. Because of this simplification, agroecosystems have undergone a loss of energy and material efficiency that, in turn, fosters a growing replacement of ecosystem services (soil fertility, pest and disease control) by industrial fossil-fuelled external inputs (Giampietro, 1997; Gliessmann, 1998; Leach, 1975; Pimentel et al., 1973).

Finally, globalization entails a virtual misappropriation of land and natural resources by external agroecosystems, which underpins an expulsion of the social and environmental unsustainability of massive meat production. All at once, the metabolic rift arising from the interrelations between exporting and importing regions ensues environmental problems because of a massive accumulation of nutrients.

In such a scenario, and considering the growing social consensus that human societies should not live beyond the means of the limited amount of resources available in nature, alternative models based on a rational metabolic approach have to be designed – as a matter of fact, a conclusion already foreseen after the first oil crises in the 1970s (Meadows et al., 1972). Even researchers from fields as agronomy, traditionally restricted to their own research area, increasingly endorse a more systemic approach (Hendrix et al., 1992; Lichtfouse et al., 2009). This is one of the challenges undertaken in the present work. As Podolinsky (1880) stated, it is about human societies making use of agriculture as an energy source for their subsistence. Therefore, we want to avoid an agriculture being an energy consumer, in order to maintain living systems without having to rely on the depletion of fossil fuel reserves.

However, we have to be aware that behind all these current agricultural dysfunctions, ideological constructs underlie which concern the core of capitalism. Mainstream Neoclassical Economics, considers land and labour as simple production factors, as a result of its commodification (Polanyi, 1944) and ignores the organic and circular nature of the biophysical processes moved by farmers (Georgescu-Roegen, 1971). But as long as they are not seen as mere commodities, we may realise that they are neither static nor permanent resources, nor a couple of

[25] This methodological chapter assesses the foundations of the *SFRA* modelling. I wrote it, and most part of theoretical developments are mine. However, I acknowledge the positive and always meaningful proposals made by Enric Tello and Inés Marco.

variables of a production function isolated from one another. Here then, Ecological Economics offers an alternative paradigm that allows to recover an organic conception of labour, land and other natural resources and to regard them from a substantive and holistic perspective as a living interrelated whole (Gerber and Scheidel, 2018; Gerber and Gerber, 2017). This means, as we will see, to consider them as the funds they are.

In order to be able to approach a design of agricultural systems in its wholeness, a reproductive perspective has to be embraced. To retrieve an organic and systemic view of agricultural systems means nothing but to conceive its dynamics and function as those of other complex living systems. Thus, in the present work we deem that the fundamental conception on which agricultural activity should rely, is the one set out by Georgescu-Roegen (1971). He stated that *'the ultimate aim of farming is not only producing useful biomass but also reproducing the funds required to upkeep the process'*.

From this perspective, it seems obvious that to preserve land and labour functioning in a sustainable way cannot be limited to a simple cash flow. In order to achieve co-production with nature, agricultural systems have to account for the full costs of their own reproduction in biophysical terms (Guzmán et al., 2011; Van der Ploeg, 2014). Farmers, for instance, need to maintain their workforce in order to sustain the required flow of labour. This, in traditional organic societies, entailed two basic material conditions: provision of enough food and fuel, and not to exceed their own work capacity. Within the context of this example, the approaches and methods of social metabolism can shed light on the implications that these reproduction costs and conditions might have (Haberl et al., 2004). As has been shown in the previous chapters, the framework set by the social metabolism offers a deep insight into dialectic socioecologial processes from a systemic perspective, taking into account pre-established social limitations on the one hand and ecological ones (i.e. physical, chemical and biological) on the other.

In the pursuit of this systemic understanding, social metabolism is at a crossroads facing two major challenges. First, the need to overcome a stock-flow analysis by incorporating a fund-flow perspective, that realizes the need to redirect specific biophysical flows in order to ensure the renewal of living funds in a clear co-production scheme with nature (Gerber and Scheidel, 2017; Marco et al., 2017). As we will see, this has a lot to do with the assessment of nutrient and feed balances proposed in chapter 2. Second, the call for an epistemological reformulation that allows to evaluate, integrate and model these fund-flow relationships and that can be used as a tool to reconsider agricultural policies, nature conservation and rural development plans (Zhang, 2013).

To sum up, the present chapter introduces the theoretical framework of our proposal for modeling agricultural systems named *Sustainable Farm Reproductive Analysis.* We embrace a reproductive perspective to devise potentially sustainable scenarios and optimize the flow distributions within an agroecosystem. Thus, in this chapter we endorse the principles of agroecology as the 'driving force' to solve the rationalization needs of the agricultural system's operation.

2. From industrialized agricultural systems to agroecology. The role of agroecosystems

2.1 The principle of reproductivity in agroecology

We cannot proceed to retrieve a reproductive view of agricultural systems, without before looking at the different existing proposals in the field. It is necessary to identify under which principles, the functioning of the agroecosystem would generate more efficient and resilient agrarian systems. In this regard, we consider agroecology as a starting point, and the point of arrival, in order to recover an organic metabolism.

Agroecology is a scientific *discipline*, a set of concrete *practices* and a *movement* all at once (Silici, 2014). Its fundamental premise is that the more the functional structure and the processes of an agricultural system resemble those of the natural ecosystem of its corresponding biogeografic region, the more sustainable the agroecosystem will be (Gliessmann, 1998). To bring the processes of the agroecosystem the closest possible to the natural processes, means to increase through human activity the loops of biomass to emulate the internal relations given in the ecosystem (Ho and Ulanowicz, 2005). From this point of view, the analysis of historical advanced organic agricultural systems – in which the cycles had to be closed locally – as well as the analysis of cultural landscapes of the past, it is crucial to understand the ways in which to approach the management of agroecosystems in the future (Antrop, 2005).

Regarding the ideological branches of agroecology, two main different groups of research can be distinguished, despite there is still some confusion among the concepts in use (Bellamy and Ioris, 2017): sustainable intensification and radical agroecology. The first departs from the point of view of Weak Sustainability Science and relies upon the feasibility of reducing the environmental impact while mantaining the current capitalistic model, by means of a market internalization of environmental externalizations. On the other side, the radical approach is committed to achieve food sovereignty and a redistribution of all productive resources, involving therefore the social system itself in the debate. Inside the radical approach, there is the political agroecology, *which considers food production as inherently political, draws attention to broader food production and consumption systems, and [which] foregrounds power and politics* (Bellamy and Ioris, 2017). Later on, we will look into this last approach in more depth.

Sustainable intensification stands for reaching similar yields under agroecological management as industrialized systems, from a productivist perspective. However, we consider that trying to compete intensively with conventional agriculture in order to make it competitive, to conventionalize it without questioning the mechanisms that render the current agroindustrial model inefficient and unsustainable, would be doomed to failure, for it just shifts the problem. Our position, instead, coincides with that of Levidow et al. (2014), according to which we need not to conform but to make a profound change and transform the current diet regime. This means, we do not want to assimilate current processes to organic functioning, but to transform the conditions under which agrarian systems operate.

Under the proposal for transforming the current system there is a proposal that we deem could be effective. This is the ‘ecofunctional intensification’ strategy (FAO, 2013). It take a stance for improving the nutrient recycling techniques and enhancing biodiversity via farmers’ knowledge as an integrated systems’ approach. Therefore, its focus not only lies on yields but on the integrated management of agroecosystem as a whole. We think this has a lot to do with recovering an organic functioning of the different funds that are part of the agroecosystems.

2.2 A metabolic approach to agroecology

While trying to understand how we can apply agroecology to agrarian systems, we recover the vision of social metabolism and regard agroecosystems as ecosystems modified by human labor to obtain agricultural products. In these modified ecosystems, farmers have to maintain a balance between the continuity of ecological processes and human intervention to manage them in their own interest (Bulatkin, 2012).

The agrarian community plays therefore a structuring role in the redistribution of the photosynthetic capacity towards the different compartments (see chapter 3). We depart from the premise that in order to develop a sustainable metabolism in balance with the biophysical limits of the territory – i.e. to apply an agroecological perspective – farmers have to take advantage of the synergies that can emerge upon different land-uses, as well as through the complementarity of flows set among various agroecosystem funds. By only considering these agroecological interrelationships, more complex, efficient and resilient agricultural systems can be designed. This leads to a substancial increase of internal matter-energy loops of low entropy that keep their underlying funds alive (González de Molina and Guzmán, 2017). This is how we consider an ecofunctional intensification can take more advantage of agroecology than sustainable intensification. To fulfill that aim a meeting point has to be found between land-use planning and socio-ecological accounting of farming, so as to analyse the reproductive capacity of agroecosystems over time.

The study of social metabolism in agricultural systems has developed in recent years, opening the black box of agroecosystem functioning and characterizing their fund elements. However, as stated before, these methodological advances have not yet made use of other ways of accounting for what could be useful for a next epistemological step towards socio-ecological modelling of agroecosystems by including a fund-flow perspective (Marco et al., 2017; Zhang, 2013). New modelling is essential to tackle the auto-reproducible funds of farm systems. Therefore, the methodologies proposed in Chapter 2 and 4, of food, livestock, and nutrient balances in order to meet the needs of funds can be used as a starting point – although they need to be conceptualized within the framework of the *SFRA* proposal.

We recall that according to Georgescu-Roegen (1971), funds are understood as those *elements that are part of a process, which provide services for a certain period but are never physically incorporated in the product.* Specifically those of biological basis which are alive (despite being individuals or living systems) are self-reproducing funds whose maintenance requires a regular reinvestment of a certain amount of agroecosystem's resources. A disregard of either the limits in rhythm or volume of extraction, or in the reinvestments required, means to jeopardize the agroecosystems' sustainability (Giampietro et al., 2013).

The modelling we propose will be based on the requirements for reproduction of the various funds of the agroecosystem. In other words, we will address a reproductive study that calls for the need of reproduction of the living elements involved in the agroecosystem – guaranteed by the biomass flows –, if production has to be sustainable. This is the conceptual principle under which we want to develop our research proposal, and for which methodological approaches and tools will be developed.

3. The silenced science, the reproductive studies of Chayanov and the Economic Planning School

3.1 Brief notes on the reproduction approach in economic theory

Although the economic vision of the general equilibrium theory predominates globally over the last decades, many economists have contributed to the alternative approach of reproduction. Adam Smith himself, Ricardo, Marx or Sraffa, regarded economy as a cyclical process. Under that conception, production is nothing more than a necessary step, together with the distribution and consumption, in an endless spiral.

These approaches were based on the fact that any line of production required natural resources, means of production and workforce, through which it generates a product. This product had to be used to guarantee the reproduction of the elements that had taken part in its production and, once this distribution was made, a surplus could be left over – which then would generate the conflict between social classes to decide how it had to be distributed. Based on these general formulations, the main problem is how these heterogeneous assets that participate in the process are to be valued (Barceló, 1994).

As can be appreciated, this approach has a lot to do with what we have been proposing in the previous sections. Thus, the reproductive study we propose is no less a scientific novelty. In this sense, we believe that social metabolism can contribute to the valuation of heterogeneous assets from a rich multicriterial perspective. Therefore, we consider it necessary to identify how, from the field of agrarian systems analysis, these theories had been raised to analyze its potential in the application to social metabolism.

3.2 Alexander Chayanov and the Organization and Production School

In the field of agricultural economics' analysis at the beginning of the 20th century, Alexander Chayanov, a Russian agricultural economist and one of the greatest exponents of the Organization and Production School, developed both a theory and a proposal of quantification of farming functioning. His fundamental proposals are mainly included in his thesis of "*Peasant Farm Organisation*". Their thesis confronted with the great collectivizations applied by Stalin. The main reason for the dispute, within the theoretical arena, was that Chayanov considered in the first place that the peasant population could not be considered as a class destined to disappear during the course of history, and at the same time that it had some intrinsic characteristics, "a typical peasant economy", that had to be taken into account when considering agricultural transformations.

However, the persecution and subsequent execution of Chayanov through a process devised by the government of Stalin, left largely forgotten their agricultural proposals. In this regard, we take up from the peasant farming model defined by him ([1925]1986). His theory of peasant economies triggered the development of reproductive studies of domestic units, by accounting for the amount and allocation of land required according to the family farm composition, livestock density and cultural practices (Minami, 2009). However, Chayanov's approach combined only units of labour time, family needs, livestock intake and farm produce translated into a monetary budget driven by an effort-consumption balance. It did not pay due attention to other biophysical requirements to ensure the reproductive capacity of other agroecosystem funds, as soil fertility. In spite of that, we regard his point of view as a good basis for the present methodological approach, by means of which the foundations of agroecology will be applied to socio-ecological relationships.

Therefore, our study retrieves the work done by Chayanov ([1925]1985; Van der Pleog, 2014) on the functioning and internal planning of economic peasant units, but incorporating a biophysical dimension for ensuring the simultaneous maintenance of a larger range of living funds. We are therefore laying foundations towards modelling the agroecosystems' sustainability with a novel fund-flow agroecological perspective.

Despite these reproductive studies have continued to develop in the field of agrarian history, sociology or political economy (see for example Barceló, 1994; Chibnik, 1984; Colomé, 2015; Van der Ploeg, 2014; Vicedo et al., 2002; Wiber, 1985), it is also true that the approach posed by Chayanov was aimed at the implementation of proposals for economic planning.

We know that we want to model the functioning of agrarian systems from a reproductive perspective. We lack the methodological tool that allows us to take this step from the assessment of agroecosystems to their modeling. Although here, as we will see, we do not consider economic planning as an objective in itself, we do consider necessary to recover the debate about the potential to socially organize agricultural resources. The reason therefore encroaches with another branch of scientific development, which is currently used little in this sense of planning and that we consider useful for this research.

3.3 The discredit of economic planning in 20th century Europe

Also in the context of scientific advances within the USSR, the need for economic planning led to the development of mathematical proposals on the organization of productive resources, such as the input-output tables of Leontief (1966) or the linear optimization initially raised by Kantorovicz (1939). The input-output tables allow us to clearly identify the distribution of resources on a micro or macroeconomic scale, while optimizations help to find the best way to distribute resources. These mathematical tools allow to clarify in which way the distribution of finite resources of a system, under a series of constraints, results in the accomplishment of particular objectives in the most efficient way. Shortly after the first approach to linear optimization by Kantorovicz, in 1947 the north-american Dantzig developed the Simplex algorithm, with which the resolution of these optimization models was greatly simplified (Dantzing, 1963). These are the ones on which we are interest the most for our purposes.

These tools to optimize the distribution of finite resources for production and the social debates they raised, were widely present within the USSR. But not only there. Economic planning was an object of study and discussion in the faculties of economics all around the world for a long time, raising abundant critical and heterodox debates. However, from the 1980s onwards, Neoclassical orthodox school imposes in most western faculties and planning becomes a pure engineering element that does not pose any debate about social organization. As a matter of fact, books such as those of Joan Robinson's and John Eatwell's Introduction to Economics (1973), in which heterodox debates were raised and neoclassical thinking was fought, are since years not referenced anymore in the syllabus of introductory courses in Economics.

Resource optimization has largely been relegated to a technical scale of production process, clearing the path for the free market as the only "efficient organizer" of the economic matrix of countries. As noticed by Polanyi (1944), elements such as labour or natural resources are therefore considered as mere inputs regulated by the market system, and the social and environmental impact they have is ignored. The discredit of economic planning and the impacts of an economy that works under the premise of economic profits, allowed the progressive increase of externalities. As shown in chapters 3 and 4, this reckless attitude to ecological and social issues, has had an enormous impact in the food systems.

The proposal we make in the present chapter, does not embrace the idea that agricultural activity should be planned on a state scale as the USSR did. We consider the hypothesis that a socially-driven planning of the flows generated in the agroecosystem, at socially affordable scales, could result in an improved efficiency of agrarian systems and could limit the negative impacts that we observe today. In doing so, however, we must include deliberative mechanisms both in the transition to new models and in our own scientific research (Duru et al., 2015; Levidow et al., 2014). One of the greatest problems in the USSR state planning that marked its inefficiency was the difficulty of achieving a bi-directional information transfer between state and society, that could have generated adaptive structures in response to the changing needs of the population (Robinson and Eatwell, 1973). In order to be able to introduce these social deliberative steps, the model we present introduces the concept of *horizons*. To make use of this concept effectively we want to take advantage of the path of these optimizations and see how to introduce the reproductive conception towards agroecosystem modeling.

4. The current tools of territorial planning, the path to sustainable agrarian systems

As we mentioned, optimizations have been largely relegated as tools for pure engineering, as well as farm-scale for territorial planning. This does not mean that they have been forgotten, but in a way reinterpreted. As we will show, since the 2000s they are becoming relevant again on account of a greater diffusion of sustainability concerns. In the present section, we do not intend to do an exhaustive study of what is being investigated in the field territorial planning of agrarian systems, but rather to identify different approaches that could contribute to the development of the modeling we propose.

From a biophysical perspective, the use of optimization analysis has risen as a tool for studies that begin considering multifunctionality on land-uses (Grabaum and Meyer, 1998; Meyer et al., 2009; Sadeghi et al., 2009; Seppelt and Voinov, 2003; Smit, 1981; Stewart et al., 2004). However, these studies do not assess the role of planning but the result of individual decisions. They have also not yet been applied to a biophysical accounting to carry out a fund-flow analysis with a socio-metabolic approach. Even if some studies use ecological and non-monetary criteria, they still consider land-uses isolated from one another, not taking into account their metabolic interactions. With few exceptions, these optimization studies do not consider the whole agroecosystem as a unit of analysis (Cong et al., 2016; Lomas and Giampietro, 2017).

From a monetary perspective, the utility of optimization in designing land-uses distribution in agriculture is also well known, but its application has been mainly limited to the theory of portfolio selection (Knoke et al., 2015). From the economic's perspective, the application of these optimizations into territorial planification, the agent-based models deserve special attention – with which the individual decision and farm-based model also have a lot to do.

Agent-based models, have been developed within the frame of theories of behavior in economics. These are models of behavior that dynamically express the probability that farms, at the individual level, or certain social agents, make decisions based on what other agents do in a society. These, again, have not widely included the deep socio-ecological criteria that allow them to identify social metabolism (An, 2012; Gilbert, 2007). While it is true that in this area we find one of the few farm modeling that adopts a socioecological point of view (Bergez et al., 2013), this again lacks an Ecological Economics and an agroecological transition's approach. Indeed, we want to point out that under our starting objective and scientific conception we do not pretend to model the social decisions that are structured in the territory, but instead to identify possible scenarios defined as *horizons* that can be reached if the existence of a joint planning is assumed.

Finally, the studies that resemble more to our proposal are those derived from the discipline of food systems. Recently, research has been carried out on how to recover optimizations in the distribution of uses in order to satisfy diets from a local or regional perspective. Food systems analysis is an approach still very new but defines strategies and proposals that we deem resemble more to a Weak Sustainability Sciences' approach than to the strong one. Thus, these are studies that, in their aim to internally meet the needs of society within the agroecosystem, do incorporate optimizations as well as a socio-ecological perspective (Desjardins et al., 2010; Meier and Christen, 2013; Peters et al., 2007; Van Kernebeek et al., 2016). Mostly, they are studies on the impact of diets and on the food supply capacity at the local level, which remain within the framework of conventional agriculture proposals and very focused on the consumption side. They do not incorporate the fund-flow analysis or the agroecological vision and, therefore, do not adopt a reproductive perspective – i.e. they do not attempt to close the cycles of assets funds on a local scale. Nevertheless, they will be very useful as comparative tools for the discussion of results.

After this brief analysis of current tools used in the territorial planning, we consider that optimization analysis through linear or non-linear programming, applied from a novel socio-metabolic and agroecological reproductive viewpoint, can be a useful method in defining desirable horizons for our sustainable farming design and land-use planning. Therefore, it has to take advantage of the approaches on food systems while introducing the point of view of Strong Sustainability as well.

Our optimization model will set off considering the self-reproducing funds as elements of the agroecosystem, in which the restrictions are the conditions that must be fulfilled in order for the system to be reproducible. In order to comply with agroecological criteria, we will consider that funds must be maintained based on the own flows generated by the other funds. We take a cyclical conception using the development of the graph on flows within the agroecosystem in Chapter 3. Based on our understanding of the relationship between society and nature, the fundamental self-reproducing funds of the agroecosystem that will be considered are: the community, domesticated species and non-domesticated species. Given the reproductive characteristics and in our aim to achieve the sustainability of agrarian systems, we will term this model as *Sustainable Farm Reproductive Analysis* (*SFRA* hereafter).

This modeling program will be based on a set of functions that restrict the range of what is possible within the agroecosystem from an organic point of view. With the constraints that concern the reproducibility of funds, the model sets the full range of configurations in terms of flows and composition of these funds. In order to optimize the system, however, it is essential to define the objective according to which the agroecosystem has to be organized. From a mathematical point of view, this means under which objective function has to converge the package of restrictions that define the system. To this end, we want to retrieve to the concept of information.

5. The role of structuring information in agroecosystems

In social metabolism we deem agroecosystems as ecosystems modified by human activity. And human activity, in its turn, is based on the social or individual goals that aims to satisfy. Therefore, there is no agroecosystems without an *intentionality* associated to it. When it comes to considering how agroecosystems can be optimized, the result will be assessed according to the objective that we want to achieve. Correspondingly, it will not be the same to organize the natural resources of a territory to maximize the amount of population that can be supplied within a territory, that to maximize the amount of total agricultural production regardless of whether it is useful or not for the consumption needs of the community in this territory itself.

It seems obvious to us, that defining a concrete purpose according to which societies are supposed to use the land and its natural resources, is not an objective but a subjective decision. Depending on the social values, the agroecosystem would be structured with regard to one end or another. Therefore, we will define the objective functions conforming to these social interests. Based on the structure of the model, these will result in different configurations of both the flows and the dimensions of the funds of the agroecosystem.

One of the indicators set forth in the *ELIA* mentioned in chapter 3, was what we termed as *message information*. There we said that information emerges in systems in which the behavior of its elements becomes unpredictable (Prigogine, 1997). This idea has led us to apply the Shannon index to the energy ratios of an agroecosystem, where we assume that the more equally distributed the flows are, the more uncertain, open and complex the agroecosystem becomes.

In applying the Shannon index to energy flows, we only accounted for the *message-information*. However, since we also want to reflect farmers' knowledge and wisdom (as agents) that upholds agroecosystem processes, we must replace the concept of *message-information* to refer to what is known as *structure-information* (Passet, 1996). What does then *structure-information* means?

We depart by assuming that labor is nothing else than the individual allocation of materials and energy flows which, in the pursuit of a particular objective, result in a socially constructed ecosystem. Thus, we understand that the pattern of flow distributions within an agroecosystem responds in itself to the structuring information that it contains. Based on the concept of funds that we propose, this *structure-information* will reflect the metabolism.

In complex systems, the information appears as soon as several degrees of freedom are at hand in the decision making process. In a completely determined system, for instance, the freedom is non-existent and consequently it contains no information (Passet, 1996). In the 'real world', conversely, the information that we imprint in the landscape is a consequence of the human capacity to make choices. In addition, the decisions taken by the people who are part of the Agrarian Community – but also society itself – define in which way and under what intent they are going to manage agrarian systems. As will be shown later, the possible configurations are not infinite, for the biophysical and technological conditions already constrain the range of possibilities available. Within this range of possibilites, however, the question of which agroecosystems will take a more or less stable structure, will be directly related to the human information incorporated to the system in form of work according to a social autopoietic decision-making process (Prigogine, 1983).

Therefore, within the different technological contexts corresponding to particular historical periods, this imprinted information has been the determining factor that has allowed the structure of agroecosystems to be sustainable or unsustainable. We consider that understanding the decisions made conforming to the degrees of freedom available, is of critical importance. This point of view breaks up with a deterministic conception of history and allows us to evaluate how human beings, provided with the capacity to make choices between the accessible degrees of freedom, take particular decisions according to external factors (institutions, social inequality, environmental conditions) or internal factors (knowledge, values, etc). Without doubt, this consideration underpins the fact that history matters (Tello, 2005).

6. Applied history as a tool to open paths towards agroecological horizons

Having defined the fundamental methodological characteristics of our model – i.e. the reproductive perspective, the structure of the model and the objective functions to which the system must converge – we want to elaborate on its usefulness as well as its necessity beyond the definition of agroecological horizons.

With this purpose, the study of the nineteenth-century advanced organic agricultures, just before agrarian capitalism fully developed, becomes an interesting natural experiment that transcends purely historical interest. These agrarian economies were still dominated by an organic metabolism, where its feasible biophysical intensification was mainly restricted to the local or regional level. This fact induced farmers to maintain a clear integration between different compartments of agroecosystems, conferring them a high resilience and imprinting complex agro-silvo-pastoral mosaics in the landscape (Antrop, 2005; Fischer-Kowalski and Haberl, 2007; Krausmann, 2004; Chapter 3). Indeed, specialization processes via cash-crops tended to push those agricultural systems toward their biophysical limits and even beyond them. Thus, studying past organic farm systems allows us to identify relevant criteria and strategies to keep a sustainable socioecological functioning, which may be useful for retrieving a new sustainable farm metabolism at the present.

Additionally, the study of past organic agrarian societies has three methodological and epistemological advantages: i) it simplifies methodology compared to current agro-industrial systems, which rely heavily on external non-renewable resources; ii) it allows to estimate the range of actual opportunities that peasants had to pave in its way to sustainable regional developments without degrading funds; and iii) it offers useful results to the current requirement of balance regional specialization with satisfaction of reproductive needs of all living funds, local farmers included (Tello and González de Molina, 2017; Tittonell, 2014). As a first step in this research strategy we will model the agroecosystem functioning of a local case study before the Green Revolution by means of an exercise of Environmental Applied History.

Yet this programming model of the biophysical fund-flow interactions in agricultural systems cannot be complete if we are not aware of the social constraints (Gerber and Scheidel, 2017). Agroecosystems are not only conditioned by biophysical needs, but by an institutional framework set up in the society at large as well. Any reproductive accountancy of their own biophysical basis has to respond to the needs arising from evolving societies (Martins, 2016). Not only society-nature interactions, but also the ruling social relations have to be considered. This means incorporating an institutional perspective to social metabolism accounting.

While applying the *SFRA* model to advanced organic societies, we believe that a counterfactual analysis can reveal itself as a very useful tool in order to determine how institutional aspects affect the biophysical and cultural possibilities of development of feasible agrarian strategies. Therefore, in its first implementation, we will analyse past metabolism, while for the second we want to go byond present and try to analyse some proposals for the future, as we present in next section.

7. Contribution to a political agroecology

Let us step back and focus now on the propositive value of our proposal, not just considering its usefulness as a tool to approach history, but from a rather broad perspective. When we consider horizons, as we have pointed out in the previous sections, we cannot ignore the fact that societies do not respond deterministically to mere technical aspects, but that their reaction is instead clearly multiple and complex. Therefore, the incorporation of a socio-ecological perspective to the planning of agrarian systems should not be limited to the consideration of environmental needs, for we would then face the risk to find scenarios that are *feasible* from a purely social-nature-related point of view but that on the other hand are not socially *desirable*.

In this section we elaborate on what we understand that a political agroecology approach should mean (González de Molina and Caporal, 2013) and make a humble contribution to it. In our advances to propose agricultural policies, we must confront the current institutional and social perspectives that play a critical role in the configuration of potentially sustainable agricultural systems.

We conceive our model as an analytical tool rather than as an end in itself that allows us to approach the assessment of the potential degree of development of agroecological strategies at the landscape level, overcoming the plot scale perspective. In this regard, Tello and González de Molina (2017) point out several elements that need to be taken into account when establishing agroecological landscape policies: i) the need to face the closure of metabolic cycles; ii) the role of biocultural inheritances in the maintenance of resilient systems and site-specific knowledge; iii) the impact of landscape ecology on the configuration of the agricultural system to maintain high levels of biodiversity; iv) the improvement of the energy efficiency of the agricultural system and the reduction of greenhouse gas emissions (GHG); and finally v) the democratization of market power and the reinforcement of fairer value chains.

Having these points in mind, the first SFRA model that will be introduced in chapter 6 takes into account the closure of metabolic cycles (i) and at the same time, as an exercise of historical analysis, evaluates the role of peasant knowledge on the maintenance of resilient systems (ii). However, it is in the elaboration of our proposal of socio-ecological models for the present time where further challenges to the design of agroecological landscapes become most relevant.

In first place, one aspect that remains absent in the first model is the capacity to infer aspects about material conditions for farm-associated biodiversity. Here is where ecology of landscapes (iii) reveals noteworthy in guaranteeing landscape patterns that allow a greater habitat differentiation (Harper et al., 2005). As noticed, the introduction of restrictions related to landscape patterns can point toward a major step for these designs.

Secondly, the strategy of closing metabolic cycles (i) also affects the current energy inefficiency (iv) of industrialized agricultural systems (Pimentel et al., 1973). The strategies of intensification of internal loops through the interrelation of various funds are clearly beneficial when compared to the linearization of agricultural activities observed today and to its high dependence on external imports (chapter 4). At this point, however, we have to make an important remark regarading the development of the *SFRA*. In restricting our analysis to potential organic inputs that do not affect the productivity of work, we are not addressing aspects concerning the mechanization of agriculture and the energy efficiency of the whole system depends on the choices made in this regard. Furthermore, our second *SFRA* model does not take the impact of GHG into account, what would also be affected by the previous aspect. Notwithstanding, with the proposed methodology we will be able to address the two unresolved issues in the future.

In third place, and finally, some aspects regarding the challenge of decisions' democratization (v) have to be mentioned. Although the elaboration of this model has counted with the collaboration of scientifics and professionals engaged in the regional agrarian field, the *SFRA* remains a theoretical and non-empirical proposal. In spite of that, it does consider relevant issues regarding the goals of the optimization function, since it requires a clear definition of the *intentionality* in handling the system. Consequently, we deem our scientific proposal to be a feasible tool to be potentially applied to stimulate debates. That could be important to address the democratization of the decision making processes by incorporating the democratic ratification or declination of the social assumptions considered therein.

8. Limitations and potentials of the use of modelling in Ecological Economics

The last aspect on which we want to elaborate in this theoretical introduction to socio-ecological modelling concerns the limitations of its use. In order to set the path towards the proposal of new horizons that reflect on the policies of sustainable agrarian systems' design, we want to avoid embracing a positivist standpoint. We are determined to keep away from the cartesian illusion of an entirely modelized society that astonishingly extends his mechanistic approach to social relations, despite the fact that it seems to be clear evidence of its irrational nature (Saltelli and Giampietro, 2017). For this main reason, a careful assessment of the factors that could be detrimental to the success of the model has to be carried out. As we already mentioned, the model does not become an end in itself but a tool which, based on the reflexive and self-poietic process of society, must be applied to achieve a specific goal – in this case, a sustainable agrarian system.

According to Saltelli and Giampietro (2017), the assessment of the likelihood of success in the application of a proposal through public policies comprises three main types of capabilities:

- *Feasibility*: these are processes which are out of reach to human control – i.e. internal processes. In our case we consider biophysical processes related to the underlying thermodynamic, physical, chemical and biological principles of agroecosystems.

- *Viability*: these include processes that are under human control, which in the present case translates to the interaction between society and nature. As we will show later, a further differentiation is appropriate in our model and we will differentiate between *technical viability* and *cash viability*.

- *Desirability*: this is a fundamental feature to be taken into account in the model, for the result of the application of *SFRA* must be desirable in social terms. This is the result of relying on social *intentionality.*

As can be appreciated in Figure 5.1, the model groups selected capabilities and tailors them in order to enhance its effects on others. To estimate wether they interact in a juxtaposed or in a hierarchical fashion, it is mandatory to go to the roots of both the discipline from which we approach the problem as well as of the particular problems that the case agroecosystem under study is challenging.

In first place, in embracing the point of view of Ecological Economics, our aim is to contribute to Strong Sustainability by means of a reinterpretation of the functioning of markets as sub-systems of human economy – which in its turn depends on ecology in a broader sense (Foster, 2000). The ultimate goal of our approach is to identify the way in which market mechanisms can be established in order to guarantee social-nature relations that do not endanger the sustainability of the territory. We understand it as a strategy of transformation that confronts the current global food regime system (Levidow et al., 2014). The ultimate goal, however ambitious it might seem, is to move forward towards a definition of novel cash exchanges effectively subjugated to particular social and territorial restrictions that allow to shape more resilient and sustainable agroecosystems.

These restrictions include not only what Cronon (1991) defines as first-nature variables (the boundaries strictly relying on biophysical constrains) but also those of second nature affected by social relationships – i.e. cultural practices, technological development and relationships between the different agents of the society. Among all possible restrictions, there are two categories that strongly determine the range of possible uses of a territory, disregarding the role of society itself, namely the biophysical limitations and the available cultural technologies and practices. According to the definition of Saltelli & Giampietro (2017), these would respectively correspond to the already mentioned *feasibility* and the subcategory *technical viability*. By means of these two main restrictions, which are determined by the environment and the context of technical-agronomic development beforehand, the structure of the model is set up (Figure 5.1). All this frames a region of technical-ecological possibilities of agroecosystems termed as *site-time specific*.

By taking into account considerations about the social suitability of the model, this region of technical-ecological possibilities defined by the restrictions of *feasibility* and *technical viability* will be further narrowed. This leads us to the consideration of *structure-information,* which requires a clear definition of the social objectives according to which we want to design agrarian systems. As pointed out in section 5, this definition implies the introduction of the *desirability* into our ‘equation’ - i.e. the need to elucidate the intent according to which we want to optimize these scarce resources. Within the structure of the model, this concerns the objective function that determines what has to be maximized or minimized in a territory based on the region of possibilities. As we will show later, it is precisely this objective function that finally leads towards different scenarios.

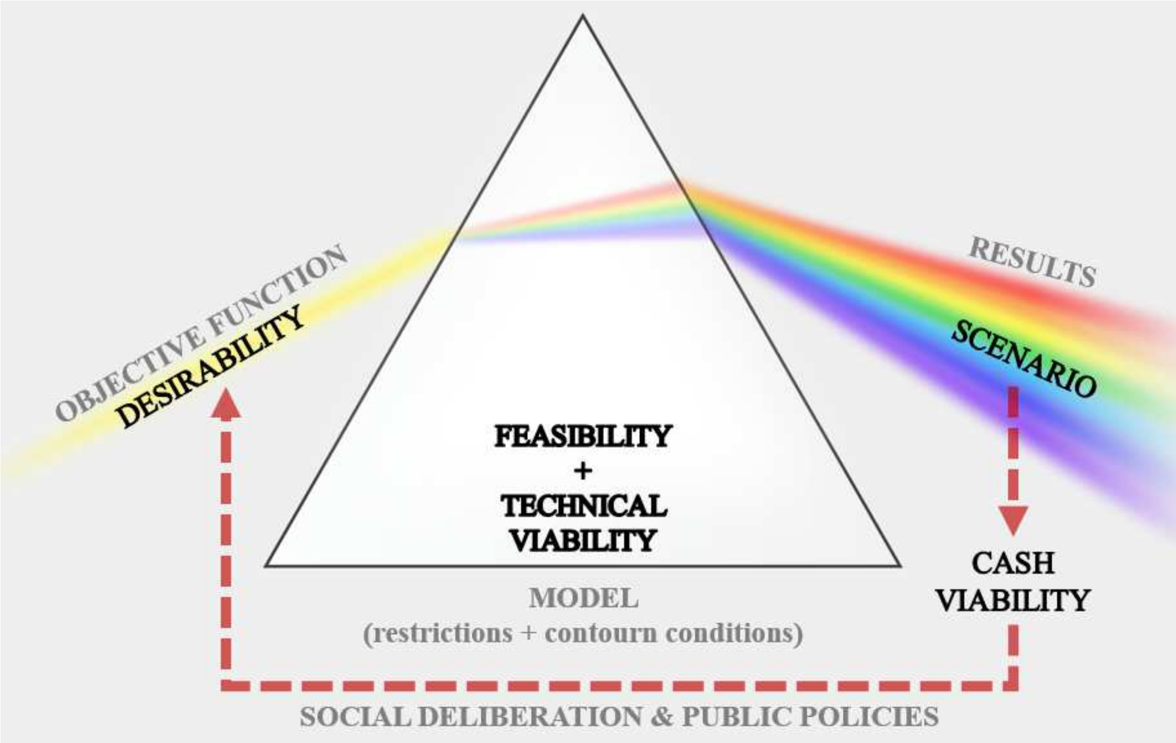

Figure 5.1. Conceptual scheme for the capabilities considered in *SFRA* modelling. Source: Our own. The bottom drawing on diffraction of light holds a Creative Common License, from Suidroot.

By saying that, we do by no means suggest that the whole complexity contained in the concept of *desirability* is going to be reduced to one single function. This would lack the dialectic approach that an appropriate consideration of social factors requires. Within the structure of the model, there are aspects that respond rather to social desires (notice again that in this sense we refer to a strict society-nature interaction) than to the prevailing needs of the biophysical or technical limiters (e.g. the conservation of certain forest areas due to its historical or cultural value). Nevertheless, from a social perspective, it is certainly required to make choices about the aspect according to which we want to optimize the use of resources. In case multiple goals are simultaneouly pertinent, they can be weighted according to relevance or a hierarchical relationship between them can be established. As will be seen in Chapter 9 about further research, there are several mathematical tools (such as multicriteria analysis or hierarchical optimizations) that allow to cope with these more complex situations indicative of the interaction of multiple social interests, while maintaining the structure of the model. Based on social desires, the process of selection of an optimal point from within a region of possibilities, urges a serious collective and social deliberation. However, as we will show, this is not the only point to be made.

Given the structure of a model that guarantees both *feasibility* and *technical viability*, we run the *SFRA* based on *desirability*. This allows us to obtain a horizon scenario in which both the structure of funds as well as the flows that guarantee the reproducibility of the agroecosystem in organic terms are defined.

In Chapter 7 we will define the horizons based on all the above mentioned characteristics. This is however just the first step towards the achievement of the ultimate goals of Ecological Economics as a tool for strong sustainability. Once we set the frame for the design of scenarios on an agroecosystem that fulfill the requirements of *feasibility*, *desirability* and *technically viability*, and assuming it is already socially validated, the next step will be to asses the *cash viability*. This requires the conception of suitable policies to guarantee that the socio-ecological aspects taken into account before are not adversely affected by an incoherent cash exchange. Based on the theoretical developments on the relative price relationships between goods, labor and capital framed by Marco et al., (forthcoming), our model could give hints about which are the most appropriate converters (prices, salaries and profits) that need to be modified and to which extent. This would clear the path towards the design of public policies in order to define regulations, tax, subsidies, planning, etc. It has to be noticed that the agricultural sector is a fundamental area for life sustainibility and that policies at European level are already subsidizing this activity in a markedly interventionist way. In view of the results of the Common Agricultural Policy and the social and environmental impacts it has had (both internally and externally), we strongly encourage a profound reconsideration of the same, with a systemic vision and a clear socially desirable horizon.

As it is now hopefully clear, our proposal addresses the material dimensions of social metabolism in its strict society-nature interaction, and not among individuals within the society. Regardless of considerations about the democratization of processes, there are issues that can reveal itself as critical in order to guarantee an agroecological commitment – above all, for instance, the access to resources. Most likely, this suggests that several institutional changes would be necessary in order to cope with these issues through a positive and confident intervention of the immaterial dimensions of social metabolism (González de Molina and Toledo, 2014). In the frame of our research, however, we have limited the study to the material dimension by identifying horizons in an hypothetically pre-established situation of equitable access to resources, assuming full information and flow flexibility. Any scenario of social relations other than the one we have assumed, would lead to a reduction in the efficiency of the use of resources and consequently to a reduction in the degree of optimization of the resulting agroecosystems.

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CHAPTER 6. BEYOND CHAYANOV: A SFRA OF PEASANT DOMESTIC UNITS AND RURAL COMUNITIES [26]

1. The methodological approach of counterfactuals, criticisms and possibilities

Counterfactual analysis, as an approach, born as a generational reaction to descriptive history. Is the starting point of the New Economic History, as a school of economic thought developed in the 70-80s of the last century. It is a quantitative approach to the debate on issues related mainly to economic development.

Among the most characteristic investigations of this methodological approach, we find counterfactual studies such as those of Fogel (Fogel, 1964; Fogel and Engerman, 1974) and North (1961). Fogel's first study raised the contribution of the rail network's construction on the economic development of the United States. In the research published in 1974, they analyzed the role of slavery as a useful institution, questioning the view that it was economically inefficient. North, on the other hand, raised quantitatively what the role of the cotton sector was in the economic development of the United States. They were strongly criticized both for the methodology used. However, these first proposals served as a starting point for a new methodological body within economic history.

Counterfactual analysis is still on the agenda in macroeconomics and is often used to analyze the impact of certain policies by comparing them with their non-existence. However, they are still not exempt from methodological criticism for the laxity of many models in establishing logical causal relationships (Cartwright, 2007). The critique of these regards to models that show the response of a variable (very often, the effect on GDP), without clearly defining the actual explanatory effect, that is, the causality of the independent variables with this dependent variable, as well as the possible implications of causal relationships derived from the first ones.

However, here we propose to use counterfactual analysis from a non-macro-economic approach, limiting ourselves to agrarian field and without trying to develop a theory of what would happened but only of what different scenarios were possible.

The scope of this counterfactual methodological approach is on understanding what impact could have had an equitable distribution of land in the possibilities of development of the territory. Thus, we will compare the real distribution of uses with counterfactual scenarios, considering the different strategies that farmers could have followed. Therefore, we are not in a context of seeing how a variable of complex composition oscillates according to well-known distribution variables. Instead of that, we intend to see how social institutions, which eventually result in a specific distribution of natural resources (land, water, livestock, etc.) affect, in comparison with a scenario where distribution of land would be equitable. And in this equitable scenario, we present possible resulting configurations according to the decisions taken by farmers (thus relying on *intentionality*).

[26] I carried out this research as corresponding author together with Carme Font, Inés Marco and Enric Tello. I have led the whole process, counting with different collaborations of the other co-authors. Carme Font proposed the programming software, and helped me to develop some first iterations. Inés Marco was at the same time developing her research on social inequality, and prepared the database of the Census allowing for the analysis of the Domestic Units. Both Enric Tello and Inés Marco collaborated in the process of discussion, linking as well the debates with the literature on winegrowing specializations and inequality in agrarian systems. The research is now under a process of revision in the journal *Ecological Economics*, was after being submitted in August 2017 (Padró, Marco, Font, & Tello, forthcoming).

2. The model SFRA for an advanced organic agriculture

2.1 A socio-metabolic modelling of agroecosystems' reproductive functioning

As we explained in chapter 5, from the point of view of society-nature relationships, three main funds stand out: the farmers' domestic unit, their domesticated species, and all the non-domesticated species that play a supporting, regulating and habitat role in the agroecosystem functioning. Notwithstanding, due to the limits of our initial programming model, we will not consider the effect on non-domesticated species as the biotic community itself. However, we will assess the status of soil biogeochemical cycles as a proxy of soil fertility (see Annex II).

The model identifies the reproducibility conditions of these funds in a specific territory throughout a year, and considers peasants' labour as main driver. Farmers' labour structures the agroecosystem by distributing the flows between the different funds.

From a peasant standpoint, the main priority was ensuring access to enough food and resources to maintain their domestic units. We call this a 'subsistence condition'. Then, in order to guarantee production for the years to come, peasants had to take care of reproducing other vital funds of their farms, namely livestock and soil fertility. We call this a 'reproduction condition', which has a lot to do with the 'land cost' to achieve farming sustainability—i.e. the amount of land required by agricultural activity that allows a cultural landscape to maintain its ecological functioning (Guzmán and González de Molina, 2009). This *Land Cost of Agrarian Sustainability* (*LACAS*) has two components, a quantitative (surface requirement) and a qualitative one (landscape functioning). The qualitative component is the structure of flows among different funds to keep their functions, organized by labour. This generates various subsystems, one for each fund, in charge of all incoming and outgoing flows needed for the agroecosystem reproduction (Chapter 3).

By using a concept stemming from an organic farming viewpoint, we define farm sustainability as the ability to maintain multiple agroecosystem funds without replacing their living function, and self-reproductive nature, by external industrial imports of chemical and mechanical nature (Guzmán and González de Molina, 2009). Although this entails a 'land cost' (LACAS), it also opens a way to enhance landscape synergy—e.g. feeding livestock involves a 'land cost', but manure also contributes to reduce the cost of keeping soil fertility. Thanks to the multiple-use of funds, and the synergic interlinkages among them, the total amount of reproduction costs is not necessarily a cumulative sum (Lemaire and Franzluebbers, 2014; Marull and Tello, 2010).

2.2. Introducing social dimensions in the analysis

The biophysical factors considered so far define only the range of possibilities and limits of the agroecosystem capacity–e.g. its possibilities for land-use and labour intensification in a site-specific context. The fund elements identified are a key factor to reach the agroecosystem's reproduction and establish a pattern of flows interlinking them. However, land appropriation and use, and the ensuing farm organization, entail other kinds of ruling forces. Exchanges of biophysical flows with other areas and non-farming social groups constantly take place, making the definition of the physical boundary of the agroecosystem considered more difficult. In order to bring to light the specific social relations that also shaped the agroecosystem functioning, the aggregate view at a municipal scope has to be simultaneously linked to the observation of the agroecosystem functioning at lower levels. To gain a more reliable approach from a societal and institutional perspective, we are going to consider simultaneously the agroecosystem functioning at farm-gate and community-level scale (Bayliss-Smith, 1982; Gerber and Scheidel, 2018; Gizicki-Neundlinger et al., 2017; Gizicki-Neundlinger and Güldner, 2017; Marco et al., forthcoming).

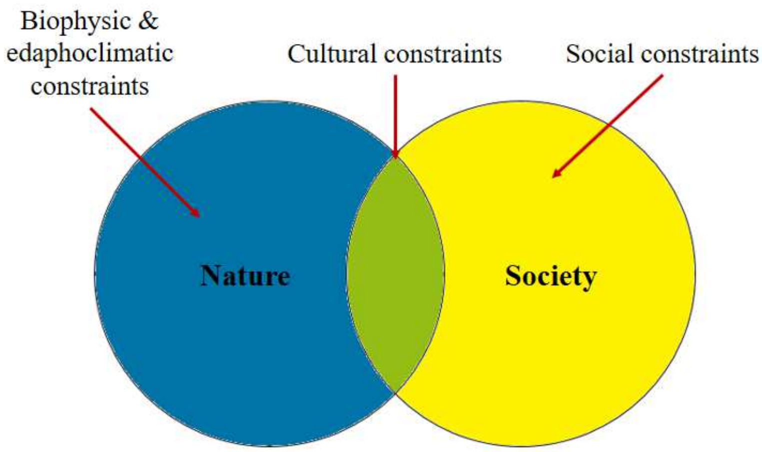

Figure 6.1. Constraints affecting territorial organization. Source: Our own.

From a socio-metabolic perspective we identify three main categories relevant to land-use allocation in farm planning (Figure 6.1): i) biophysical constraints (nature-nature relations), including biotic and abiotic factors present in the farm units; ii) cultural factors (nature-society relations) such as the set of technologies and managements available in a site-specific context[27]; and iii) the prevailing social conditions (relations among people) including all societal constructions (institutional, economic, political or cultural) that affect agricultural practices. We consider biophysical constraints as variables of 'first nature', and the rest of 'second nature' (Cronon, 1991). Setting the distinction between ii and iii, allows counterfactual analysis, by identifying how the relations among people (iii) affect farm decisions and agricultural development, by assuming the potential agricultural practices determined by cultural and biophysical conditions.

Ester Boserup (1981) considered population density as an endogenous social factor that determines cultural conditions and crop intensity under certain biophysical restrictions. Accordingly, population density is seen as a main driving force for land-use intensification without considering other social ruling agencies at stake. This implies assuming that the historically recorded population density would fit the theoretically maximum density allowed by cultural and biophysical conditions. If so, accounting the minimum area required to reproduce a domestic farm unit would become a key factor to identify the driving forces of the agricultural intensification processes at stake. However, in the context of class society there may be other explanations for intensification derived from social relations, such as coercion exerted over farmers' labour (Nell, 1992).

Assuming that power relations can play a role in crop intensity, and even a more relevant one than population density, we carried out a counterfactual analysis on how an agroecosystem would be in order to maintain its self-reproduction under specific biophysical and cultural conditions. By defining a maximum sustainable intensification under an equitable land distribution, we can approach by comparison how social relations may have shaped the actual land-uses observed. Summing up, the study of past organic agricultural societies allows us to start a *SFRA* model able to reveal through linear-programming scenarios how the agroecosystem could have been shaped or modified, based on different prevailing farming objectives. This also allows us to identify the role different social relations played either hindering or facilitating such scenarios.

[27] These are what we called *feasibility* (i) and *technical viability* (ii) in Chapter 5.

3. Sentmenat c.1860: A winegrowing specialization at the dawn of agrarian capitalism

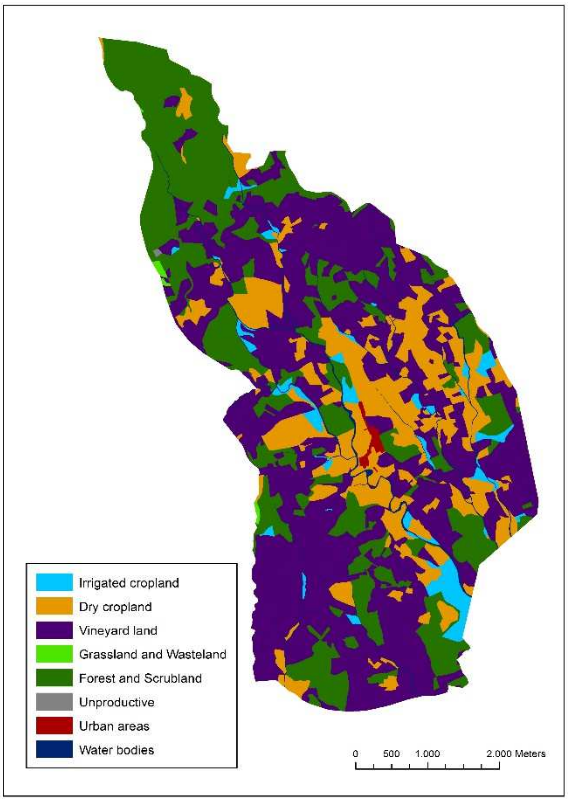

Figure 6.2. Land-uses in Sentmenat circa 1860. Source: Our own.

We test our first *SFRA* model in the context of an advanced organic agriculture of the municipality of Sentmenat (Catalonia, Spain) that circa 1860 had adopted a partial vineyard specialization. As we said before, there is a vast amount of socio-metabolic research for this case study (Cussó et al., 2006; Garrabou et al., 2010, 2008, Marull et al., 2010; Olarieta et al., 2008; Tello et al., 2016, 2012), based on an array of documentary sources such as the Estudio Agrícola del Vallès (Garrabou and Planas, 1998).

In this chapter, we will only focus to Sentmenat, because we have data on the Population Census, Cadastral Map, and Land-Use Register (*Amillaramiento*), which allow us to infer the characteristics of the Domestic Units.

Sentmenat is located along the tectonic boundary between the Vallès plain and the Catalan pre-littoral mountain range. It comprises 2,880 ha with a great topological, geological and soil diversity affected by a sub-humid Mediterranean littoral climate. It is located in the middle of our broader case study of the Vallès (Figure 2.3). Figure 6.2 shows how c.1860 vines coexisted with dryland polycultures and woods forming agricultural, pasture and forest mosaics. Population density was 60 inhab./km^2 in the mid-nineteenth century, which according to Badia-Miró and Tello (2014) fits demographic optimal conditions for vineyard specialization. Vineyards covered 42% of the total surface, 72% of cropland, and produced some 17,000 hl of wine a year. Although no data on vineyard surface is available for 1890 at the time when it reached its peak, we know that wine production increased up to 26,000 hl (Planas, 2015) during the period when the Phylloxera Plague started destroying French vines in the 1860s and ended up devastating those of the Valles in the late 1880s. Afterwards, very few vineyards were recovered (Badia-Miró et al., 2010).

Most important, until 1860 the agroecosystem functioning of Sentmenat was still mainly restricted at regional level from the reproductive view of its funds' maintenance. Local food and firewood needs were still largely met at regional level, while livestock and soil fertility maintenance were kept strongly integrated one another at local level (Chapter 4).

4. Methodology

4.1 The Sustainable Farm Reproduction Model for peasant units

In order to obtain different profiles of possible biophysical flow distributions in traditional organic farm systems, we develop a socioecological model based on the ability to reproduce their basic funds under the prevailing natural and technical endowments (Figure 6.1). We adopt the farmers' standpoint, and set the scope and temporal boundaries of the case study in the municipality of Sentmenat along a year c.1860, following the analytical frame proposed by Tello et al. (2015, 2016) based on a fund-flow approach (Mayumi, 1991), and the ensuing graph modelling put forward in Chapter 3. The funds considered are, as mentioned: domestic unit (DU), domesticated species (livestock), and farmland (soil). Through a socio-metabolic linear programming we account for the multiple interactions (flows) set among these three funds (Figure 6.3).

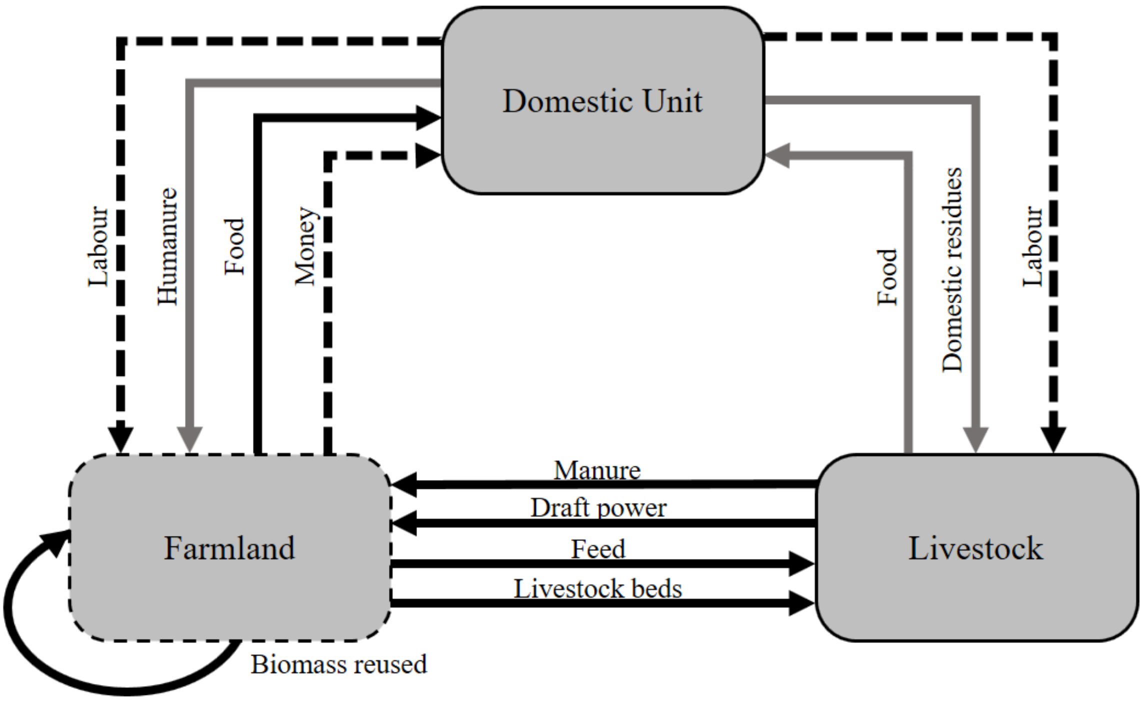

Figure 6.3. Modelling diagram for the SFRA c.1860. Source: our own. Squares represent funds and arrows the flows interlinking them. Grey arrows are fluxes constrained as boundary conditions, while black ones are the restrictions calculated with the optimization model. Discontinuous lines emphasize the objective functions to optimize.

The interest of this *SFRA* model lies on how farmland can be optimized through the allocation of possible land-uses. To establish which size one fund should be within a farm, we consider boundary conditions the size of the other two funds, despite having to double check if in the optimized scenario livestock density changes would increase efficiency on resource allocation. This is because through linear programming we are constrained and for calculating the optimum dimension of one fund, both the others have to be fixed.

Therefore, we start the accountancy by defining the size and composition of the DU, and this involves an important decision that affects interpretation. The representative family selected supposes a rate of consumers/producers consistent with the average dependence rate of the whole municipality, so as to allow us to extrapolate the DU results at local level. Indeed, following Chayanov ([1925]1986), we also run five different stages of the life cycle of this representative family in order to see how requirements would change over time, and not under or overestimate the capacity of land to host population. Thus, we will only present the results for the DU composition stage that reaches highest requirements.

4.2. The linear programming model[28]

The mathematical procedure for running the model is linear programming. This method achieves the best result by maximizing or minimizing (optimize) a linear first-degree function, allowing infinite variables and constraints as long as they are linear. Once the model is defined, it is run through Simplex algorithm programmed using Java software Gusek. The model comprises main variables (22), secondary variables (128), parameters (3), constraints (105) and objective functions (3). In this initial case study, we cannot implement a sensitivity analysis for optimization due to the lack of data owing to the historical character of the case study. Therefore, results will have to be considered cautiously, but we think that still have explanatory effect. We consider it to be relevant for further studies to guarantee more consistent results.

4.2.1. Variables and parameters

The main variables, from X_1 to X_{22}, represent the surface of each land-use. Each secondary variable (Xi,j) belongs to a use Xi, and represents a fraction of the total surface of land-use. As pointed in section 4.1, dimensions of DU and livestock heads are boundary conditions. We then define a parameter Z that represents the total number of members in the farm unit. When results for the whole municipality are extrapolated, the surface will be accounted by weighting farmland surfaces of each Z for its frequency in census and cadastral data. Small livestock numbers depend on the size of the DU (Z), while draught animals depend on the cropping surface through another parameter M representing its density.

4.2.2. Constraints

All variables are subject to a number of biophysical constraints expressed by linear inequalities. These restrictions contain boundaries imposed by the conditions for the agroecosystem reproduction, ranging from obtaining enough food, fuel and money, feeding livestock, closing nutrient soil cycles, to keeping the historically prevailing crop rotations. We define minimum and maximum flows for the three funds, which allow each of them to ensure agroecological sustainability (minimum for inputs, and maximum for outputs of the fund). Table 6.1 summarizes the main aspects considered in the programming model, from which constraints are derived.

Regarding DU consumption, we consider basic human material needs as determined ex-ante, and not considering the improving of farmers' well-being (Harrison, 1975). Given that we are setting a threshold for farming family reproduction, and not on how to organize farm counting with abundant means of production, we consider this demand to be inelastic. Indeed, we estimated the ability of a DU for doing labour at monthly scale, versus requirements from farmland and livestock. And for consumption we estimated the requirements of the typical diet (Cussó and Garrabou, 2012), the fuel for heating (Marco et al., 2017) and monetary requirements for clothing, footwear, housing, tools and tax burdens (Colomé, 2015, 1996; Vicedo et al., 2002).

About livestock, we consider the energy requirements for its maintenance and work, mainly from Church (1984), as well as their stall bedding for the barns (Soroa, 1953). However, we do not include here any specific diet but we only estimate the whole sources of feed and left the model decide them according their requirements. As well, an important flow from livestock is manure, which will be fundamental for soil nutrient restoring.

[28] We explain the whole model with their variables, assumptions, boundary conditions and constraints, in Annex II.

Table 6.1. Constraints and main sources considered in the programming model. Source: our own.

Domestic Unit	Livestock	Farmland-soil
Food (Cussó and Garrabou, 2012)	Feed (Church, 1984; Roca, 2007)	Nutrient balances (González de Molina et al., 2010)
Fuel (Marco et al., 2017)	Stall bedding (Soroa, 1953)	Soil qualities
Money (Colomé, 2015; Vicedo et al., 2002)		Irrigated land
Labour (Marco et al., forthcoming)		

Finally, regarding soil fund, we assess three dimensions: nutrient balances, total available surface, distribution of soil qualities and yields and the total amount of irrigated land. Nutrient balances involve many different flows (both natural and anthropic), and sources of nutrients. As well, we want to note that here we only consider nutrient balances for cropped areas. Instead, for forest and pastures we continue with the proposal stated in chapter 2 of ensuring a flow of biomass lower that estimated net biomass production within a year.

For land distribution we consider, in order to extrapolate results to the whole municipality, farm surface have to be representative of the constraints with regard to soil qualities. Behind this guarantee on having the same surface of soil qualities as in the total surface, there is a strong assumption that we made in order to be able to carry this modelisation. That is soil quality valuations for different crops are interchangeable, i.e. that a vineyard in 1st soil quality can change to cereal with the yields associated to 1st soil quality. This assumption obviously strongly affects the results, mainly in the case of changes from extensive to more intensive uses. Therefore, we will be cautious when inferring some conclusions on land-use changes, assessing at least what would it have supposed.

3.2.3. Objective functions

We optimize the resulting model according to the goals farmers might have adopted under the conditions set in each agroecosystem context. Therefore, we consider three functions that characterize different farming objectives: i) the minimum surface to ensure a reproducible exploitation, called ‘intensive optimum’ (Eq. 1); ii) the area required for the reproduction minimizing total labour, or ‘extensive optimum’ (Eq. 2); and iii) the maximum sustainable wine-growing area, or ‘monetary optimum’ (Eq. 3).

$$min\left(\sum_{i=1}^{i=22} X_i\right) \text{ (Eq.2)}$$

$$min\left(\sum_{i=1}^{i=22} W_i X_i + f(X_i, M, Z)\right) \text{ (Eq.3)}$$

$$max(X_{19}) \text{ (Eq.4)}$$

Where X_i is the area of each land-use, W_i the required workdays for each land-use, f(Xi,M,Z) the workdays associated with fertilization practices resulting from the model, and X_{19} the vineyard area.

3.3. Three different farm goals and scenarios

As we have seen in the previous section, we have run the model for the three different scenarios, so as to then compare them with the historical profile. The first function corresponds to the *Minimum Reproduction Unit* (*MRU*), which sets the minimum surface and land-use composition a sustainable farm should have. The profile is first set by seeking the area required to meet the needs of each fund (DU, draught animals, animals for consumption, soil fertility), and then by identifying both *LACAS* (Guzmán et al., 2011) and the landscape synergy resulting from the integration among funds (Lemaire and Franzluebbers, 2014; Marull and Tello, 2010).

The second objective function determines the *Peasant Reproduction Unit* (*PRU*), or the amount of surface and land-use composition that minimizes the labour required in the farm. This criterion minimizes the labour required to obtain the same product as *MRU* (Tannenbaum, 1984). Then, for both *PRU* and *MRU* we study the energy efficiency of the farm by calculating the *Final Energy Return on Investment* and *Final Energy Return on Labour* obtained (Tello et al., 2015, 2016). Both profiles allow us to define a range of possible sustainable eco-functional intensification, under a theoretical condition of equal access to land and livestock. Then we use these counterfactual scenarios to identify the potential institutional forces that prevented the achievement of those agroecological optimums.

The third farm scenario is the *Maximum Sustainable Specialization* (*MSS*). This would have been the amount of vineyard land that might have been sustained under a reproduction condition, maintaining population density. Hence, we can figure out what the possible evolution of vineyard specialization would had been in comparison to the real one, revealing its biophysical limits, and helping us to identify the social driving forces at stake.

5. Results and Discussion: Drivers of agricultural change in each scenario

5.1. The metabolism of a *Minimum Reproduction Unit* (*MRU*)

The first scenario minimizes land requirements of the farming population (Eq. 1) to assess the existing capacity for eco-functional intensification, by identifying the minimum land cost to maintain the three funds. Our representative DU of five people (the average family type in Sentmenat c.1860) would comprise a girl between 0-5 years old, a boy from 5-10 years old, a woman and a man between 18 and 60 years old, and a man older than 60. The results are shown in Figure 6.4[29]. In order to meet their food, fuel and income requirements the surface needed would have been 3.77 has (case 1). Note that, in this case, the family would have had to buy meat and fertilizers from the outside, as there would not have been domestic animals nor nutrients replenishment into the soil.

If we were to include two sheep, a pig and some chickens and rabbits estimated as average for a family farm, we would have had to add 1.81 has more (case 2). The high proportion that in this case would correspond to the rotation with dryland olive groves is consistent with the need to produce fodder legumes (e.g. lupines) to feed livestock (Roca, 2007). Feeding a mule, or providing a share of this feed for the 0.25 mule required for ploughing the minimum land, would have entailed 0.63 additional ha (case 3). If we sum these three surfaces (i.e., if each one would have been devoted to fulfil one goal), our standard family would have required a total amount of 6.21 has of farmland to guarantee the reproduction of both the DU and livestock funds (case 4).

[29] As you can see in this figure, we present the three funds as separate goals. While in the case of DU and animals (split into draft power and other domestic animals) we can analyse them separately, fertilization has intrinsically not a cost on surface; you can calculate the increase of the total land cost due to fertilization only with respect to other requirements.

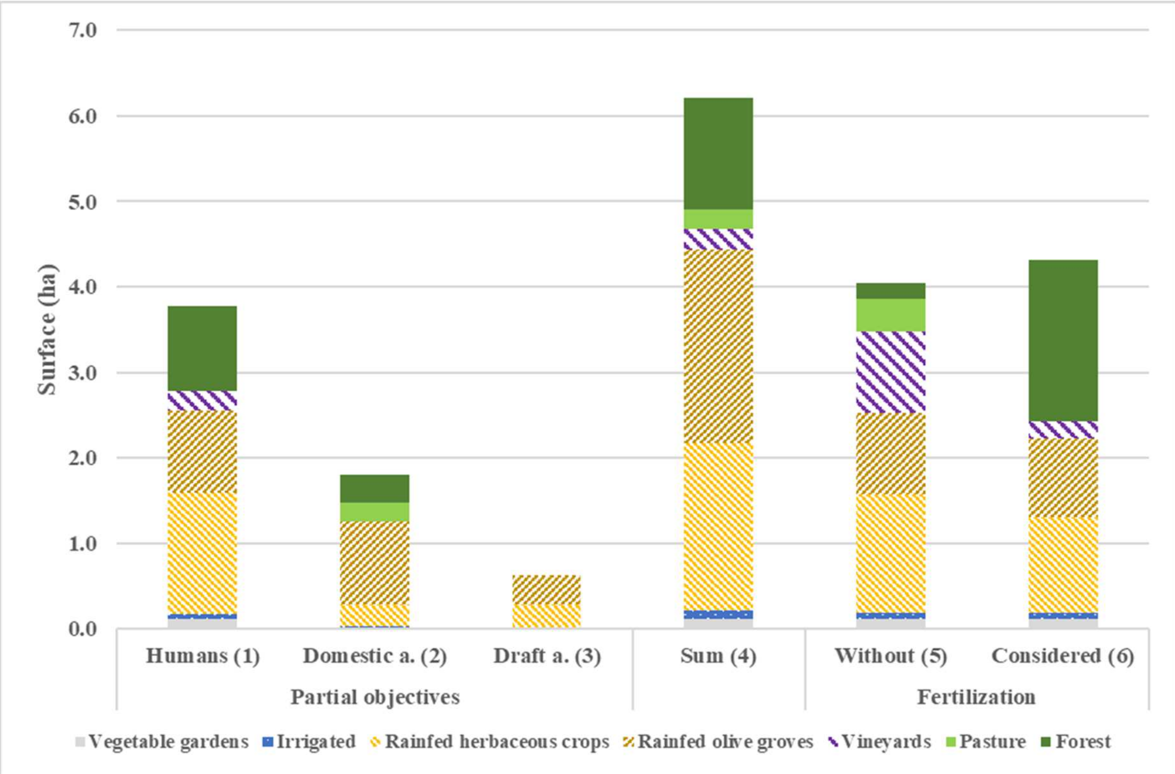

Figure 6.4. Land-use distribution for MRU scenario by goals, for a family of five people in Sentmenat c.1860. Source: Our own.

However, by taking advantage of the existing multi-purpose options and land-use synergies among funds, together with the possibility of using crop by-products for animal feed, the minimum area actually required for such a family farm would have been reduced from 6.21 to 4.04 has (case 5). This reduction would have been attained thanks to the multipurpose nature of land and livestock uses. For example, farmers used forest for pasture, and for firewood and timber provision, setting complementarities. Feeding livestock in ways that did not compete with human food also played a role. While in the first run of the model animals would be fed with crop main products, such as corn or vegetables, in the second run animal intake would rely on crop by-products such as straw, stubble, husk and pomaces, as well as natural pastures. Other synergies between different compartments of the agroecosystem would appear when soil fertility maintenance was taken into account. As a result, land-use synergies and livestock multi-functionality would allow reducing 54% of the total area required to reproduce the farm unit.

At first glance the maintenance of nutrient cycles in cultivated soils does not change significantly the surface needed: it increases only by 7%, from 4.04 to 4.31 has (case 6). However, this increase of 0.27 has is also associated with a change in the use of pastures in favour to forest as a nutrients' supplier, as well as a restructuration of land-uses according to soil quality. Thus, *LACAS* over a purely subsistence condition (case 1) was only 0.54 has, 14% above basic level, while the incorporation of livestock increased farmland surface 8% over farmers' needs. Here the generation of internal loops through biomass reuses becomes relevant. As the amount of available manure was not enough, farmers had to rely on burying biomass. This was a much more labour-intensive task and represented 37% of the total nitrogen replenishment. This is the reason why the upkeep of soil fertility produces a decrease in the overall energy efficiency (*FEROI*, the amount of energy product per total input), which drops from 1.18 to 0.43. Likewise, labour energy efficiency (*FEROL*) decreases from 59.0 to 33.8 MJ produced per MJ of labour performed.

These results reveal that more intensive land-uses required a greater flow of biomass reuses (*BR*), which in turn led to a decrease in energy efficiency. So, land-use intensity also determines what the energy returns may be. This means that taking as a single criterion the final energy efficiency (*FEROI*), regardless of the reproduction of funds and the *LACAS* involved, would incur in what Georgescu-Roegen (1971) criticized as an 'energetic dogma'. Hence, land-use intensification has to be taken into account when assessing the energy efficiency of agricultural systems.

We have also found that the required surface for *MRU* (case 6 in Figure 6.4) was 4.31 has. Here more than a third was forest, although dryland herbaceous crops also predominated together with olive trees associated to herbaceous rotations (26 and 22% respectively). On the contrary, vineyards only covered 5% (compared to 24% in case 5). Even in this *MRU* case 5% of production would have gone through market as surplus. From these, a third would have been animal feeding (that would have covered less than 9% of the animal feed requirement). This allows us to draw two conclusions: the adequacy of the prevailing historical rotations fitted the multiple needs of the agroecosystem; and that livestock density proposed in the model was fairly well adjusted to natural endowment—as the average livestock density left few biomass surplus in the optimal conditions.

To find the local possibility frontier to intensify population density, we should weight case 6 for each DU of the municipality (regarding the number of family members). The average surface required was 0.86 ha/person. This value matches a rough estimation made only in monetary terms by Garrabou and Tello (2008)—according to it, 4-5 ha of wheat were necessary to maintain an average family of 4.5 people in the same period and study area. Land distributions of less than 0.86 ha/person would not allow internal reproduction of peasant farms, and families would be compelled to perform other tasks off farm to get money to pay the goods acquired outside to fulfil self-reproduction. Indeed, they might also transfer part of this pressure towards other funds, thus hindering the condition of sustainable reproduction.

Hence, an equitable land distribution would allow 3,228 people to live off the 2,781 has of agrarian land in Sentmenat. In 1860 the population registered was 1,686 people. This potential population increase of 91% would have meant moving from 60 up to 116 inhab./km^2, surpassing the threshold of dense-medium population density (7) towards the highest dense rank (8) defined by Boserup (1981). Boserup associated this highest dense rank (8) to the change from short fallow cropping to annual cropping. However, the agricultural system and practices observed corresponds more to her dense population category rather than a medium-dense one (7). Although there were still fallowing practices carried out in Catalonia at that time, it had virtually disappeared in the Vallès County (Garrabou and Planas, 1998). Therefore, we observe a gap between the population density threshold put forward by Boserup and the one registered in Sentmenat in 1860. In other words, there was more intensive land-use than would have been necessary with an equitable distribution of farming resources—a relevant result suggesting that probably social inequality was a major driving force towards land-use intensification, beyond simply a population density pressure (Nell, 1992).

The greatest implication that this strategy would entail in terms of land-use changes at municipal scale would be a shift from vineyards to herbaceous crops of 334 ha. It could seem difficult to reach that in a sustainable manner. However, at least in terms of slope there were around 700 ha of vineyard in slopes lower than 20%, where it would be possible to cultivate cereal crops. Moreover, a study on land suitability of the study area estimated that in 1860 around 60% of the land in the four municipalities of the Vallès was either moderately suitable or very suitable for wheat cultivation (Rodriguez Valle, 2003). Therefore, we deem that a total surface of around 30% of herbaceous crops would have been quite *viable* and *feasible*. In terms of other uses, this would have also required some changes from vineyards to both olive groves and forestland, which does not seem to have presented more difficulties.

5.2 An extensification scenario with the *Peasant Reproduction Unit* (*PRU*)

MRU defined the possible threshold to minimize land-use requirements and host the maximum population. As Chayanov argued, a peasant economy might respond to different criteria other than labour allocation efficiency, crop diversification and risk minimization (Chayanov, [1925]1986). Peasants might also have been interested in minimizing labour, provided that their land endowment would allow this. So we define objective function 2 (Eq. 2), in which we are minimizing farm labour in the *Peasant Reproduction Unit* (*PRU*) scenario.

A reproducible land surface to minimize the labour required in a peasant community equally-endowed of land would be of 5.83 has for a 5-people family type in Sentmenat c.1860. This is 29% more than for a *MRU* strategy aimed at accommodating as much population as possible to the available land (see Figure 6.5). As expected, more extensive uses increased over 52% the surface under pasture and forest. Vineyards increased to 14%. The latter makes their role as cash-crop apparent, in contrast with *MRU* case, where olive groves played a major role. Cereal rotation associated to olive trees yielded higher gross revenues than vineyards, but required 87% more labour per hectare. Therefore, the aim to minimize labour costs, and get a higher net income, favoured the growth of vines instead of olive trees.

In order to reach the reproduction goals of a peasant family with a lesser labour requirement, a *RPU* strategy required increasing by 35% the land surface at its disposal. Conversely, energy labour productivity (*FEROL*) would have increased 51%, from 33.8 to 51.0 MJ per MJ of labour. This becomes a good trade-off example between labour intensity and land cost (Sahlins, 1971). In the *RPU* case gains in labour productivity would have been higher than land costs. Therefore, the *RPU* strategy would have meant an improvement in the population wellbeing with only a moderate increase of land available for each peasant unit.

The comparison between *MRU* and *RPU* counterfactuals sets the difference among a hypothetical land distribution (e.g. a land reform) aimed at accommodating as much population as possible on the land, or increasing farmers' wellbeing. Indeed, the labour-saving *RPU* case might have allowed a population density up to 86 inhab./km^2—still a higher value than the recorded data in 1860. This suggests, once again, that the actual population density was conditioned by the prevailing inequality that allowed a small group of wealthy landowners to accumulate a large share of the better lands, and to manage their estates in an extensive, poly-cultural manner. They rented in tenancy the poorer sloping lands to many smallholders who had no other choice than to farm intensively with vineyards these small plots, so as to supplement the family income by selling their surplus labour to larger landowners (Badia-Miró and Tello, 2014; Marco et al., forthcoming). Hence, vineyard intensification was not mainly driven by population density. Despite limitations of the counterfactual analysis—as we cannot assume that inequality was responsible for all the divergence between the modelled scenario and the actual situation—, we deem that social conditions to land entitlements played a relevant role. We acknowledge, however, that this should be addressed in further research that would compare the individual farm functioning of different social groups.

5.3. *The Maximum Sustainable Specialization* (*MSS*), deepening vine-growing strategy

Using the third scenario, we can go deeper in the analysis of the role of vine-growing specialization in our case study. Land distribution did not respond to the basic needs of peasants' self-sufficiency. The region was undergoing a process of wine specialization linked to international Atlantic markets (for wine exports) and to inner Iberian Peninsula (for wheat imports). As seen in the previous sections, population dynamics seem were not the main driver behind this agricultural intensification. It seems that the land entitlements that prevailed in the transition from feudalism to agrarian capitalism in Catalonia, and the ensuing social polarization

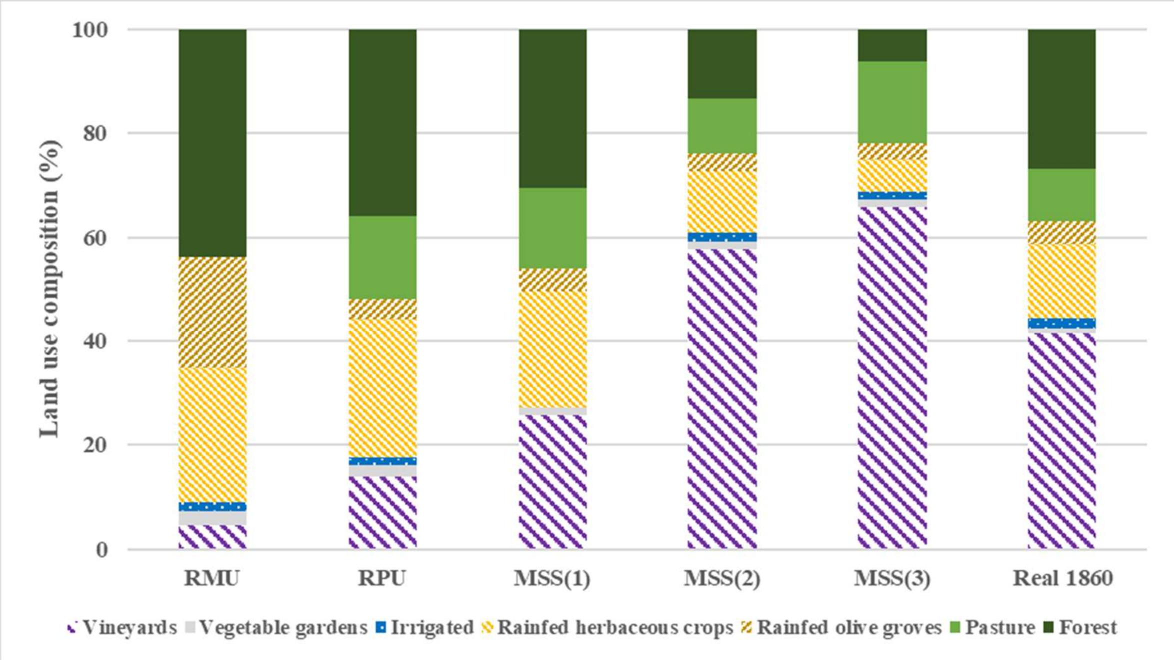

Figure 6.5. Land-use distribution for MRU, RPU and MSS scenarios according to the limiting factors considered, and actual data for Sentmenat c.1860. Source: Our own.

between wealthy landowners and small vine-growing tenants and labourers, played a major institutional role (Garrabou, Tello and Cussó, 2008, 2010; Congost, 2015). The Catalan emphyteutic contract of *rabassa morta* set a long-lasting lease on the vineyards the tenant planted, by paying to the landowners a third or more of the vintage. It allowed them to plough brushwood and pastureland, and to make a profit from growing grapes without having to carry the burden of planting and hiring labour to manage the vines (Colomé and Valls, 1994). Through these *rabassa morta* contracts many landless families managed to make a living and stay in the village, providing landowners a local job offer with low wages when they needed to hire day labourers. As a result, and despite its land-use prevalence (Figure 6.2), vineyard specialization remained a partial option, combined with the poly-culture of the larger estates, as well as with the pluriactivity of smallholder peasant units. In spite of a high market integration level—voluntary for landowners and forced for smallholder tenants and labourers—, all these farms took decisions considering several reproductive dimensions (Chayanov, [1925]1986).

It is interesting to figure out how farmers could have developed further this process of winemaking specialization, under an equitable land distribution and ensuring the agroecosystem's sustainability. The aim is to identify through this counterfactual analysis whether the actual strategies followed by those socially-polarized farm units created conditions for social and/or ecological instability. Our scenario of *Maximum Sustainable Specialization* (*MSS*) is the result of implementing the third objective function (Eq.3) and defining, with the actual population density given, what the highest share of vineyard would have been while ensuring the reproduction of funds, and identifying the factors limiting a further expansion of vines.

Figure 6.5 shows the results, according to different additional assumptions. The standard farm size for five active people would have been 8.25 ha/DU. If we consider the need to satisfy the restrictions of the three funds (*MSS1*), the highest share of land devoted to vines would have been 26%, far from the 42% in c.1860. Analysing the flow profile, we identify that the limiting factor was labour availability in the key months for vine management such as October (harvest) and April (leaf removal). If we then consider the feasibility of hiring external labour in the peak seasons, as was the case in Catalonia at that time (Garrabou et al., 2015), the vineyard threshold would go up to 58% of cropland (*MSS2*).

The reluctance to depend riskily on the market may have also played a role, as shown by comparing *MSS2* with model *MSS3*. In the *MSS3* model, crops would have been aimed at meeting only a basic subsistence fraction of the diet of the local population consisting of vegetables and fruit, as well as firewood for heating their homes. In this case, vineyards could have reached 66% of the whole municipal area (*MSS3*), but the village would have had to import 60% of its diet, mainly in the form of wheat and potatoes. In this case, therefore, an important share of reproducibility would be relying on imports, not only of labour or food, but as well regarding nutrient soil cycles. We estimate humanure, under this scenario, would satisfy 19% of nitrogen requirements, thus setting sustainability on external imports of food. The actual figure of wheat consumed covered by imports was 35% in Sentmenat c.1860 (chapter 4), while vineyards covered 42% of the area. The difference can be attributed, once again, to the unequal land distribution that concentrated irrigated facilities and woodland among wealthy landowners, depriving smallholders from the vegetable gardens and firewood self-provision supposed in *MSS3* (Garrabou, Tello and Cussó, 2008, 2010).

If we wonder why winegrowing specialization did not reached such a high level in 1860, we immediately see that it would have been necessary to clear more forestland, brushwood and pastureland. About 37% of the total surface c.1860 was forest and pasture, so cultivating these additional 416 hectares would had involved a huge amount of labour, and an important opportunity cost in terms of firewood, timber, wood pasture and nutrients for cropland. Again, we care for the land suitability of this extreme scenario. There were 440 ha of forests and pastures located in slopes lower than 30%. Therefore, regarding this constraint it seem not difficult to have changed them into vineyards, despite the effort this would have supposed in terms of building terraces in the steepest areas (Olarieta et al., 2008). Using again the suitability assessment of for the whole study area (including also the other three municipalities we used in other chapters), only around 21% of the available surface was definitely not suitable for cropping vines. Despite that, 20% of vineyards were actually located within this category, and vine-growers had to deal with all the difficulties that would entail. Thus, we consider that this scenario, although we cannot totally ensure its suitability, might have been reliable under the conditions of land-use intensification we observe for that period—always keeping in mind that this would only had been possible if population would have chosen that goal.

In short, our counterfactual programming models reveal that market vineyard specialization might still have had room for reproducible development, but only under an equitable land distribution, and at the expense of reducing farm self-sufficiency by increasing even further market integration of labour and food.

5.4 Discussion of the scenarios

It has long been criticized that in the study of carrying capacities (Murray, 2009) defining biophysical limits for the anthropogenic use of ecosystems has to consider explicitly which objective is going to be optimized. This holds true for agroecosystems as well. The comparison between our counterfactual *SFRA* scenarios and the actual ones makes the usefulness of linear optimization models apparent, when they are built from a socio-metabolic accountancy to reveal many of the configurations that agroecosystems and land-uses could have, all sustainable, depending on the main goals farmers adopted.

For example, the upper agroecological limit of 116 inhab./km^2 set by our *MRU* model under an equitable land distribution suggests that the existing cultural and biophysical conditions allowed greater population density. Yet, it is quite likely that social inequality could have prevented this. The actual path was a commercial wine specialization (Figure 6.5) in a socially-polarized rural society ruled by medium and large landowners who offered sharecropping contracts to smallholder winegrowers, forcing them to carry out a highly-intensive vine cultivation. Despite limitations of current model regarding land-use allocations, it seem reliable that this vineyard specialization would still have had a potential for a sustainable expansion, but under an equal social condition. By making these contrasts apparent, our programming models also help us to identify which factors may explain the differences between the counterfactual scenarios and the real data observed, bringing to light the role that institutional settings, social inequalities, market asymmetries and coercive forces might have played (Marco et al, forthcoming).

Following the classification proposed by González de Molina and Toledo (2014), those ruling social agencies were: i) competitive exclusion in access to the land; and ii) parasitic ways of land rent extraction by wealthier landowners from tenants' grape vintages, and labour surplus extraction from farmhands hired in the labour market. For example the Marquis of Sentmenat, who was the richest landowner of the municipality in terms of land ownership and rent collected (Garrabou et al., 2001; Tello and Badia-Miró, n.d.), seized 49 ha of forest and pasture, while very few smallholders had access to this fund which was so necessary as a source for soil nutrients, firewood and timber. Deprived from woodland, smallholders had to rely on their own vines' pruning, and faced the dilemma of either using them for heating and cooking at home or fertilizing their vineyards.

In turn, competitive exclusion (i.e. private land property) ensured land rent and labour surplus extractions via socio-metabolic parasitism (i.e. the redistribution of biophysical flows through market leases of land, and of labour hiring). As a result, smallholder vine-growers and labourers had to increase their labour effort, as well as the amount of land they had to till, in order to cope with the extraction of land rents and labour surpluses from wealthy landowners. In the case of vineyards contracted through sharecropping (*rabassa morta*), tenants had to pay around a third of the grape harvested (Colomé, 1990). This required a one-third increase of cropped area in order to fulfil self-reproduction. If many smallholders could not have access to this additional land, they had to find other ways to balance their family budget through markets.

Future research will have to deepen into these comparisons using the entire distribution of land and livestock ownership in the municipality, and their uses, in order to identify which strategies of socio-metabolic coercion were exerted, or combined, and how they affected the reproducing capacity of each farm. This would help to confirm the hypothesis that concentration of landownership, as well as the advantageous land endowment of wealthy proprietors, prevented the rest of this rural community from attaining the optimal options explored. Previous studies show a Gini index of 0.73 in landownership distribution of Sentmenat c.1860, where 206 out of 261 landowners held less than five hectares each (Garrabou, Tello and Cussó, 2008, 2010; Garrabou et al., 2014). This means, compared to the minimum of 4.3 ha/DU we reached, that very likely 79% of DU did not have enough land to meet their family needs. Moreover, given the importance of forest and pasture as a source of nutrients to restore soil fertility, and its skewed social distribution, it is likely that social inequality forced smallholders to enter a process of soil mining (Tello et al., 2012).

6. Conclusions

In this chapter we applied for the first time a *Sustainable Farm Reproductive* Analysis (*SFRA*) through linear optimization modelling of the different flows that interlinked three necessary funds for agroecosystem sustainability: the peasant family unit, the livestock, and soil fertility. Our *SFRA* model relies on the approach put forward by Alexander V. Chayanov ([1925]1985; Van der Ploeg, 2014), but it goes beyond it by adopting a socio-metabolic perspective from a fund-flow standpoint. It aims at generating scenarios for more sustainable farm systems based on the biophysical limits of agroecosystem functioning. Further chapters aim to include a more robust optimization analysis by using non-linearity to include a fourth fund: the farm-associated biodiversity that guarantees a large array of regulating, sustaining and habitat ecosystem services, together with the provisioning ones (MEA, 2005).

This study has assessed quantitatively, for the first time, the possible synergy that can be set among land-uses and land-livestock relationships to reduce land requirements when funds are interrelated. Agroecosystem funds have a dual condition, as suppliers and consumers of biophysical flows. By linking the product and by-product flows of one fund to the consumption another requires, the amount of land to meet their needs could be substantially reduced. This is relevant to assess the *Land Cost of Agricultural Sustainability* (Guzmán and González de Molina, 2009) and the *Energy Returns On Investments* of agroecosystems (Guzmán and González de Molina, 2015; Tello et al., 2016). Currently agroecosystem funds are increasingly fragmented by linear industrial farm and livestock management which are kept separated from abandoned forests and pastures (chapter 4). This raises a growing concern for the harsh competition among land-uses devoted to feed animals or provide food for humans (Haberl, 2015), and for the food-biodiversity dilemma. In this sense, we deem our *SFRA* modelling can help to plan more sustainable farm systems.

Despite the limitations as a first approach, the methods proposed and the results obtained are also relevant for the advance of organic farming towards more agroecological landscapes. They highlight the relevant role that forests and pastures can play as soil nutrients suppliers, when they are agroecologically integrated with cropland through a complex multi-purpose livestock feeding. They show the importance of keeping complex crop rotations and multi-crop associations, and its associated territorial synergies as farmers did in past organic agricultures to maintain some coherence between regional food production and consumption, which created ecologically functional landscape mosaics. They also highlight the greater labour efficiency by following an extensive strategy instead of only promoting a higher rural population density when searching for more equitable land distributions. Last, but not least, they show that a certain degree of cash-crop specialization can be done while maintaining relevant levels of local food sovereignty in a sustainable manner.

Modelling the functioning of agroecosystems from a reproductive standpoint opens the door for a deeper Ecological Economics analysis of the socio-ecological functioning of organic farming and agricultural communities, either in past times or at present. The *SFRA* model is aimed at devising and planning more sustainable farms and farm systems, in order to tackle a relevant share of the current global ecological crisis. It is high time that ecological economists developed new proposals for future scenarios based on what history may teach us.

7. References

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CHAPTER 7. POSSIBLE HORIZONS OF AGROECOLOGICAL LANDSCAPES, *SFRA* FOR 2009 [30]

1. Local food systems: top-down or bottom-up strategies?

In light of the current food regime (McMichael, 2009), we have observed a need to put forward proposals that advance toward an agroecological transition, bearing in mind that sustainable systems are much more complex to create than unsustainable ones (Wallner et al., 1996). As we have noted, a key role in such strategies falls to the retrieval of peasant knowledge insofar as there is a capacity and willingness to understand such knowledge as an adaptive system to new challenges and not from a perspective of “frozen memory” (Gómez-Baggethun and Reyes-García, 2013; Toledo and Barrera-Bassols, 2008).

In this chapter, we apply the *Sustainable Farm Reproductive Analysis* (*SFRA*) to the current situation in order to define desirable horizons. As indicated in chapter 5, it is crucial in the definition of such horizons to establish *desirability*, that is, the *intentionality* by which we wish to manage the agroecosystem. When presenting the model, the assumptions to be applied to the flow of foodstuffs will be critical. That is, what is the *intentionality* and what are the social values by which we wish to manage the agro-ecosystem? This is a key question to define the objective function that will be run in the model.

As noted earlier, our approximation to agroecology lies in the radical approach, which aim to confront the current global food regime and find alternatives (Levidow et al., 2014; see section 2.1 of Chapter 5). Specifically, the proposals being developed in these branches quite often support Food Sovereignty as a rationalization strategy for farming systems (Edelman et al., 2014). In the context of food sovereignty proposals, however, we must avoid to fall into an apriorism about the ability of local strategies to achieve ecologically and socially just systems, the so-called *local trap* (Born and Purcell, 2006). The requirement is to identify the limits of any possible development of food strategies through the strengthening of horizontal and vertical networks, but without essentializing the local *per se*.

In 1902, Leopold Pfaundler argued for the need to find an equilibrium in international trade between autarky (which constrained the sustainability of the world’s population), and absolute specialization (which entailed a high environmental cost because of transport requirements; Martínez Alier, 1987). The specific characteristics of specializations stems from advantages in soil and weather conditions, but also in geographic position and available labor. We deem that Pfaundler’s approach is a good starting point for a debate on the extent to which territories should engage in sustainable specialization. However, this follower of Justus von Liebig said that under autarkic strategies, territories would face nutrients scarcity on the nurient with lower presence in the territory, in relative terms. The evolution of science from the early twentieth century to the present day, however, indicates that Pfaundler’s view of limiting factors requires further elaboration because of the ability of biodiversity to cope through synergistic strategies among species (Cadotte et al., 2009; Tilman et al., 1996). Thus, while an agroecological

[30] I carried out this research together with Mar Grasa, Inés Marco, Carme Font and Enric Tello. As in chapter 6, I have led the whole process counting with different collaborations of the other co-authors. Together with Mar Grasa we defined the nutritional requirements for estimating food baskets and constraints, while she analyzed the resulting diets in nutritional terms. Carme Font, as a mathematician, assisted me for the non-linear programming model. Enric Tello and Inés Marco contributed to the general discussion and building of the model. I want to acknowledge as well to Eduard Balsells, Vanesa Freixa, Pep Tusón, Isart Gaspà and Teresa Cervera (all of them professionals on agricultural and forestry activities) for their commitment on debating the model foundations and assumptions. As well I thank Fernando Rodríguez Valle for sharing his maps on land suitability of the Vallès case study for different crops, and to Jose Ramón Olarieta for his comments regarding the soil fund and the use of nutrient stocks.

strategy to manage the agroecosystem could enhance its degree of self-provisioning, we still need to solve the extent of openness required to gain the maximum benefit from each environment while also meeting the organic need for cycle closure at an ecologically feasible scale (Tello and González de Molina, 2017). Therefore, while this gap between both strategies (autarky or specialization) could be reduced by synergies of biodiversity, it is still unknown the degree of openness that takes more advantage for a sustainable human needs satisfaction.

We start from the premise that for international trade the issue is to design systems that do not create an unequal exchange at the ecological or social level (Foster and Holleman, 2014; Hornborg and Martínez Alier, 2016). In this position, we consider that the better way for doing those exchanges would be through value in use while assessing its environmental costs. However, it is clearly difficult to find a way on how to account for these costs. One example of the multiple impacts, even under traditional organic societies can be found in the study area of Vallès. Circa 1860, the area had a high degree of specialization in very advanced winegrowing. Nevertheless, 69% of the area's foodstuffs were provided locally (chapter 4). The remaining food mainly came from inland regions of Spain. But with the cash exchange between inland regions of Spain and Barcelona's province, there was a degree of imbalance between imports of cereals ("*virtual land import*") and exports of wine ("*virtual labour export*"; Garrabou and Tello, 2008). The result is an historical example of how these systems once functioned at different scales and with diferent environmental and social costs that have to be assessed through multicriterial methodologies.

Therefore, we assume that the search for socially and environmentally desirable optimum can only be resolved when a set of several optimums have been defined at different multi-scalar levels. As staring point, we know two different situations: on the one side, the maximum level of autarky; and on the other side, the maximum level of potential food production making use of possible land-use synergies in the agroecosystem. They set the range in between we deem that a Pfaundler optimum can be found. These two notions will useful to define agroecological horizons, and to compare them one another. This is what we want to assess in this chapter, as a first approach.

At the social level, Busch & Sakhel (2016) maintained, from the perspective of industrial ecology, that it is easier to enact a strategy involving the creation of islands of self-preserving autarky and create bottom-up synergies (from local to global scale) in response to the current situation of unsustainability than it is to enact top-down strategies (from global to local scale). According to the authors, autarkic strategies of this type foster innovation and the search for local solutions, even while they can also trigger strong opposition from certain social agents because of the drastic changes that they require. Two other factors are conducive to these strategies. The first is the feasibility of the existence of institutions at lower scales that are convinced to initiate the necessary transitions toward strong sustainability, while the second concerns the problems of scale relating to strategies of participative democracy (Wallner et al., 1996). We must bear in mind, however, that bottom-up strategies run the risk of not correctly transforming their own current food system because regulatory decisions may lie outside their scope of action (Levidow et al., 2014). Indeed, this is one of the problems plaguing European agricultural integration (Fritz, 2012).

In short, the aim of this chapter is to apply *SFRA* in order to meet four chief objectives in defining agroecological horizons: i) to identify the potential of agroecological reproduction strategies in a local context; ii) to compare them to a conventional farming model; iii) to identify the potential on changing current diet to a healthier one; and iv) to contribute to the debate on the equilibrium between autarkic strategies and production specializations.

2. Theoretical development of the *SFRA* model for the present day

In chapter 6, we applied *SFRA* for the first time to gain an understanding of potential agricultural development without inequality, using an historical counterfactual example in an advanced organic society. At a theoretical level, this enabled us to test the potential of socio-ecological modeling as a tool to develop sustainable scenarios from the standpoint of three living funds (the domestic unit, livestock and approaching soil biogeochemical cycles). As an exercise in applied history, moreover, it also helped us to grasp the key role played by the integration processes among different living funds that permitted the pursuit of strategies to minimize environmental and territorial impacts (Guzmán and González de Molina, 2009; Lemaire and Franz Luetbers, 2014; Marull and Tello, 2010). Today, these would be labeled as ecofunctional intensification strategies (Schmid et al., 2009), but they have a strong value of biocultural inheritance lost amid the processes arising from the Green Revolution (Agnoletti and Rotherham, 2015; Altieri and Toledo, 2011). As noted in the previous chapter, however, the initial *SFRA* remained limited as an historical and contextual exercise and because of the shortcomings of linear approximation and their assumptions.

In this chapter, we propose moving forward with the *SFRA* to consider new elements. Our aim is to apply *SFRA* to current farming systems in order to identify agricultural scenarios that are *feasible*, *technically viable* and *desirable*. To do so, it is necessary to review how the general structure of the model is established at the scale of agroecosystem. Once again, the initial elements of the socio-ecological model are self-reproducing living funds.

We return to the three groups of living funds that are fundamental to an agroecosystem: people, domesticated species and non-domesticated species. Based on these groups, we characterize five more or less distinct living funds, namely: society and agrarian community (people), livestock (domesticated species), soil fertility and also a proxy for farm-associated biodiversity (non-domesticated species), following the structure of funds set out in chapter 2 (figure 2.2).

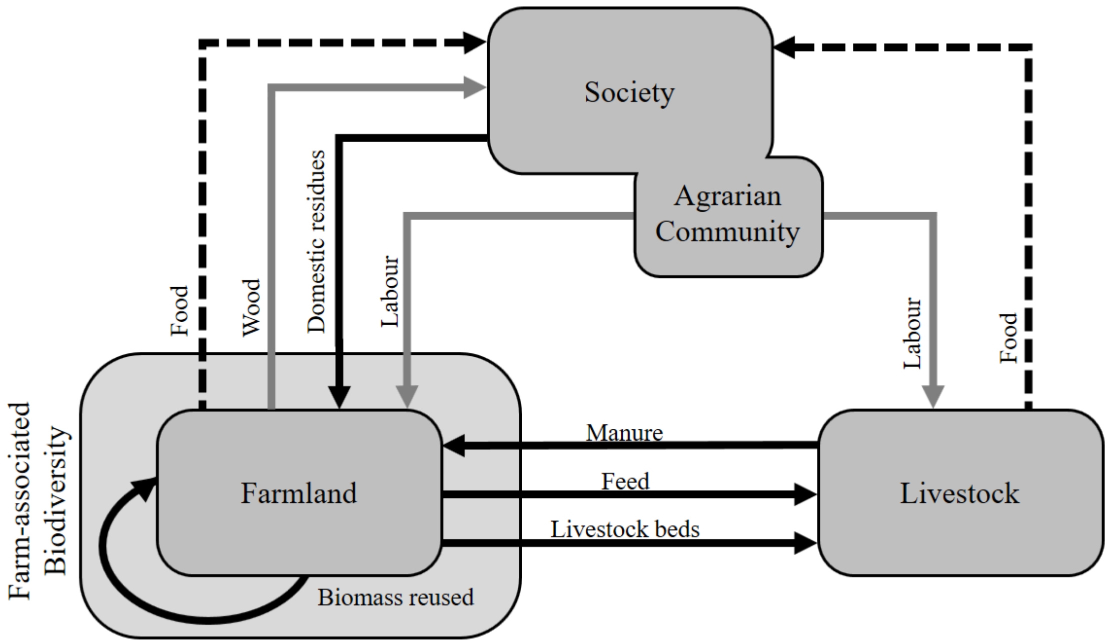

Figure 7.1. Modelling diagram for the SFRA for 2009. Source: Our own. Squares represent fund elements while arrows fluxes. Black lines are the models' structure while labour and fuelwood are not considered constraints. Dashed lines refer to the objective function.

We address the reproductive requirements of these funds by means of the flows presented in Figure 7.1. To ensure reproduction, we take an agroecological perspective in terms of meeting the needs through biophysical flows and not by importing external inputs (Gliessmann, 1998), except for the application of labor as indicated in section 2.1. We will perform an approximation of the organic flows involved in the system.

Since we are studying a dynamic system in non-equilibrium, it is fundamental to establish a time dimension, which would logically be annual given the characteristics of farming, as assessed in Chapter 6. The extractions to be made of a fund at an annual time-scale, therefore, must be sustainable and the return of flows for the maintenance of the fund should also be sufficient to begin the following year without having been degraded.

A last key question to address in the new approximation of the *SFRA* is the unit of analysis, given that the farm scale used in the previous chapter does not make sense in current societies. We are considerin here the ability of the territory to feed the whole society and not restricted to the previous domestic units. In agronomic or bioregional models, the unit of study is defined in terms of watersheds, topographical units or bioregions based on biotic composition (Dodge, 1990). However, for a socio-ecological model to make sense, the units of analysis need to be representative of historical cultural interactions. As a result, it is necessary to identify an appropriate agroecosystem scale from the viewpoint of socioeconomic exchanges, transport and coherence as a bioregion. In light of our limited sources, time constraints and the amount of available information from the four municipalities in the Vallès county, we will again consider the same unit of analysis used in chapters 3 and 4.

Below we present the basic features of the funds considered in the *SFRA*, looking at their composition, their interaction with other living funds and the limitations in the model's development. The *SFRA* must be subject to potential evolutions in the range of technological and agronomic options and any proposed modifications that follow from the establishment of a dialectic with the wishes and interests of society, i.e. through its deliberation. The model that will be applied as an example, therefore, must be understood as flexible because new elements can be introduced for consideration at any time, as shall be seen, for instance, in the case of sewage sludge.

2.1 Agrarian community and society

In this case, the aim is to apply *SFRA* to an industrial society, which has a level of complexity in productive social relations that is much greater than in the mid-nineteenth century. Agriculture now plays a minor role in terms of employment, given the impacts of the Green Revolution. Agricultural labor productivity has risen from 67 GJ/h to 650 GJ/h, giving rise to a profound shift in the production matrix (see chapter 4). In 2010, employment in agriculture for the European Union 27 was a little over 5% of total employment (EUROSTAT, 2010). The challenge has now become how to supply food to the entire society and not only to farmers, while also ensuring that the needs of the other living funds are met.

It has been amply demonstrated that the mechanization of farm activities is one of the bottlenecks in the loss of energy efficiency in farming systems, and that the current high dependence on fossil fuels makes it unsustainable in the long run (Leach, 1975; Pimentel et al., 1973; Tello et al., 2016). Nor can it be ignored that mechanized farming has resulted in a major social advancement, minimizing the most physically taxing activities of farmers. Whether drawn by animals or driven by steam, electricity or fossil fuels, machinery has brought an unquestionable improvement to the living conditions of farming communities (Martínez Alier, 1987).

Whereas in the case of the other self-reproducing funds we hold that an agroecological transition should promote the functioning of the funds strictly based on biophysical flows, a complex and underdeveloped debate in the field of social metabolism is left open here. The degree to which mechanization is sustainable lies beyond the object of our study. Without denying the interactions that it supposes with the *SFRA* model[31], therefore, we will consider a degree of mechanization similar to the current level as a first approximation.

Another modification since 1860 is the disappearance of the flow of fuelwood as a constraint in the agroecosystem. This is due to the change in the energy matrix caused by the socioecological transition from an organic society to an industrial one, in which biomass now represents 2% of total consumption, with an estimated potential contribution of 9% (Codina and Koua, 2015; FAO, 2013; Institut Català de l'Energia, 2009). Because of limited access to certain sources on the potential of biomass use, we do not include this flow in the present paper.

As for flows from society to the agroecosystem, there are two main sources of resources, which we considered in the *SFRA* c.1860: the use of domestic residues and the re-use of human excreta. In the current context, we will make two distinct assumptions by type of resource. For domestic residues, we will include only the return of composted materials from foodstuffs produced in the territory in order not to estimate imports of nutrients external to the agroecosystem. As well, despite they were used in traditional organic societies for feeding livestock at the farm level, in this case we will consider them for restoring nutrient cycles to soil.

In the case of human excreta, which was fundamental for the closure of nutrient cycles in traditional organic societies (Tello et al., 2012), a vigorous debate revolves around the effects of their use on agriculture. Because of the risks associated with the presence of heavy metals, organic components such as pharmaceutical wastes, and a lack of knowledge about the potential processes of increased antibiotic resistance from the application of sewage sludge, it is advisable to adopt a precautionary principle that must yet be validated or rejected based on scientific findings (Bouki et al., 2013; Smith, 2009a, 2009b; Wuana and Okieimen, 2011). As a result, the flow of human excreta is not used in the agricultural metabolism for the *SFRA* in 2009.

2.2 Livestock fund

The role of livestock in agroecosystems has changed significantly as the integration among living funds has declined (chapter 4). In this *SFRA*, we propose recovering at least the function of providing fertilizer materials and the role of such animals in taking advantage of resources that do not compete with human consumption.

We distinguish three categories by the type of food that they can supply and by their current functions within the agroecosystem:

a. Monogastric animals for meat consumption: basically pigs[32]
b. Monogastric animals for meat and egg consumption: chickens and hens.
c. Ruminant animals for meat and milk consumption: historically, the characteristics of ruminants have been critical for sustainability because of their metabolic ability to make use of fibrous materials (Krausmann, 2004). Basically, we can distinguish sheep, goats and cattle.

[31] A proposal to return to animal traction would affect livestock, while a proposal to recover traction with fuelwood would affect land-use.

[32] Rabbits and horses are also monogastric animals, but they have a much greater capacity to consume forage and grasses than pigs. Because of this reason and because of their extremely low consumption in today's diets (MAGRAMA, 2009), we do not consider them in the model, nor do we include them in the first group. Their substitution for pigs is not as directly proportional as it would be among the types of poultry in the second group, for example.

For the applied *SFRA*, we select a representative animal species from each group, with the understanding that there should be a possibility of substitution (to a large extent, if not absolutely) with any other animal of the same group. In the future, if the study should incorporate the possibility of animal traction, these groups would need to be modified in order to make distinctions on this dimension as well.

2.3 Soil fund and farm-associated biodiversity

Similarly as in the previous *SFRA*, here we will approach the satisfaction of the biogeochemical cycles through nutrients balances as a proxy of the mantainment of good conditions for soil fertility (González de Molina et al., 2010; Hendrix et al., 1992). A good ecological condition of the soil will correspond to any practices that are carried out at the plot level, not merely the biogeochemical cycles because we are not including dynamic analysis of nutrients inside soil. While it is obvious that the organic amendments being considered here will promote better conditions for physical and biological fertility, the model does not capture their effect, but rather that of biogeochemical cycles. However, as we are focusing at landscape level we deem enough only considering them for this approach. At the same time, a further change from the previous *SFRA* will now be to incorporate nutrient balances in forest land so that sustainable agricultural processes are not supported by their degradation.

For this new case application, we will also include a constraint regarding material conditions for farm-associated biodiversity. The problem when dealing with farm-associated biodiversity is that is distinct from domesticated species because, as we already stated, it cannot simply be supplied a set amount of food and a barn. So in order to develop a fund-flow analysis implies much more complexity.

At the same time, biodiversity has several levels, so that any agroecological approach should be planned at various scales (de Groot et al., 2010; Gliessmann, 1998). At the scale of plot, there is the *alpha* biodiversity, which is always lower in farmland than in undisturbed land, although agroecological practices can mitigate the gap. As we are working at the scale of agroecosystem, however, what interests us is *beta* biodiversity, which concerns aspects of the landscape (Gliessmann, 1998).

One of the important conditions for the provision of these services is the structure of land covers, which is an emergent property of the landscape (chapter 3). The leap from the farm scale to the regional scale enables us to take into account how the different distributions of farms independently affect the emergent properties of the landscape, which also require planning (Cong et al., 2014; de Groot et al., 2010). As we mentioned, we will limit the analysis to biological aspects in this *SFRA*. That is, we will focus on the material conditions left to species that can provide specific regulation services, such as pollination and pest control, or cultural services, such as the intrinsic value of the associated biodiversity. As indicated further on, in the current approximation we will incorporate landscape patterns.[33]

3. Case study

The selected area of study covers the four municipalities from chapters 2, 3 and 4. They are located in the historical county of Vallès: Sentmenat, Caldes de Montbui, Castellar del Vallès and Polinyà. In this case, the selection is conditioned by the existence of a study on the agrological

[33] Other important issues such as flood control, water purification and climate regulation, which also depend on the configuration of the agroecosystem, are not considered here. This is because they do not fall within the scale or capability of the model and because they form part of the overall social objectives beyond the reproducibility or not of the agroecosystem (Bagstad et al., 2013; Vihervaara et al., 2010).

suitability for different crops (Rodríguez Valle, 2003), as well as access to cartographic information on the composition of soil uses in the mid-nineteenth century (Marull et al., 2008). Because of the issue of limited sources, and its character of test bench, we take these four municipalities as the unit of analysis for the agroecosystem. For future approximations of the *SFRA* model, however, it would be desirable to define the unit of analysis more precisely, taking into account the aspects noted in the previous section. As well, in this chapter, instead of using data from 1999 we adapted the study to the next agrarian census, done in 2009.

Figure 7.2 shows the distribution of land-uses for that year. The most predominant use is woodlands and scrublands, which cover 62% of the total surface area, primarily in the northern and western region of the four municipalities. *Pinus halepensis*, or Aleppo pine, covers three-quarters of the woodlands and scrublands, while the remainder features *Quercus ilex subs. ilex* (or Holm oak), shrubs and riparian or other forests. Urban sprawl has had a severe effect on the landscape. Nearly 19% of the land is now dedicated to urban areas (16%) or to other infrastructure or unproductive agricultural uses (rocky areas, ravines and riverbeds; 3%). Between 1956 and 2009, cropland was cut practically in half as a result primarily of two forces: first, the urban area quintupled, swallowing up formerly irrigated, high-quality cropland; and second, a slight process of forest transition subsumed marginal lands that could not be mechanized or that had been abandoned. The decline in cropland has resulted in a subsequent loss of agro-silvo-pastoral mosaics, which are the typical cultural landscape of the Mediterranean region (chapter 3). Within this landscape, grapevines represented the main crop before the advent of the Phylloxera plague, but now they occupy little more than 0.7% of land under cultivation. By contrast, the predominant use of cultivated land at present falls to crops for animal feed, which account for 75% of all crops, followed by fruit trees and olive trees.

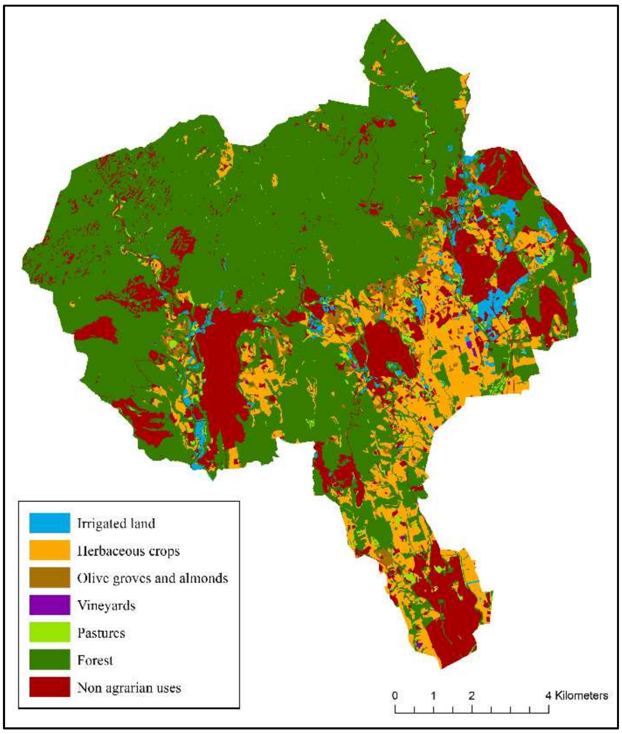

Figure 7.1. Land-use map for the Vallès case study in 2009. Source: Our own, adapted from CREAF (2009).

The predominance of crops for animal consumption is consistent with the high livestock density of the four municipalities. While the livestock density has fallen 40% from the peak recorded in 1999, it continues to be extremely high at 111 LU500/km^2. This figure is absolutely exorbitant in comparison with the level of 7 LU500/km^2 in 1860.

As for population, the proximity of the Barcelona metropolitan area resulted in an explosive upward trend until the middle of the last decade, when residents numbered 55,433 and the population density was 462 inhab./km^2, with only 0.25% of total population dedicated to farming. The high population density stands in stark contrast with Spain’s national average of 92 inhab./km^2 and with the 1950 average of 100 inhab./km^2 in the case study.

Obviously, the selection of this case study for an analysis of the potential development of agroecological landscape strategies has some particular characteristics relating to high population density that must be taken into account when drawing conclusions. As we propose, however, these studies should be done with local particularities taken into account so as to proceed subsequently to a networked analysis of the capacities of regions. It is necessary to take it as an example, therefore, without seeking to extrapolate the results to larger scales.

4. Methodology

Based on the structure of funds and flows defined in Figure 7.1, we put forward the main characteristics of the present-day *SFRA*. The modeling will be done through a mathematical approximation using non-linear programming. Below is an explanation of how the programming, the sensitivity analysis and the analysis of the results will be carried out.[34]

The objective will be to compare several scenarios, varying the analysis on two main axes: the type of diets provided by the agroecosystem (production strategy to meet social needs) and the amount of land for crops (whether the area under cultivation can be increased or not).

4.1 Programming the non-linear optimization model

The methodology of non-linear programming identifies the best possible result for a system based on the maximization or minimization (optimization) of a function with a finite number of variables and constraints that may be linear or non-linear. The constraints can be affected by what are known as boundary conditions, which are certain assumptions that can vary as a function of the *desirability* explained in chapter 5. Thus, to identify a range of scenarios under different assumptions, the boundary conditions and the function to be optimized can both be modified. We considered to run the structure through the RStudio program using NLOPT_LN_COBYLA for the different scenarios. However, while we attempted to follow this procedure, we ultimately ran the model through the GUSEK program with the SIMPLEX linear algorithm for technical reasons, adding parameters that allowed, by means of iteration, to obtain similar results to those from applying a non-linear program. In total, the model has 1,417 variables, 560 constraints and 3 different optimization functions.

4.1.1 Boundary conditions

The non-linear approximation has strong implications for the *SFRA*'s initial conditions. Here, the model will define the appropriate livestock density, the structure of land-use (and, therefore, the composition of farmland), and the size of the population that can be fed by the agroecosystem itself. While the size of the domestic unit and the number of livestock were preset in the 1860 *SFRA*, the size and composition for the three self-reproducing funds in this case are outcomes of the model. Non-linearity also permits a reduction in the number of assumptions that in the earlier approximation in chapter 6 constrained the model's degrees of freedom. However, several other boundary conditions are set that will affect the general structure of the new *SFRA*.

In relation to population, the nutritional and energy needs depend on age, sex and physical activity level. Food production must meet requirements according to the age pyramid for the set of municipalities based on census data (IDESCAT, 2009a), taking into account the current estimation of energy expenditure as a function of physical activity level (ESFA, 2017) and the average physical activity level for each age band in the Catalan population (Ministerio de Sanidad, 2014). This will be considered a stable relationship[35], which makes it possible to set the average energy requirement of the population at 2,256 kcal/day per person.

In the case of livestock, we use three distinct species: pigs, chickens/hens and sheep. Each type is representative of one of the functional categories identified in section 1.2.

[34] The complete model and all the associated assumptions appear in Annex III.

[35] That said, if the reproduction rate is not reversed, the current ageing processes in the population could result in a shift in the proportions of the age bands and in a decline in population density, at least at a national scale (INE, 2014).

Of the limits defined regarding the soil fund[36], the most clearly determinant one is the unit of analysis, that is, the amount of land that can exist for each use. Of the 11,996 ha in the four municipalities, 2,237 ha are urban or infrastructure and 30 ha are riverbeds and rocky outcrops. These do not form part of the agricultural metabolism. By contrast, the remaining 9,729 ha do play a role. Here the boundary condition regards to forest area. We calculated that 5,528 ha have to remain as forest from figures on nature conservation land and also from stable woodland areas over the past 150 years. As a result, this land is not subject to changes of use because of its value[37]. For the final remaining 4,201 ha, the freedom exists to change use under various precepts of a technological and agronomic nature, which will be used to define the constraints later on.

Lastly, in the case of herbaceous crops, three possible rotation types are laid out. These types reflect proposals made in a nearby organic agricultural park (Safont & Artal, 2008) and recommendations on herbaceous crops native to the territory (Tuson, 2011, 2009).

Rotation 1. Montcada wheat – Chickpeas – Spelt – Lentils – Green Manure

Rotation 2. Mustard – Triticale – Fenugreek – Green Manure – Barley

Rotation 3. Potatoes – Broad Beans (Favas)

The various agricultural uses viewed as possible within the model are indicated in Table 7.1. The yields from these uses are primarily estimations based on information from the agricultural census of 2009 (IDESCAT, 2009b) adapted to the conditions of organic cultivation to avoid overestimating their productive potential (De Ponti et al., 2012; Seufert et al., 2012). Some other specific information comes from yields of the area's own ecological farmland or from studies in comparable Mediterranean conditions (Consorci de Gallecs, 2010; Tuson, 2009). In the case of woodlands, the levels of productivity are estimated based on the annual growth in the aerial biomass of the dominant species (CREAF, 2007), while the pasturage potential is estimated using information provided by Robles (2008) and Taüll & Baiges (2007).

Table 7.1. Possible land-uses considered by the model SFRA for 2009. Source: Our own.

Irrigated	Herbaceous crops	Woody crops	Pastures	Forest
Vegetables	Rotation 1	Olive oil	Improved pastures	Holm oak
	Rotation 2	Wine		Pines
Fresh fruit	Rotation 3	Almonds		Other forests and brushland

As was the case with livestock, the proposed crops are also indicative and representative of the different categories. We reiterate that it would be necessary to consider other crops and rotations to ensure the system's diversity and resilience. However, this would refer to the scale of plot, when the approximation in the present case is at the scale of landscape.

[36] As in the first *SFRA*, boundary conditions and constraints regarding surface are associated to the soil fund because it is the only one fund with territorial expression (unlike society or livestock).
[37] While it is true that this criterion did not generate consensus among the people consulted, the lack of time to discuss the results has impeded the possibility of undertaking other approximations. In any event, we consider that it is a conservative criterion for a first iteration of the model, whereas other approaches would probably result in greater farmland expandability.

4.1.2 Constraints considered

Once the boundary conditions are defined, it is necessary to indicate in the *SFRA* what constraints are set by the model's socioecological limits. Starting from the flows in Figure 7.1, we proceed to indicate the constraints these flows entail for ensuring the reproduction of living funds.

Constraints for society

Diet is calculated differently according to the conditions set for *desirability*. Three scenarios are considered. The first one applies the current diet (MAGRAMA, 2009). The second one is expressed in the form of constraints to obtain a healthy diet. The main initial conditions of the healthy diet come from a study on the cardiovascular benefits of the Mediterranean diet (Estruch et al., 2013) and various nutritional criteria that strike a balance between sources of proteins, fats and carbohydrates (SENC, 2016). The third scenario is defined by a constraint that enables the maximization of total food output in the agroecosystem in terms of metabolizable energy. This would allow us to follow the objectives set in section 1.

Domestic residues that are returned to close nutrient cycles are estimated through the actual diet provided and a number of technical factors concerning the consumable fraction of these foodstuffs (Farran et al., 2004).

Constraints for livestock

The largest part of the defined constraints regards to livestock. We distinguish between input flows (feed, stall bedding) and output flows (manure, food). Some fundamental initial constraints are to link livestock in the different stages of their life cycle and to their rates of reproduction. In total, the three types of species are defined as having 31 stages in which their requirements and flows are different.

As for animal feed, this is one of the areas with the greatest uncertainty because of the products and by-products that animals can consume. Based on a review of recommended animal diets in organic production, therefore, we set the required energy consumption in terms of metabolizable energy (ME) and the minimum and maximum crude protein (CP) contained in the diet. Then the data on crop yields are transformed into ME or CP with technical coefficients taken primarily from Church (1984), and the general constraints on feed are defined. In addition, to ensure that the results are valid from a physiological standpoint, maximum thresholds are set for the incorporation of specific kinds of feed that could cause problems either because they contain antinutritional factors or because of their palatability (FEDNA, 2010).

For stall bedding, we use the criteria of Soroa (1953), and for the manure produced, we estimate the composition through an iteration process starting with data from ASAE (2000) and then checking results with a literature review.

Constraints for soil fund

With regards to the soil as a fund, constraints are established for crop rotations, for the total amount of land as a function of preceding use and crop adaptability to the soil, and for nutrient balances. The first constraints are simply equalities that must be fulfilled so that a specific use (e.g., *Montcada* wheat) has the same amount of land as the other uses that correspond to the rotation (e.g., the surface area of *Montcada* wheat must be equal to the surface area for chickpeas, spelt, lentils and green manure).

The second group of constraints relate to the possible uses that can be established as a function of the preceding use (use for 2009) and the uses that can follow. In this respect, based on the cartographic data on preceding and subsequent uses (CREAF, 2009), protected spaces (DTS, 2017), land-use maps for 1860 and 1956 (Tello et al., 2004) and crop suitability and slopes in the territory (Catalan Geological Institute, 2010; Rodríguez Valle, 2003), each point on the map is translated into a specific category that denotes the possibility of one use or multiple uses (X_{ae}). From this data, we define the constraints that set the amount of land in each category.

As noted earlier, two distinct scenarios can be considered: one in which the amount of land of current woodlands (7,407 ha) must be maintained or increased and another in which it is only necessary to maintain the woodlands that have been given special conservation status or have been woodlands for the past 150 years (5,528 ha). As a result, the second scenario offers the possibility of increasing farmland by 1,879 ha above the current figure. Depending on the defined scenario, one set of constraints or another is activated. The two sets are labelled I and II, respectively. It must be also added that woodlands that are not dominated by *Pinus halepensis* or *Quercus ilex subs. ilex* are not considered suitable for a change of use either. This is to protect habitats that have little presence in the area (e.g., deciduous trees, oak groves, stone pine, European black pine or riparian forests).

Lastly, there are constraints concerning the maintenance of biogeochemical cycles, which can be closed in four main ways: incorporation of surplus biomass from crop residues, manure, domestic residues, and also the possibility of incorporating a certain amount of green forest biomass.

To generate these constraints, first the nutrient extractions of nitrogen, phosphorus and potassium (NPK) are determined for all crops. Then all other inputs and outputs of nutrient flows (volatilization, denitrification, weathering, leaching, etc.) are determined and the total fertilization requirements are set for the re-establishment of chemical fertility. Next follows the characterization of all the various nutrient sources (manures, crop residues, domestic residues and imported green biomass) in what is understood to be a process of joint composting. Once all the sources are defined, the constraint is established so that the incorporated material in NPK terms meets the NPK requirements resulting from the total needs of different land-uses. The construction of this nutrient balance takes into account the criteria defined by González de Molina et al. (2010) and the IPCC (2006a, 2006b) among other sources.

Constraints on farm-associated biodiversity

Lastly, we indicate the constraints in relation to the final fund, the farm-associated biodiversity. The focus here is on non-domesticated species. In this case, however, we are speaking of *beta* biodiversity (Gliessmann, 1998). The question, therefore, does not concern agroecological practices carried out at the scale of plot, but at the scale of landscape.

The debate on biodiversity is complex and the hypotheses are still open on the best ways to conserve it. The perspective adopted here is that of a *land-sharing strategy* (Fischer et al., 2014), according to which the best way to maintain or increase beta biodiversity is through the establishment of spaces in which productive human activity is combined with a degree of intermediate disturbance that does not impede the presence of diversity (Loreau et al., 2003; Perfecto and Vandermeer, 2010). This approach is not incompatible, however, with the need to conserve certain spaces to prevent the degradation of priority habitats in which specialist species need low or null levels of disturbance. To this end, we also consider it necessary to maintain certain protected conservation areas as indicated earlier.

Therefore, there is a clear link between landscape patterns and biodiversity (Tscharntke et al., 2012). Agroforest mosaics provide a range of habitats that can sustain many species (Harper et al., 2005; Pärt and Söderström, 1999). For this reason, we have selected a widely used indicator as an approximation of habitats for biodiversity through landscape patterns: the Shannon index, adapted for agrarian metabolism as in chapter 3 (Vranken et al., 2014). The Shannon index, when analysed together with human disturbances values, has shown that the portion of associated biodiversity in agroforest mosaics is highly significant in the region, while another important part accounts for much less disturbed areas (Marull et al., 2018).

However, the main problem with indicators and landscape patterns, is that they do not have threshold values by which to ensure a specific level of biodiversity. At present, they only permit comparative assessments. Thus, as the only constraint possible, we will consider that values of the Shannon index for the resulting landscape and, therefore, the equidiversity of land covers must be greater than the value of the index in the original landscape of 2009.

4.1.3 Defined scenarios

Once the mathematical structure of the model was defined, it was run for various scenarios. As can be seen in Table 7.2, six different scenaries are defined on two axes. The first dimension is the possibility of bringing woodlands under cultivation to increase cropland, while the second refers to diet, or food intake.

In the case of diet, we consider three different situations, which will determine the objective functions. First, the aim is to look at the potential for developing food provisioning strategies with the current diet, then with a healthy diet. Finally, this provisioning can be constrained to the number of complete diets that can be provided (so that the maximization function would be over the variable T for population) or to the maximum amount of food that can be produced in the territory (so that the maximization function would then be the variable U for total amount of food). This is done to see whether there is any local trap effect by which the desire to provide complete diets is significantly reducing the capacity of the territory.

Table 7.2. Defined scenarios in the SFRA for 2009. Source: Our own.

	Current diet	Healthy diet	Maximizing output
Bosc ≥	CDI	HDI	MOI
Bosc ≤	CDII	HDII	MOII

4.2 Sensitivity analysis of the model[38]

A final significant aspect of the model is the sensitivity analysis, which identifies an important part of the model's limitations. The sensitivity analysis seeks at least to minimize the risk of confusion about the results of the model through transparency and an adequate characterization of the sources of uncertainty (Saltelli and Funtowicz, 2013).

The sensitivity analysis is performed on the modifications to the input variables. We consider the variability of farm yields by introducing as an input the crop yield data at the scale of County between 2007 and 2016. In this way, we compare whether the modifications to the input data result in an increase in variability in the resulting values. Because only the variation in productivity is considered, we view this criterion as conservative for possible causal relations that would be established with the other technical factors under consideration. Thus, the variations observed in the coefficients of variations in the model's results will be relatively greater than the ones we estimate would occur in reality.

[38] The complete presentation of the sensitivity analysis and the definition of the conservative criterion appear in section 5 of Annex III.

4.3 Analysis of the results

To present the results, we first calculate the state of current agricultural functioning for 2009 using the same methodology put forward for 1999 in chapter 4. We identify the initial situation of the four municipalities in order to look at the potential for developing an agroecological strategy. Using the data on food consumption at the level of Catalonia (MAGRAMA, 2009), we draw a brief analysis on current situation regarding the potential to self-provisioning population.

Then we set out the results for the six scenarios. First, the potential of the model is analyzed, including all of the constraints set in the methodology and identifying whether or not the condition of reproduction limits the development of agroecological strategies. Second, CD and HD diets are analyzed comparatively in relation to the conventional scenario. The comparison is carried out from the point of view of impact on soil, in terms of *Land Cost of Agrarian Sustainability* and territorial synergy (Guzmán et al., 2011; Marull and Tello, 2010), such as health. Then a comparative analysis of MO and HD specialization strategies is conducted, before concluding with the sensitivity analysis of the model.

5 Results

5.1 *Initial context, El Vallès in 2009*

In the analysis of the initial situation (Figure 7.3), it appears that the agroecosystem's total conventional production permits an average degree of food self-sufficiency that could sustain as much as 50% of the population in terms of metabolizable energy (ME). However, there is a great imbalance between plant and animal products. Total output consists of 3,223 t of plant products and 8,964 t of animal products. The amount of plant products is far less than the 21,173 t required to satisfy local diets, contributing only some 12% of the necessary ME. In the case of animal products, by contrast, the figure climbs to 65% of necessary ME, despite the imbalances in their composition, which tips enormously toward pork, while beef and eggs would be close to

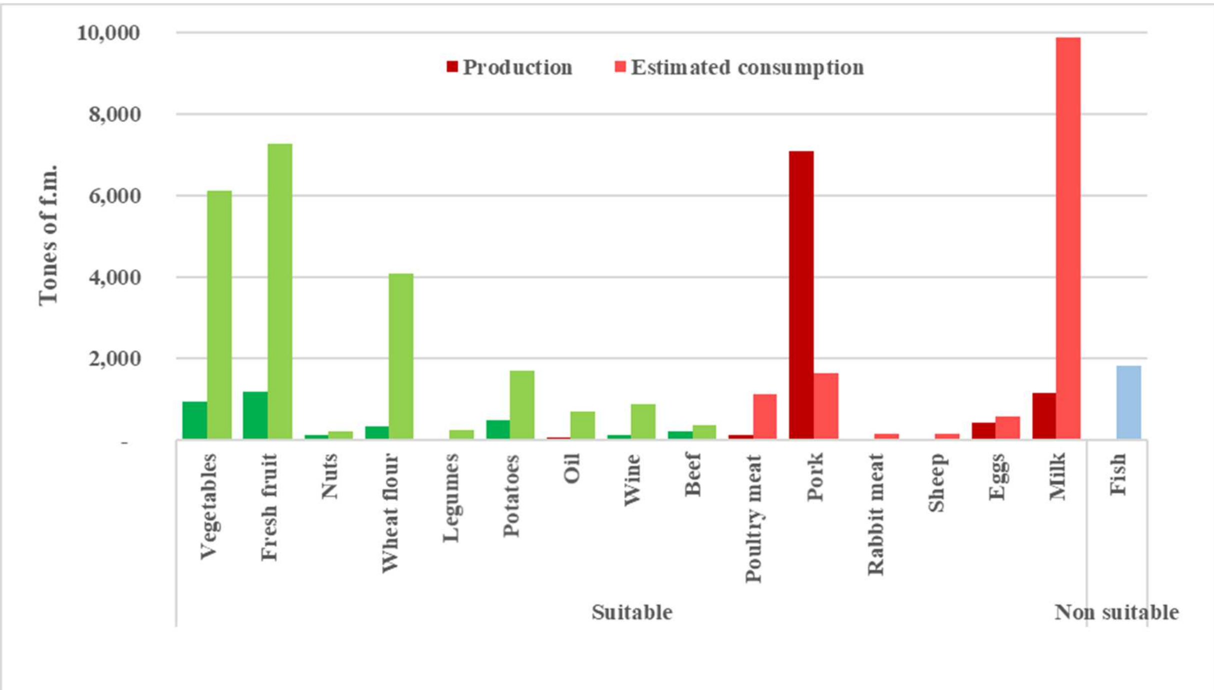

Figure 7.2. Production and estimated consumption, in tones of fresh matter, for the Vallès case study in 2009. Source: Our own.

equilibrium. Within total agricultural output, however, it is necessary to take into account various aspects of concern, which have been mentioned in chapter 4. If we take into account the limits of the territory, results change.

First, the feed for this livestock is sustained largely by imports from outside the agroecosystem. By maximizing the use of products produced within the four municipalities, the total amount of feed appropriate for animals would be 16,460 GJ versus the 76,870 GJ of ME necessary for this production[39]. Maintaining the intensive feeding model, it would only be possible to maintain 21% of existing livestock locally, even though 75% of cropland is put to this purpose. Thus, of the 50% of self-provisioning capacity initially estimated in terms of ME without consideration of the imported virtual cropland, we would be speaking, in reality, of an overall degree of self-provisioning of 16%. That is, it would be possible to satisfy the proportional diet of 9,080 equivalent people (again, in terms of ME).

In the second place, the scenario clearly continues to be as inefficient as it was in 1999. First because chemical fertilizer is still being used to meet nutrient needs. But also because the production of composted manure would potentially rise as high as some 370,000 kg of N when the agriculture only requires 87,000 kg of N. This is over four times more than requirements. Obviously, the waste again becomes important as an indicative flow of these inefficiencies. It reaches 145 GJ, which is nearly as high as the figure for all complete livestock production, 165 GJ. Indeed, taking into consideration all the imports of nutrients in feed and fertilizers, the total amount circulating in the agroecosystem would be 370 kg of N, 111 kg of P and 228 kg of K per agricultural hectare. This represents an enormous surplus of nutrients, which has both internal and external implications as we have previously noted.

In short, because of the high degree of mechanization, the use of herbicides and pesticides, and the lack of crop diversity, the scenario differs a great deal from an agroecological approach in terms of the material conditions for farm-associated biodiversity. At the level of landscape patterns, the current configuration of the territory reflects an impoverishment of habitat diversity similar to the situation in 1999, with the Shannon index modified declining slightly from 0.38 to 0.37 (chapter 3).

5.2 Sustainable farm systems? Rethinking the concept of sustainability

Now that the initial situation has been defined as one in which the degree of self-provisioning satisfies the food intake of 9,080 people with conventional farming, we run the model under the constraints set for the three defined agroecological scenarios: meeting the current diet (CD), meeting a healthy diet (HD) and maximizing sustainable agroecological output (MO). The results appear in Figure 7.4 as “reproductive”.

As Figure 7.4 shows, when all the constraints set for the *SFRA* are met, the population that could be sustained within the territory is only 1,900 people with the current diet, 4,600 with a healthy diet and 6,000 equivalent people when maximizing output[40]. The population densities are 16, 38 and 50

Table 7.3. Nutrient losses by no recycling human sewage into the agroecosystem in the SFRA for 2009. Share over the total nutrient extractions. Source: Our own.

	N (%)	P (%)	K (%)
Current Diet	27.2	13.1	9.9
Healthy Diet	23.9	21.7	16.7
Maximizing Output	15.7	22.2	21.6

[39] These data are given in GJ of metabolizable energy weighted by livestock composition, because this approach provides a much better approximation of productive potential than kg of fresh matter.

[40] For the MO scenarios we will use the term “equivalent population” as we are not optimizing complete diets but an amount of metabolizable energy. Then, an equivalent person means the average amount of metabolizable energy required within a year, despite its composition does not have to be satisfying the real requirements of a diet, but only its ME content.

inhab./km^2, respectively. These figures are far below the sustainable population densities for scenarios with advanced organic farming such as the ones defined in chapter 6, which could rise to 116 inhab./km^2 in the better case[41]. If we look for reasons for such a sharp decline in the theoretical carrying capacity of maximizing population in the territory, there appear to be two main elements that distinguish the present model from the one in the previous chapter.

The first element is a preventive assumption. The return of human excreta to the agroecosystem could provide between 22% and 38% of all nitrogen inputs in the *SFRA* scenarios for 1860. For the four municipalities as a whole, the estimate at an aggregate level was that applied human excreta provided 12% of total nitrogen requirements and an even more important 21% of phosphorus requirements (Tello et al., 2012). In current scenarios, the losses from not applying human excreta involve a highly significant potential loss of nutrients, including 22% of total phosphorus needs, as shown in Table 7.3.

Given the uncertainties over the impacts that these scenarios could have in terms of incorporating pollutants into the agroecosystem, the decision wee took was not to consider this flow here. The adoption of the precautionary principle of returning nothing to the soil clearly constrains the potential development of the agroecosystem because of a sustained extraction that is not even partially returned to the soil. The significance of these losses must also be pointed out, particularly in the case of phosphorus, which as we shall see is more difficult than nitrogen to re-establish in the agroecosystem, in terms of non-anthropic flows.

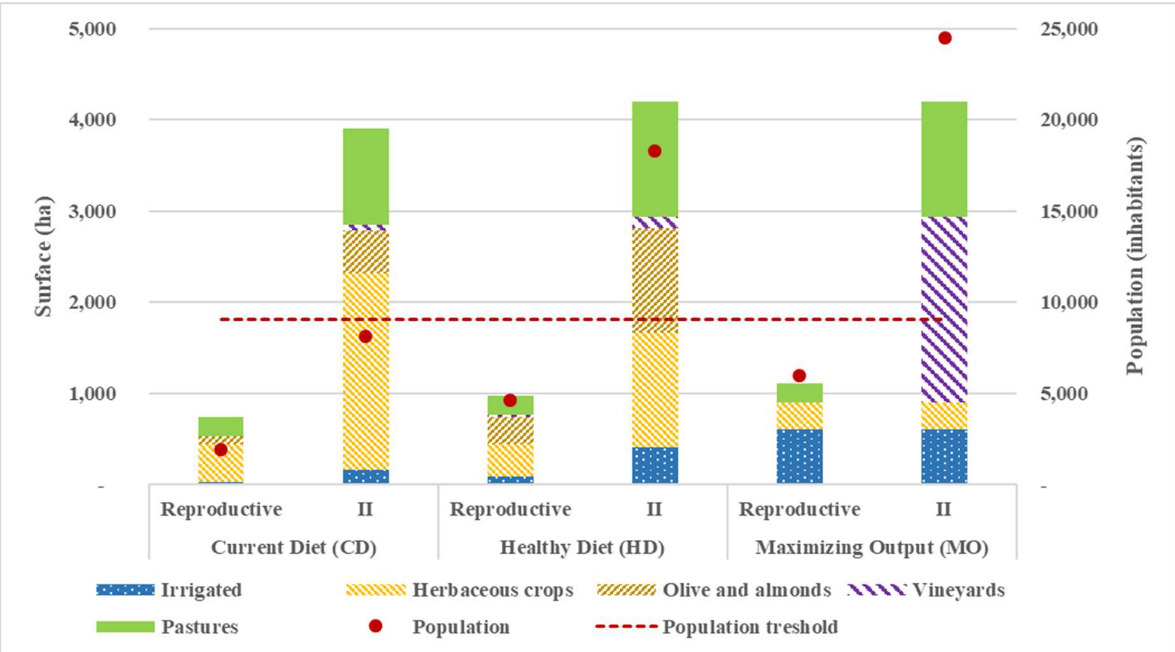

Figure 7.3. Dimensions of the soil covers, except for the forest area, and amount of equivalent sustainable population for the reproductive analysis in the SFRA for 2009. Source: Our own.

A second distinctive feature of the current approximation, however, is equally or even more significant, and it also stems from the limitations of the initial *SFRA* model for 1860. In the 1860 model, the forest extractions were considered sustainable *per se* based on the principle that, as they did not involve an extraction of biomass greater than the estimated growth of the forest mass, they were sustainable. That is, it involved a criterion of forest management, but not in terms of the nutrient cycles in forest land.

[41] It should be taken into account that the two models are not entirely comparable, because the unit of analysis is different. While the *SFRA* for 1860 is limited to the municipality of Sentmenat, the analysis for 2009 involves four municipalities. In addition, the technological and agronomic conditions are obviously very different. Indeed, the total surface under cultivation has declined.

For the *SFRA* for 2009, constraints have also been established for the limits of nutrient circulation in forest land. The view is taken that nutrients extractions cannot exceed their natural inputs. In the case of nitrogen, inputs from atmospheric deposition and symbiotic fixation going to shrub and herbaceous species are estimated at an aggregate level to provide around 8 kg N/ha per year. In the case of phosphorus and potassium, the input sources are much more limited; the primary source of nutrient inputs in the soil system is from the weathering of geological material, while another portion comes from atmospheric deposition. Thus, their annual incorporations are estimated to be 15 kg K/ha for potassium and only 0.35 kg P/ha for phosphorus. As a result, this effect highly limits the possible import of nutrients from the forest from a reproductive standpoint.

The result we observe as "reproductive" is the threshold for sustainability in terms of the population residing in the territory, understanding sustainability from a reproductive standpoint. While that scenario may be the one estimated as reproductive, however, this is not to say that it is *desirable*. Limiting population density to a maximum of 50 inhab./km^2 in a territory with a current average density in excess of 450 inhab./km^2 within a nation that has a density of 92 inhab./km^2 is obviously an entelechy that could only be resolved materially through the massive importing of agricultural products, thus maintaining the removal processes of unsustainability noted in chapter 4. There also may be other changes regarding how society could face that situation (e.g. a redistribution of population along territories or a population decrease), but as long as they would entail changes in demography and not in agrarian systems, we do not consider them into the analysis. Therefore, we take a point of view of how can we sustain current situation with agrarian responses, not regarding demographic strategies.

While this case study is being conducted at a local scale and is therefore affected by the characteristics of population density and agrarian production possibilities, it is clear that the bottleneck would not resolved at a greater territorial scale. As a result, it is necessary to establish a distinction between the concepts of reproductive and sustainable. So far we have used a conception of sustainability requiring that a sustainable model must necessarily be reproductive. From the standpoint of civilization, however, the territorial cost that this assumes we consider is not acceptable.

There is another way to resolve the bottleneck that must not be underestimated from an ephadic standpoint and makes sense at a human scale when we propose close-to-sustainable systems. Soils, in addition to being self-reproducing funds, contain certain stocks of nutrients. There is not a great deal of information on the subject, because studies are typically limited to the amount of assimilable nutrients in a context of abundant external inputs. However, taking estimations from various sources, we approximate total contents of 7,250 kg N/ha, 1,600 kg P/ha and 41,000 kg K/ha for forest land[42]. For farmland, by contrast, the contents are estimated at 5,400 kg N/ha, 2,600 kg P/ha and 55,000 kg K/ha[43].

In this case of using stocks, therefore, we would not be speaking of a reproducible system *ad infinitum*. From a social standpoint, it is necessary to debate the particular horizon over which we want to propose strategies to restore an organic metabolism, while being cognizant of any impact that such strategies would have on future generations. It is important to know the impact that would result, therefore, from nutrients imported from woodlands or the use of farm stocks not constrained to these reproductive thresholds. In this way, we can identify the minimum and maximum scenarios and hold a social debate on the subject based on the obtained results.

[42] These estimations are made on the basis of the following amounts in the top thirty centimeters: 0.16% of total nitrogen, 350 ppm of total phosphorus and 41 Mg/ha of total potassium (Batjes, 1996; Bosch-Serra et al., 2015; Cantero et al., 2012; Kizilkaya et al., 2007; Olarieta, 2017).

[43] In this case, the initial data are 0.12% of total nitrogen (Bosch-Serra et al., 2015), 29 ppm of available phosphorus using the Olsen method and 245 ppm of exchangeable potassium (Arán, 2001.; Cantero et al., 2012) in the top fifty centimeters. For estimation purposes, the percentage of available phosphorus out of the total is considered to be 2%, as is the exchangeable potassium out of the total.

We ran the three models[44] removing the constraints corresponding to the imported nutrients of N, P and K from the forest, simply establishing that the use of stocks should not be proportionately greater in forest land than in crops or pastures, given that there is a greater nutrient demand in the cropping areas. The results for these scenarios appear in Figure 7.4, but also in Figure 7.5, which identifies the impacts on nutrient stocks at an aggregate scale.

As can be seen in Figure 7.4, removing the constraints corresponding to forest nutrients has a highly significant impact in all cases in terms of sustainable population. All values more than quadruple, rising to population density levels that are 68 inhab./km^2 with the current diet, 153 inhab./km^2 with the healthy diet and up to 204 people equivalents per km^2 with the maximization of agricultural output.

What do these increases in sustainable population involve, however, in terms of importing nutrients from woodlands and in the fields themselves? As can be seen in Figure 7.5, the most determinant element in the increase in carrying capacity is phosphorus. The figure depicts only the extractions that are greater than the replacement rate and that are therefore drawing on nutrient stocks.

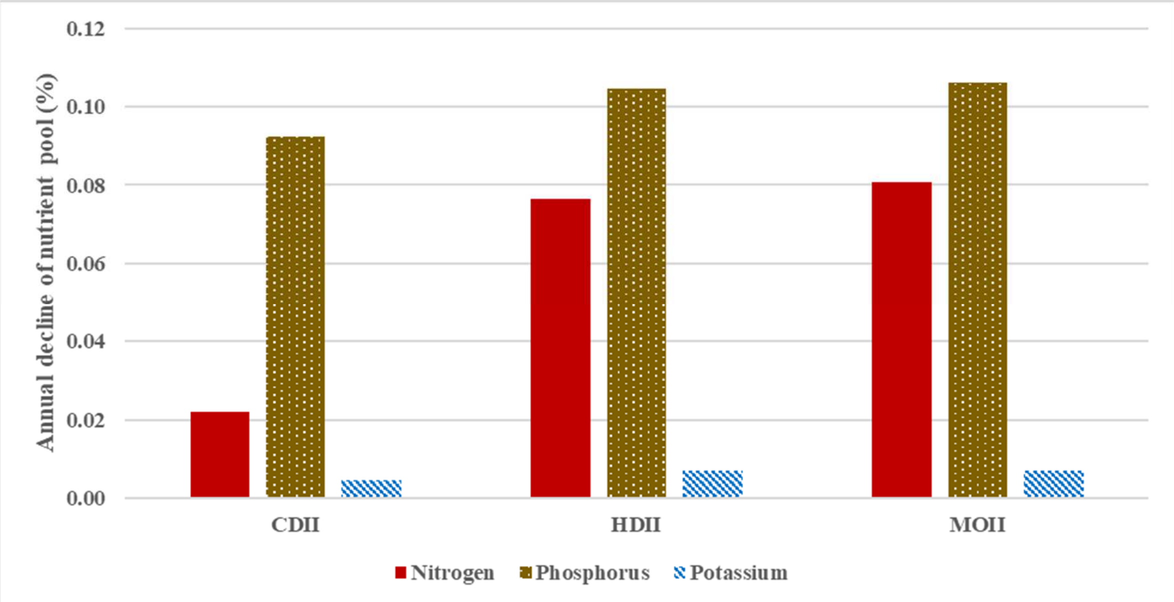

Figure 7.4. Use of nutrients pools for different scenarios regarding its reproductive limits for the SFRA for 2009. Source: Our own.

In the extreme case, MOII, the requirements in agricultural areas are offset by the use of stocks from woodlands and farmland, consuming 0.11% of the total pool annually. This generates a time horizon of 950 years before the total depletion of phosphorus in the soil, with annual extractions of 2.2 kg P/ha in farmland. However, the case in which the greatest extraction of phosphorus from farmland occurs is CDII, where the lack of sufficient processes to import nutrients from woodlands causes the extractions in farmland to be 4 kg P/ha. We are aware that it will be necessary to give particular attention to the gradual degradation of crop yields along time, given that the dynamics of nutrient bioavailability are complex. However, this is something that would have to be addressed in other researches.

In addition, recovering the metabolism of flows of human excreta would allow for a reduction in the use of stocks in the soil by between 28% and 92% of phosphorus requirements

[44] For this section, it only makes sense to put forward scenarios with a possible increase in the amount of farmland (CDII, HDII and MOII), so that we can observe the scenario that exerts maximum pressure on nutrient cycles.

depending on the case, resulting in agroecosystem conditions that have much greater stability over time.

As for the other two nutrients, nitrogen and potassium, they are clearly not as constraining as phosphorus at the level of extraction in the considered scenarios, particularly in the case of potassium. For nitrogen, the extractions in the case of the healthy diet could rise to 3.7 kg N/ha from farmland. In this case, the estimated depletion horizon would be some 1,500 years. Even then, a potential increase in the proportion of leguminous plants, e.g., in the associated crops of oats and vetch, could potentially improve the inputs if a greater nitrogen constraint were observed.

Thus, when we speak of processes that can be maintained over such a long time-scale, the social and environmental costs from pursuing the reproductive scenario would surely be greater than the tendency to extract nutrients in the long run. Among the challenges that have been posed by the environmental crisis and pointed out from an agricultural standpoint by Tello and González de Molina (2017), the time horizon proposed above allows for sufficient margin so that it is not emphasized as one of the more daunting factors in the stability of human population at current density levels. This is a matter, however, that must obviously be decided socially, putting the various alternatives on the table for discussion.

To conclude, in this section we have indicated the constraints of an entirely reproductive approach due to the pressure on nutrient cycles and identified a relatively sustainable approach involving a non-intensive use of nutrient stocks. To proceed to a comparative analysis of the results of the models, we will now only consider the scenarios in which the nutrient stock can be used without jeopardizing sustainability in the medium run.

5.3 Territorial impact of diets

We now move to an analysis of the results of the first two scenarios, which look at the current diet (MAGRAMA, 2009) and then compare it to an open diet that only establishes thresholds to ensure fulfillment of the nutritional standards of a healthy, balanced food intake (Estruch et al., 2013; SENC, 2016). This analysis is developed on two axes: the two diets, and the possibility, or not, of increasing the amount of farmland. The resulting four scenarios are CDI, CDII, HDI and HDII.

5.3.1 Confronting the productivity gap in ecological farming

As Figure 7.6 shows, in an agroecological context the current diet cannot reach levels above the estimated threshold for meeting needs in 2009. Holding the amount of current cropping area steady, it can only sustain 68% of the population that can be maintained with a conventional farming system. The gap of 32% is due partly to the 20% fall in productivity caused by a shift from conventional farming to ecological farming. Indeed, another reason is because the animal cycles are longer for reasons of animal welfare and the adaptation to less productive, but ecologically better adapted breeds.

For the conventional production of a chicken, for example, the feed conversion factor is 2 kg feed concentrate/kg final liveweight, while the figures for ecologically produced chickens are 2.8 kg feed concentrate/kg final liveweight. This represents a 40% increase the cost of animal feed and it is therefore a factor that further reduces the potential in an agroecological landscape.

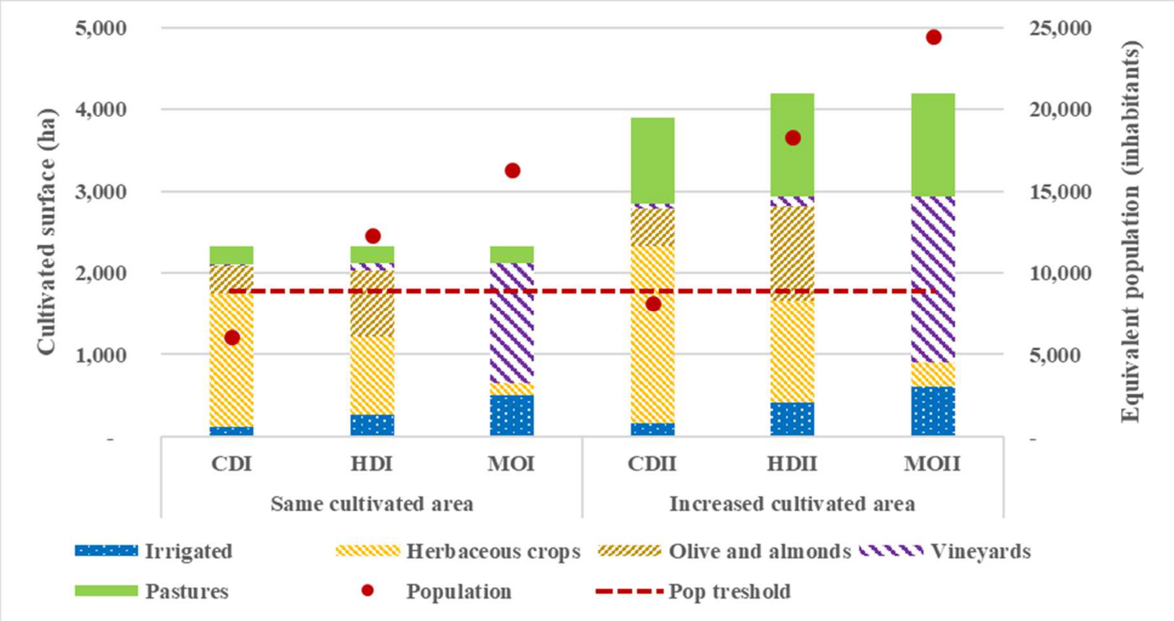

Figure 7.5. Dimensions of the soil covers, except for the forest area, and amount of equivalent sustainable population for the non-reproductive analysis in the SFRA for 2009. Source: Our own

According to the CD results, the maintenance of the current diet requires that 40% of produced grain must go to animal feed to obtain only 13% of the diet in ME (while the other animal products came from other feed sources). This fact clearly shows the impact of livestock production on the agroecosystem. In the same case, however, 65% of animal feed comes from the use of crop residues or pastureland and this percentage rises to 99% in the case of healthy food. The difference is huge when compared to the animal diets in industrialized livestock production, in which only 14% of the products are crop residues.

The provision of such a diet with so large a disproportion between animal and plant production results in a very high territorial cost of sustainability. While it did not present a serious internal problem in the case of conventional farming because of the massive importing of external nutrients and the disconnection among funds, the imperative of closing nutrients cycles under an agroecological strategy, poses a constraint on the possibility of a greater increase in farmland. This is the reason why in the CD scenario with a possibility of increased farmland, the requirement of such a high fraction of cereals to feed pigs and poultry imposes an extremely high pressure on nutrient balances that cannot be satisfied without making use of nutrient stocks.

5.3.2 The impact of diet on nutrient cycles

As Figure 7.7 shows[45], in the case of CDI, that significant imports of nutrients from woodlands would be needed to make the agroecosystem sustainable. The large amount of green biomass entails an additional cost in the fertilization process to ensure the maintenance of the agroecosystem. Analysis is necessary to identify whether this would have an unacceptable impact, at least in terms of employment, but also ecologically. Strategies to import green biomass from woodlands have been described historically, such as importing foliage or even gorse from

[45] In figure 7, AP manure is the manure produced from the consumption of agricultural products and therefore collected directly from stalls. FC manure is the manure produced from the consumption of forest or pasture products and can be recovered from nests as well as stalls. Crop residues refer to the burying of surplus biomass, domestic residues refer to the return of the unconsumed fraction of products generated in the agroecosystem, *in situ* excreta refers to the fertilization effect from *in situ* consumption of pastureland or crop stalks and stubble directly in the field, and forest imports are the imports of green biomass from woodlands.

scrublands to maintain soil fertility, or the so-called *formiguers* (Corbacho et al., 2015, Olarieta et al., 2011).

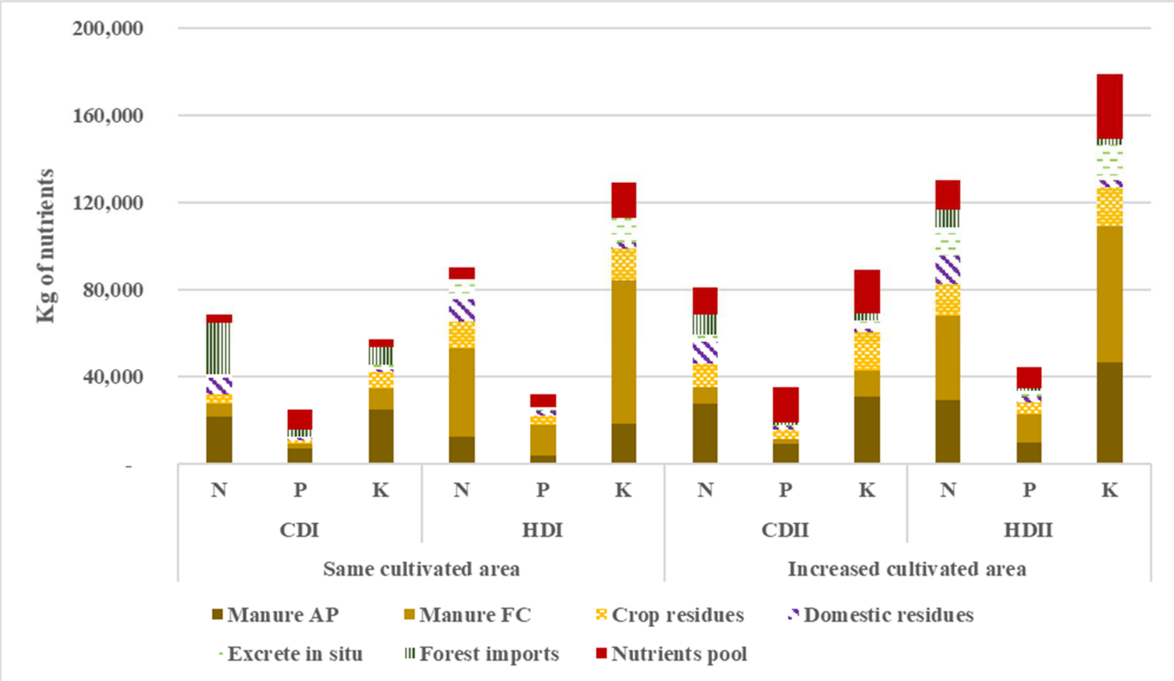

Figure 7.6. Nutrients devoted to restore soil fertility regarding the source for the non-reproductive scenarios of the SFRA for 2009. Source: Our own.

On the other hand, the HD scenario shows a much better adaptation to the agroecosystem in terms of nutrient flows. As can be observed in this case, a key role is played by the import of nutrients through manure collected in stables after pasturage. The nutrients, which come from forest land, can provide as much as 45% of the phosphorus needed to re-establish soil fertility. By contrast, crop residues and domestic residues involve little more than 20% and 10% return of nutrients, respectively, in the best of cases.

The healthy diet also involves a substantial reduction in the livestock load in the diet. While animal products accounted for 41% of total consumed energy in the CD, they account for only 24% in the HD. Because of this and the much greater degree of freedom that exists in the model to define the distribution of uses and animals, it is possible to achieve levels of needs satisfaction above levels in 2009 with conventional farming without even increasing the amount of cropping area. Indeed, if cropping area were allowed to increase, the amount of population that could be provided with this diet would theoretically total more than 18,300 people, achieving population densities higher than 150 inhab./km^2.

By comparing the healthy diet in agroecological farming with conventional farming for 2009, however, the demonstrated results do not appear to be an effect solely of the reduction in the proportion of animal product versus plant product. They must also be due to the effect of territorial synergy that occurs when combining livestock, crops and forestry activity in an integrated mosaic that results in a much more appropriate use of the territory's potential and reduces the territorial cost of sustainability, as demonstrated in chapter 6.

5.3.3 *The effect of territorial synergy and landscape diversity by type of diet*

Figure 7.8[46] shows the minimum costs in the amount of land associated with maintaining the sustainability of the different funds for the CD and HD diets with conventional and agroecological farming. In these cases, woodlands do not appear until the last scenario, but there is a very high proportion of pastureland, given that the grazing productivity of pastureland is higher than the forest itself. That is, when fertilization is introduced, pastureland is practically substituted by forest. Thus, the role being played by pastureland is complementary to the forest. When extrapolating the results at the municipal scale, the areas of pastureland would largely be substituted by woodland areas. Therefore, we deem the role of metabolic competition for the land is really being played by the remaining uses.

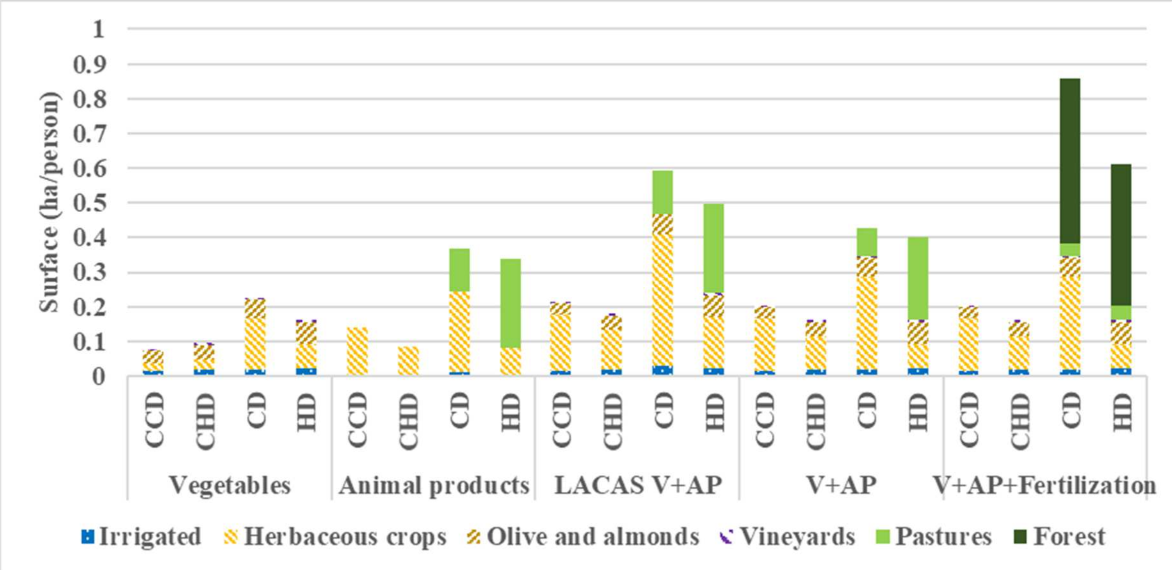

Figure 7.7. The Land Cost of Agrarian Sustainability by funds and scenarios for the SFRA for 2009. Source: Our own.

In the agroecological case, if we consider the maintenance of livestock and the production of plant foodstuffs separately (LACAS V+AP), the total cropland needed for the current diet would be 0.47 ha/person, while the amount needed for the healthy diet would be 0.24 ha/person, a reduction of nearly 50%. In the case of diets produced with conventional farming (CCD and CHD), adding together the total territorial cost of plants and animals makes it clear that conventional farming requires less land for production than agroecological farming, with the agroecological/conventional ratio being 2.2 for CD/CCD and 1.3 for HD/CHD.

Since the two production systems (vegetal and animal foodstuffs) are taken as integrated on an agroecological horizon, however, the effect of territorial synergy lowers the total land in agroecological contexts by 26% for CD and 33% for HD. Considering all funds (V+AP+Fertilization), the maintenance of the current diet would require 0.35 ha/person, while the figure for the healthy diet would be 0.16 ha/person. In other words, each satisfied current diet could satisfy 2.2 healthy diets with the same amount of land. This figure coincides with the sustainable population ratio between CD and HD, which also varies in a range of 2-2.3 times greater for HD than for CD depending on the case.

By contrast, the integration of uses has a much smaller effect for conventional farming, where animal diets are less tied to the use of by-products and the reduction is more moderate,

[46] Where ‘vegetables’ indicates the land required to produce only the plant fraction of the diet; ‘animal products’ indicates the fraction of the diet corresponding to products derived from animals; ‘LACAS V+AP’ refers to the aggregate sum of the two previous items; ‘V+AP’ is the production cost of a complete diet altogether, but without taking nutrient cycles into account; and ‘V+AP+Fertilization’ is the territorial cost of producing a complete diet while also maintaining the nutrient cycles.

namely 6% for CCD and 11% for CHD. Ultimately, the differential effect between agroecological and conventional farming has the following result: to produce a current diet under agroecological management requires 75% more land than conventional, whereas to produce a healthy diet requires the same amount of land under agroecological cultivation as conventionally. In HD, the lower productivity of ecological production and the lower efficiency in livestock consumption are addressed by means of this multifunctional effect of the funds, ultimately resulting in a territorial cost that is equal to conventional production, which does not benefit as much from the synergy. This largely explains why the sustainable population in HDI is 28% higher than the threshold of 9,080 people that can be maintained in the current situation.

Once the territorial costs are known, it is also necessary to examine the type of landscape diversity that results. Starting from a situation in which the diversity of land covers was 0.37 on the Shannon index, the CDI holds exactly at this level, while the indicator rises by 7% for HDI. Obviously, these values go up when more land can be cultivated, though the orders of magnitude remain unchanged. While CDII rises to 0.49, HDII increases an additional 12% over CDII to 0.55. It is clear, therefore, that if HD presents patterns of greater equidiversity, then with CD the resulting system would also have a greater number of frontier habitats than the initial situation.

5.3.4 Healthy diets, benefits for the body and the territory

Table 7.4. Resulting diets for the scenarios CD and HD, grams per day and average person. Source: Our own.

	CD	HD
Vegetables	302,7	400,0
Fresh fruit	359,3	367,9
Wheat	201,4	207,7
Legumes	12,2	40,1
Olive oil	33,6	31,8
Almonds	10,3	30,0
Potatoes	83,9	0,0
Wine	43,0	120,0
Pork	86,8	7,2
Lamb	25,0	43,8
Chicken	54,4	0,1
Eggs	28,2	1,8
Sheep milk	488,0	324,1
Fish	90,2	90,2

To conclude the comparison between CD and HD, we would like to make some remarks on the impact of diet on the health of the population. Table 7.4 shows the diets resulting from the model, where CD is the pre-defined one and HD is the one resulting from the *SFRA* by ensuring that the diet is healthy and at the same maximizes the amount of population sustainable in the agroecosystem.

Among the most significant differences, the consumption of legumes is much higher in HD, as is the consumption of nuts, while the consumption of potatoes disappears completely. There is a significant rise in the consumption of wine, which would nevertheless be roughly a glass a day (the recommended intake according to Estruch et al., 2013). While the consumption of wheat is similar, it is necessary to appreciate that while the wheat is refined for CD, it is whole wheat for HD and therefore involves a much higher intake of fiber.

In relation to the consumption of animal products, the differences are also significant. While the consumption of pork, chicken and eggs falls sharply, there is a substantial rise in the consumption of lamb[47], even though the intake of sheep's milk declines. It should be recalled that the consumption of lamb is included within the white-meat group. While 36% of animal products (and 81% of meat) came from monogastric livestock in the first case, the proportion falls to little more than 4% in the healthy diet. There is, therefore, a clear substitution in livestock composition, which is explained by the lower impact of ruminants in terms of *LACAS*.

[47] It is necessary to remember that sheep have been considered at the expense of cattle in order to simplify the model. As a result, the current consumption of lamb incorporates beef consumption.

If we analyze these diets in terms of the contribution of different macronutrients to total energy, we find an imbalance in CD. First because carbohydrate intake is only 40%, when the recommended intake varies between 50% and 55%. The difference is due to the weight of fats, which exceeds 37%. This percentage is higher than the recommended threshold of 35% of total energy intake. If we look at fats in greater detail, saturated fats are 38% against the recommended 25%, which also corresponds to a healthy diet. The imbalance, therefore, stems from the high consumption of animal products. We reach the same conclusion when we focus on protein. In both cases, the amount of protein is greater than 15% of the energy intake in the diet, which would be a sufficient upper limit. In CD, however, plant protein is only 27% of total protein, far below half, which would be the recommended percentage. Lastly, in terms of micronutrients, both diets are capable of providing the population's nutritional requirements.

It is clear, therefore, that the current diet not only limits the potential carrying capacity of the population, but that there are conditions to provide diets that improve the agricultural situation in the territory and the health of its population.

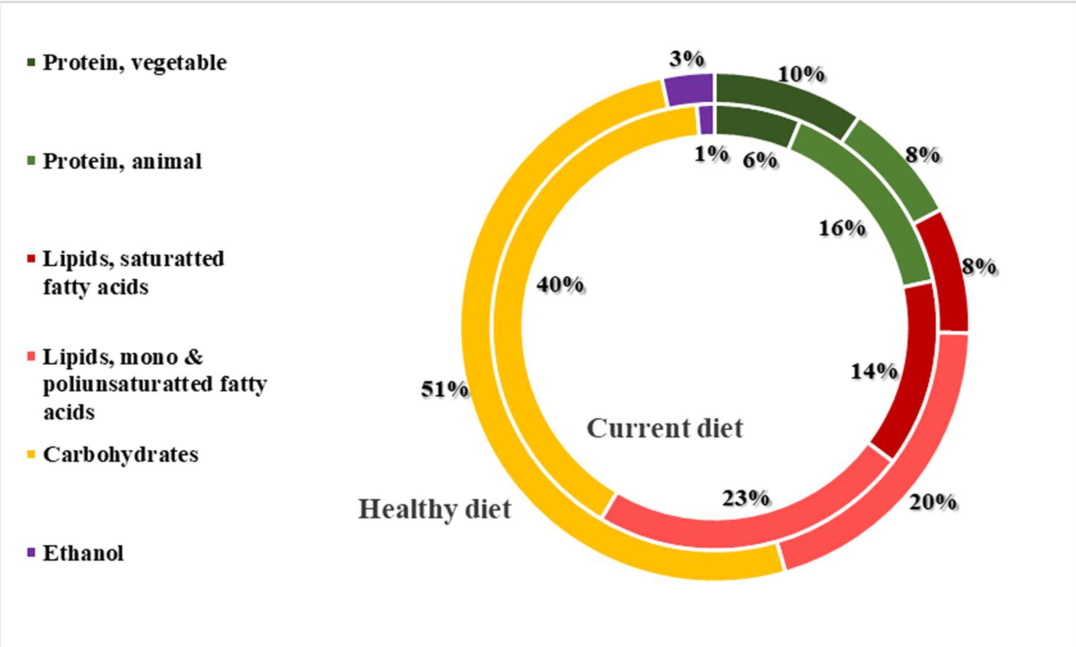

Figure 7.8. Energetic contribution of different macronutrient sources for CD and HD of the SFRA for 2009. Source: Our own.

5.4 *The potential of agroecological specialization strategies*

The last scenario examines the maximization of total agricultural output (MO). In this scenario, the aim is to look at the potential development of specialization strategies in comparison with the provision of diets in the territory, i.e. to assess the Pfaundler's spectrum. As a methodological aside, it should be remembered that we are maximizing the amount of ME produced as an approximation of the use value that can obtained. As shall be seen, obtainable ME is the determining factor in crop selection, whereas the adoption of another criterion (such as kg of fresh matter) would give rise to other results. A debate is needed on this subject in order to avoid using a criterion as arbitrary as prices, which do not reflect the environmental or social cost of production.

As Figure 7.6 shows, the amount of ME produced would rise between 32% and 34% for MOI and MOII, respectively, in comparison to HDI and HDII. This would increase the equivalent sustainable population densities to 136 and 204 inhab./km^2, respectively. The top figure would be nearly 44% of the territory's total population, far greater than the current figure of 16% with conventional farming.

For these densities to be sustainable from an agroecological standpoint, however, the complete diets for the population should be equally satisfied through the exchange of surplus products for deficit products. The result, in terms of output per person per day, is indicated in Table 7.5, where it is compared with HD and the difference between the two is laid out.

MO production presents highly significant deficits and surpluses with respect to HD production. First, the production of vegetables is null, while the production of fruit is more than twice the required amount. For wheat and legumes, only 14% of the required amount is produced. In the case of animal products, they account for 19% of total output, which is slightly lower than 23% of the healthy diet. Above all, however, the deficit appears in the provision of olive oil and almonds. This is because their production is relatively low (266 liters of olive oil and 624 kg of almonds per hectare per year in 2009) and they provide metabolizable energy of 8,900 and 15,675 MJ/ha, far below the 22,700 MJ/ha provided by grapevines.

Table 7.5. Resulting diets for the scenarios HD, MO, its difference, in grams per day and average person, and average production of ME per crop. Source: Our own.

	HD	MO	Difference	MJ/ha
Vegetables	400.0	0.0	400.0	22,115
Fresh fruit	367.9	701.4	-333.5	21,017
Wheat	207.7	30.2	177.5	37,762
Legumes	40.1	5.6	34.5	7,722
Olive oil	31.8	0.0	31.8	8,900
Almonds	30.0	0.0	30.0	15,675
Potatoes	0.0	0.0	0.0	17,814
Wine	120.0	1524.4	-1404.4	22,255
Pork	7.2	0.0	7.2	
Lamb	43.8	30.8	13.0	
Chicken	0.1	0.0	0.1	
Eggs	1.8	0.0	1.8	
Sheep milk	324.1	310.4	13.7	
Fish	90.2	90.2	0.0	

Thus, grapevines come to have a highly significant weight in the agroecosystem, representing 60-62% of total cropland and producing the equivalent of 11.3 times the requirements for the population that they could sustain. This reflects a clear commitment to specialization in winegrowing, and it would leave a landscape that tended heavily toward monoculture, although there would also be a greater diversity of land covers compared to current situation (0.37 for MOI and 0.51 for MOII).

But how is then that other crops that contribute a greater energy density like wheat (Table 7.5), do not contribute more to the agroecosystem? and why fruit trees appear as a crop with a greater weight when their productivity is lower than vines? The reasons are manifold.

Cropland planted in wheat is rotated with legumes, which have much lower yields. In reality, the rotation causes a drop in productivity to 22,750 MJ/ha, practically the same as the cultivation of vines. In addition, vines also have an associated crop, pastureland of vetch and oats, which provides 21.3% of total feed for sheep. If we associate this fraction of animal production as well, vines ultimately exceed the productive potential of the wheat rotation, rising to 24,450 MJ/ha. The output, therefore, is 7.5% higher, tipping the balance in favor of grapevines. This is a clear case where the decision to plant associated crops can be a good strategy to increase the agroecosystem's total output.

In this situation, therefore, it would seem logical to increase the amount of vineyard land as a monoculture at the expense of land for the wheat rotation. However, wheat rotation occupies 230 ha and fruit trees would cover 607 ha. This is where nutrient balances come into play.

In the case of vines, if we consider all flows in the main and associated crops (grape juice, pomace, vine shoots, stalks and pasture) the total requirements are 78 kg N/ha, 15 kg P/ha and 69 kg K/ha. Of these requirements, a portion can obviously be recovered through *in situ* consumption of the associated crop or through burying by-products. This circulation, however, always involves losses. By contrast, the wheat rotation has low requirements, once again because of the presence of leguminous plants and green manure, falling to 10 kg N/ha, 8 kg P/ha and 18 kg K/ha. Thus, while the territorial cost of putting the cereal crop ahead of vines is only a 7.5% loss of productivity in ME, the nutrient cost of vines is much higher than that of the cereal rotation. As a result, a degree of equilibrium is established between the two, even though the amount land in vineyards always occupies more surface.

The same thing occurs with fruit trees, which have a requirement of phosphorus, the most constraining element, of only 5 kg P/ha compared to 15 kg P/ha needed by grapevines. In the case of nitrogen, the requirements can be very low, of the order of 15 kg N/ha. This estimation assumes the presence of a herbaceous cover of leguminous plants that is similar to the one established in other woody crops, as well as nutrient imports derived from irrigation. Although the productivity of fruit trees is slightly lower at roughly 21,000 MJ/ha, therefore, there is an easing in total nitrogen requirements and they can replace wheat, for example, which requires more phosphorus. In this equilibrium, therefore, the amount of land for fruit trees becomes very important, rising to the maximum possible limit of 607 ha set by irrigation conditions. Once again, this shows the strong role played by the difficulty of nutrient cycle closures in agroecological strategies. However, it also shows the need, to analyze the water metabolism together with the metabolism of funds in order to see the real potential of irrigation in the area.

Before concluding this section, we want to offer a counterpoint on the impact of this strategy in terms of trade. In total, maintaining 43% of the population with an agroecological approach would require annual imports of 6,300 t of foodstuffs and exports of 17,550 t. These flows are not inert and they would have implications for transport costs and for nutrient losses or gains, given that their compositions are very different. As can be seen in the discussion, therefore, agroecological approaches entail an increase in complexity.

In terms of employment, we would start from a situation in 2009 requiring some 104 AWU (agricultural working units). For the CDII case, the figure would rise to 119 AWU; for HDII, 226 AWU; and for MOII, 307 AWU. In terms of population, this would imply that all scenarios (even the conventional one) would require between 1.1% and 1.5% of the population dedicated to farming, when the current figure is only 0.25% of the total population. Obviously, however, scenarios like MOII generate landscapes with such a low diversification that there would be very sharp peaks and troughs in employment over the course of the year.

5.5 *Results of the sensitivity analysis*[48]

Before moving on to the discussion, we want to comment on the robustness of the model and its configurations according to variations in annual conditions. The general results appear in Table 7.6.[49]

After taking into account how the variations in the input variables affect the output results for the composition of living funds, our conclusion is that most scenarios present variations that are smaller than the variations in the input data. It should be remembered that this is a conservative scenario that overestimates the expected variability in the agroecosystem. Thus, they demonstrate the robustness of the model, which would be not severely affected by year-on-year variations to a significant extent, save in a few exceptions.

[48] For the remaining results and the specific analysis for each living fund and scenario, see Annex III.
[49]The asterisks indicate those coefficients of variation that exceed the variation of the inputs.

Table 7.6. Variation coefficients in inputs and main outputs of the model SFRA for 2009. Source: Our own.

	Equal cropping area			More cropping area		
	CD	**HD**	**MO**	**CD**	**HD**	**MO**
Input variation	*12,7*	*15,2*	*15,7*	*14,3*	*15,9*	*16,4*
Population	9,7	9,3	3,5	11,0	9,4	3,8
Surfaces	5,4	7,7	25,2*	13,0	8,1	20,9*
Livestock density	9,7	11,2	4,6	11,0	9,2	8,0
Shannon	1,0	0,5	2,5	6,5	1,5	2,8

The exceptions include the results for MO, which are scenarios that present a greater variation in the amounts of land, far above the level that would be tolerable in any hypothetical land-use planning for the territory. Thus, from the standpoint of model construction, it appears that this scenario would be less robust and involve a greater degree of risk.

6 Discussion and conclusions

As indicated throughout the theoretical development of the model in chapter 5, we have no knowledge of other studies that adopt a methodological approach focusing on agroecological reproduction like the *SFRA* in this chapter. Therefore, a discussion of the results at an aggregate level is difficult, because the results cannot be compared with previous studies. However, there do exist other studies and theoretical developments that revolve around the issues that have emerged throughout the previous section. For this reason, the final section will be structured around three debates that we consider the most important ones based on the obtained results.

6.1 Sustainable or reproducible farming systems?

One of the factors that has the greatest effect on the analysis is the difficulty of dealing with nutrient cycle closure on an agroecological horizon. The cost arising from constant nutrient loss through human excreta is clear and it is particularly concerning in terms of phosphorus. This finding has been noted in various studies, which have estimated the loss of phosphorus circulating annually at an overall level of 50% and found that the recovery of excreted phosphorus is critical for the closure of cycles (Liu et al., 2008; Mihelcic et al., 2011). Indeed, this element is the one that led Liebig to reflect on the cycle closures between city and countryside. Liebig's growing concern prompted him to write the work *Letter on the Subject of the Utilization of the Municipal Sewage* in 1865, which served as inspiration for Marx when the latter coined the concept of "metabolic rift" (Foster, 1999). While these phosphorus deficiencies have been on the scientific agenda for some time, however, they do not appear on the political agenda, even though a century and a half has passed since these initial considerations (Cordell et al., 2009).

By contrast, in the case of the other two macronutrients under consideration, they either involve a factor that is not very limiting, such as potassium, or there are strategies that can be established to increase their symbiotic fixation, as in the case of nitrogen (Badgley et al., 2007).

There are two ways to solve the dilemma within the agrarian strategies. The first is to ensure a complete reproductive system in terms of nutrients, which would reduce the sustainable population density to levels of between 16 and 50 inhab./km^2. To do so in a context of high population density such as the present it would involve maintaining an agroecological environment at the local level, but dependent on massive imports of external foodstuffs, expelling unsustainability and delving even more deeply into the metabolic rift, with the environmental and social implications that would ensue (chapter 4).

The second way is to make use of nutrient stocks. This approach is assiduously rejected from an agroecological perspective and there are too few studies that address the use of stocks and quantify them (among the few exceptions, see Smaling, 1993). For the present case study, however, the establishment of this constraint involves having sustainable densities that are more than four times lower than if the use of nutrient stocks is considered feasible. With a healthy diet, more than 150 inhab./km^2 can be sustained, making use of little more than 0.10% of the phosphorus stock, that is, over a depletion horizon of some 1,000 years. While it would be advisable to analyze how the gradual depletion of stocks would lead to declining crop yields, we understand the horizons are on such a long time-scale that the social context itself would call for different responses.

In addition, a possible future in which it was not necessary to apply the precautionary principle to human excreta would reduce the use of stocks between 20% and 90% for phosphorus, sharply lowering the use of stocks in the soil.

6.2 The potential of agroecological landscapes

The next field in which we have aimed to contribute with this research is in the definition of a methodological framework to estimate the potential of agroecological strategies at the scale of landscape. We have also sought to make use of knowledge integrated from earlier research on advanced organic farming to address the ways in which the multifunctionality of various funds can be a key element to meet the various challenges of the ecological crisis through the design of sustainable food systems.

The impact of diet on the potential provision of foodstuffs by agroecosystems is a subject that has been studied extensively. It is not a new result to find that current diets have a significantly higher territorial cost than a diet with a lower animal intake in the total (Peters et al., 2007; Van Kernebeek et al., 2016).

Specifically, while the maintenance of the current diet would require 0.35 ha of cropland per person in agroecological conditions, the figure would fall to 0.16 ha of cropland per person for a healthy diet, only 46% of the cropland required for the current diet. These values are consistent with what is observed in several cases involving a conventional farming scenario, where the figures varied between 0.10 ha and 0.86 ha of cropland per person (Desjardins et al., 2010; Meier and Christen, 2013; Peters et al., 2007; Tuson, 2014).

As for the differential functioning of the model with respect to the remaining items analyzed, we would like to stress three key objectives that emerge from the study: the role of livestock farming, the functional recovery of woodlands and, as a consequence of these and other strategies, the territorial synergy that arises.

6.2.1 Livestock integrated in the landscape and the agroecosystem

First, by considering the closure of nutrient cycles and the possibility of using by-products in this case, livestock also turns again into a key living fund beyond the provision of animal products, recovering a portion of its lost multifunctionality (chapter 4). In a study done for the Netherlands at the national level, the ideal proportion of animal protein over total protein was estimated at 12% (Van Kernebeek et al., 2016). In the current study, by contrast, the ideal proportion reaches 45%, considerably higher than the former figure. The difference results from allowing freedom of choice in the composition of the diet, within certain nutritional constraints, while maximizing the use of secondary resources that do not compete directly with human foodstuffs, with less than 2% of produced grain devoted to animal feed.

This approach involves a fundamental role for the use that can be made of what is now called crop residues (Oltjen and Beckett, 1996; Roos et al., 2016). Using by-products lowers the current amount of grain allocated for animal feed, which we estimate in the conventional case for the current diet at 86% of total feed and which could be reduced to 40% with an agroecological strategy while maintaining the same diet. These figures are similar to the ones estimated by Stuart at a global scale (2011).

With respect to the numbers and composition of livestock, there is clearly a decline of 41% in livestock contribution in a healthy diet compared to the current diet, falling from 6 to 4 LU500/km^2. These densities are even lower than the ones observed for 1860. Above all, however, it is significant that ruminants would increase from 5% to 88% of all livestock. Indeed, this result is consistent with what is observed in countries without industrialized farming, where ruminant animals represent an extremely high fraction of all livestock because of their ability to mobilize nutrients and because they can consume quality diets through the use of resources that do not complete with human consumption (Eisler et al., 2014).

The potential of ruminants as efficient bioconverters in the agroecosystem, however, clashes with their role in total greenhouse gas emissions at a global scale (Herrero et al., 2013). Nevertheless, when compared with the conventional situation in 2009, aggregate emissions would clearly be lower because the densities when only considering ruminant livestock would fall from 11 LU500/km^2 to 3 LU500/km^2. In future analyses, it will be necessary to include the study of global greenhouse gases arising from agroecological activity to draw conclusions at an aggregate level of the impact that this could have in comparison with the current diet applied with agroecological practices.

6.2.2 *Recovering the multifunctionality of woodlands and agro-silvo-pastoral mosaics*

Second, returning to the differential functioning of the model with respect to other optimizations, we believe that it is necessary to recover woodlands as an active agricultural space. That is, we need to restore their functionality, and also their role as a key element in the sustainability of nutrient cycles. By pursuing a *land-sharing* strategy, the combination of woodlands and ruminant animals would help to reduce the pressure on areas under cultivation and at the same time ensure a certain level of management of forest masses.

Taking landscape indicators into account and considering the possible recovering of croplands, the *SFRA* model shows how landscape equidiversity can improve considerably. While equidiversity has fallen from 0.56 to 0.37 over the past century and a half, even the impact of strong urban expansion could be mitigated, with levels climbing again to 0.55 in the case of healthy diets. As some studies indicate, also planning the provision of ecosystemic services at the level of landscape can have a more positive impact on overall biodiversity than actual agroecological practices on plots *per se* (Bengtsson et al., 2005; de Groot et al., 2010). In our view, these changes, together with the recovery of functional integration among different uses, would also enable progress toward the creation of an agroecological matrix as an alternative to *land-sharing*, which would improve the material conditions for greater beta biodiversity (Perfecto and Vandermeer, 2010). This would involve depolarizing uses and restoring agro-silvo-pastoral mosaics (chapter 3), and the recovery of pastureland would also have a significant weight. Ultimately, while we have been able to introduce landscape aspects in this non-linear approximation for the first time, other important questions, such as the internal diversity of the forest cover, should be investigated in future models in order to improve the approximation, as well as to incorporate empirical models correlated with biodiversity measurements.

As for forest biomass extractions, the analysis in this study has not incorporated the flows of wood for non-farming uses. Based on recorded extractions (MAGRAMA, 2009), however, they generate a relatively low impact on the agroecosystem, in fact, less than 10% of estimated nutrient extractions in forest land in the scenarios considered. This is largely due to the abandonment of forestry activity. In subsequent studies, it would be interesting to analyze this flow from an optimization standpoint as well, though this would also involve the total dimension of energy consumption and losing the specific perspective of agricultural metabolism. By focusing on fuelwood flows, however, the import of green biomass from woodlands has also been viewed as key to establishing equilibrium for nutrient balances, making use of the typical strategies of advanced organic farming (Corbacho-González, 2015; Olarieta et al., 2011).

6.2.3 Territorial synergy vs. conventional farming: letting the territory determine the diets

Lastly, as a third differential element and largely as a result of the previously emphasized aspects, the reproductive perspective also enables us to see the potential of landscape strategies when tackling the lower productivity levels of ecological farming compared to conventional farming (De Ponti et al., 2012; Ponisio et al., 2015).

An agroecological approach would permit significantly high sustainable population densities through the use of different diversification and integration strategies among the funds. Such strategies have been noted throughout the results. We find a variety of key elements, some already analyzed, that would address the greater territorial cost of ecological farming in different ways, thus reducing the metabolic competition for land-use (Haberl, 2015; Wezel et al., 2014):

1. The integration of livestock, especially ruminant species, as bioconverters of agricultural products that do not compete with human consumption (Oltjen and Beckett, 1996; Roos et al., 2016).
2. An active role for woodlands as a contributor of nutrients and resources for farming and livestock activity.
3. The use of diversification strategies such as crop association and agroforestry, which help to increase the total volume of biomass generated in the agroecosystem (Eichhorn et al., 2006).

In many respects, these practices reproduce some of the operational strategies of advanced organic farming aimed at optimizing the use of resources, but adapted to the current context. By using such strategies, it is possible to reach the point at which the healthy diet produced by conventional farming can have a territorial cost in terms of the amount of farmland that could be equal to the healthy diet produced by agroecological farming. This would involve the use of strategies not of ‘ecological intensification’, trying to make organic agriculture compete with conventional in terms of yields, but of what we understand to be ‘ecofunctional intensification’ (González de Molina and Guzmán, 2017; Levidow et al., 2014).

On the other hand, the current diet, even in an agroecological context, would continue to act as a severe limit on sustainable population, which would be as low as 44% of the population density that could be maintained with the healthy diet. In addition, it would involve a comparatively greater pressure on the soils and generate less diverse landscapes, while at the same time being unsuitable for health. In relation to the percentage of sustainable population, however, what has been indicated in the case study bears repeating. The area in question is one of high population density and this characteristic is precisely what makes it logically a deficit area. This is not to say, however, that we are speaking of low territorial capacities, but rather an excessive level of settlement that has grown over a period in which population at a local scale has become virtually decoupled from nature.

Lastly, all these synergistic processes are further reinforced because, under constraints based on nutritional and palatability criteria, they are the actual conditioning factors of the agroecosystem, which by means of optimization determine healthy diets. This is a new feature of the present study that differs from what has been observed in other research (Desjardins et al., 2010; Meier and Christen, 2013; Peters et al., 2007; Van Kernebeek et al., 2016). In our view, planning diets from the standpoint of the actual potential of the agroecosystem may be critical if the aim is to optimize the use of the territory with site-specific foodstuffs.

6.3 Assessing Plaundlers' spectrum

Lastly, the debate over the specific intentionality by which agroecosystems must be designed cannot be neglected. One of the aims of this research was also to identify whether we could speak in metabolic terms of a *local trap* that would cause strategies for the provision of diets at a local level to reduce the productive potential of the agroecosystem significantly.

We observe that following a strategy of output maximization would result in production of between 32% and 34% more metabolizable energy than the provision of local healthy diets would achieve. The approach also entails a proportional change in sustainable population, which would rise to 204 inhab./km^2.

The consequences at the level of agroecosystem and the dependence on other farming systems, however, would not be minor. In total, 43% of the entire diet at the local scale would have to be imported and the tendency toward monoculture could definitely limit the positive impact in terms of beta biodiversity, owing to a less diverse landscape. In addition, it is a significantly sensitive scenario in terms of the robustness of the model and land-use allocation. Once the strategy is configured, the increase in produced metabolizable energy with respect to the local diet could plummet in years of crop failure. At the same time, the trend toward specialization in woody crops also generates a landscape that is not very resilient to major crop disturbances, such as happened with the Phylloxera plague (Badia-Miró et al., 2010).

To ensure this strategy, it would also be necessary to count on areas where the optimal production was cereal and legume crops, other areas where it was fruits and vegetables, and still other areas where it was olives and almonds. Obviously, given that this is a local study, we cannot say categorically that such a scenario is implausible, but we do question whether, for example, in the case of vegetables, there is any region that would be optimal for large-scale cultivation on them, given the severe nutrient constraints that would be involved.

We take the view, therefore, that an appropriate scenario would lie at an intermediate point between the healthy diet scenario and the scenario that maximizes output. Such an intermediate scenario would take full advantage of the local environment without entailing a severe constraint on the total productivity of the agroecosystem and falling into a local trap. For instance, it could be achieved to some extent by linking the agroecosystem of Vallès to another, more arid region in the interior of the country, where the cultivation of olive and almond trees could be better crop strategies and would require only a moderate circulation of nutrients. Therefore, regarding Pfaundler's spectrum, in this research it could be ranging between a 33% of local needs satisfaction with an autarkic strategy (HDII) and 44% with a completely open agrarian system (MOII). However, we have to keep in mind the limitations of this model and take cautiously these results, especially in relation to the unit of analysis we have used and the deliberation process it would need before defining this range assessed.

As well, as we are presenting an *SFRA* at the regional scale without interaction with other regions, we cannot quantitatively resolve the issue here. We understand, however, that it is a necessary step toward this horizon. It will require future research to look at two territories with different agroecological productive potentials and see how the appropriate degree of specialization might be defined to maximize the satisfaction of social needs within tolerable ranges of environmental impact. Clearly, network theory will play a key role in such research (Kneafsey et al., 2001), which can also draw on studies conducted in the field of “foodsheds”, where the debate is now addressing the cost of the circulation of foodstuffs (Galzki et al., 2015; Peters et al., 2012), gradually bringing us closer to the equilibrium called for by Pfaundler.

Finally, we want to emphasize the importance of identifying consensually agreed units of measure for a maximization-based approach. Here we have used metabolizable energy instrumentally, but in other cases (for example, if transport becomes a highly limiting factor) the unit of measure could be kg of fresh matter or some other indicator. These results must be confined to the approach that we have taken to illustrate the model, which would require social agreement on the way to proceed.

6.4 Final considerations on the model’s limitations and potentials

In these final considerations, we would like to return to aspects that, in our view, limit the robustness of the study and note other aspects that are important to bear in mind in future research. In any event, the decisions taken here as approximations of *desirability* (such as, the amount of land to protect, how to optimize diets, or the diets themselves) need to be validated socially and with the assistance of subject-matter experts.

The first aspect that we would like to recall is that we have not incorporated the institutional dimension of social relations in the study. Rather, the study assumes freedom of access to resources and the feasibility of changing their use. As a result, we show a situation of maximum efficiency in the use of resources. We have conducted a theoretical exercise decontextualized from the reality of private property. While the fragmentation of land-holdings is greater in Catalonia than in other corners of Spain, ownership presents a trend toward concentration and crop extensification, and the price of land is very high (Fernández Such, 2011). These factors limit the establishment of new farmers and impede the crop diversification that would be required to pursue these strategies.

With respect to extensive uses, we have not incorporated the time limitation on the availability of specific sources, such as pastureland, in the second *SFRA*. It would be appropriate to take such time limitations into account in future research and in the ultimate requirements for farm labor. As noted in the earlier discussion, it would also be important to take into account the interaction and competition from any increase in forestry activity in the production of biomass for energy recovery. It is also critical to delve more deeply into the analysis of strategies for quantifying the farm-associated biodiversity in order to ensure their positive impact. In this respect, it will be necessary to work shoulder to shoulder with ecologists of biodiversity and landscape in order to find common ground for addressing the subject.

As for having more reliable data on the crop potential of irrigation, it would also be necessary to address water metabolism, as is now being done in other methodological approaches to social metabolism (Madrid-López and Giampietro, 2015). Another important consideration would be the impact of greenhouse gases, taking into account as well which strategy is established in terms of the mechanization of farming activities (Aguilera et al., 2015). As in the case of forestry, the chief problem with these considerations is that we are entering into the use and management of living funds and stocks (organic and inorganic) that compete with other non-farming uses, thus changing the scale of analysis that we would need to undertake to settle the corresponding debates.

Also, given the limited sensitivity analysis, the model obviously represents a simplification of reality and there is a high level of uncertainty about what would happen if the measures were applied. In our view, however, this is an insufficient reason not to evaluate the new methodological approach on the basis of the precautionary principle, but rather the contrary. The stark inefficiencies in the operation of the current farming system, which have been addressed in chapters 2, 3 and 4, clearly show its severe erosive impacts, both socially and ecologically. From a humble and prudent standpoint, it is hard to believe that these impacts could be exacerbated with an agroecological approach. This involves seeing that the precautionary principle can always be inverted (Wynne, 1992) and, therefore, that inaction in the current scenario is not better than an agroecological scenario involving the restoration of an organic metabolism.

On the positive side, we consider the model to be successful in its ability to evaluate each flow in its corresponding units, constructing a socio-ecological scheme that does not limit the combination of different units in order to see feasible and viable results. As a result, we can go beyond cost-benefit analyses in which technical criteria take precedence in order to engage in multi-criteria discussion processes in which social deliberation plays a dominant role (Martinez-Alier et al., 1998). While these are only initial approximations, we consider that the study has demonstrated the value of using optimization tools from an agroecological perspective to design horizons for sustainable farming systems, as well as the potential of agroecological landscapes to face today’s challenges.

The ultimate aim is to call on the various scientific disciplines that contribute to Ecological Economics and on public policy-makers as well to make headway toward systemic conceptions of agroecosystems that will enable us to restore their organic functioning. Only in this way can we move forward with collective conviction toward agroecological landscapes contributing to solve the current ecological crisis (Tello and González de Molina, 2017; Wallner et al., 1996).

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CHAPTER 8. CONCLUSIONS

In this chapter I present some general conclusions on the methodological advances, theoretical developments and empirical results obtained in this PhD thesis. I organize the chapter in four sections with the aim of contributing to a final reflection combining the different fields on which my research has been focused. First, I summarize the methodological contributions made; next I comment on the learning drawn from the historical socioecological transitions from advanced organic agricultures to current industrial ones; thirdly, I point out some challenges and potentialities for a transition towards sustainable agroecological landscapes, a task for which the methods proposed and the results obtained can be useful. And, finally, I propose some possible paths to help the advance of a Strong Sustainability Science by developing a Substantive Economics.

1. New methodologies for a new transition towards sustainable food systems and agroecological landscapes

As I stated from the beginning, this thesis has mainly been focused on developing novel methodologies. Some part of what we learnt about the socioecological transition, has been the result of novel methodologies that we have proposed throughout this thesis. However, these methods can also be useful to enlarge the available toolbox of the Social Metabolism, and to connect it with other disciplines. In this section I will summarize them and the transdisciplinary connections set in the same sequence they have been presented in the thesis, and by linking those to new forthcoming paths which I consider that might be opened.

1.1 A consistent methodology for energy balances of farm systems

First of all, and thanks to the collective research undertaken by our SFS project, a common methodological framework of reference for accounting energy balances of farm systems has been consolidated. This multi-*EROI* accounting allows analysing the functioning of agricultural systems, and their multidimensional energy efficiency, in order to study their evolution along socioecological transitions in a comparable way in space and time.

The adoption and implementation of the criterion of a '*forced local fund sustainability assumption*' has allowed us to reduce the uncertainties in these comparisons, especially in historical studies, by considering what the maximum values of energy efficiency achievable would have been if the agroecosystem considered had been managed ensuring the sustainability of their funds. This was done by taking into account animal feed balances, soil nutrient balances, and a sustainable exploitation of forest resources. This triple balance establishes a sustainability test of those three fund elements, and in chapter 4 has been complemented with a balance of nutritional and fuel requirements for the maintenance of the farming community and society. In this way, a full reproductive analysis of the material social metabolism has been carried out taking into account the closure of all socio-metabolic cycles considered.

In the same vein, I have introduced waste flows when the biophysical relationship between society and nature is accounted. This allows fine-tuning socio-metabolic analysis by introducing a possible third path. This waste path became previously hidden when all possible directions were restricted to whether flows exited or were left within the agroecosystem boundaries. Yet there can be a third type of flow that appears mainly in industrial societies: the ones that become resources out of place. This means bringing to light the environmental impacts of wasted resources in an economy that does not consider negative or positive externalities of market decisions. True, it is not easy to characterize quantitatively which part of a flow actually performs a potential benefit or not for the agroecosystem—as it always happens in balance sheets of everything, by the way. However, to consider the opportunity cost that this type of flows might entail in a certain position (a waste) or another (a resource) may help to clarify the issue—at least as a first approximation.

We adopted an accounting model where the process of calculating energy balances of farm systems does not fall into reductionism, an energy dogma. In each case, we account for the flows using the units that are significant for the specific fund element to which they are going (metabolizable energy, nutrients, gross calorific value). Subsequently, at an aggregate scale, we use energy analysis as a proxy that allows us to make a series of calculations of both multidimensional and joint energy efficiencies. In doing so, we are aware of the simplification that adding flows of different energy qualities and power levels involves. We warn that the qualitative differences lost this way of accounting must always be kept in mind when it comes to interpreting the meaning of the different energy efficiency indicators obtained.

At the same time, the impact that inequality in access to natural resources and the decision making power has on energy balances has to be taken into account. If these social conditions are not accounted for at farm scale, as was done in Chapter 6, we cannot analyse the specific biophysical limits set forth by the immaterial sides of social metabolism—such as property rights, inheritance systems, institutional settings, prevailing social values, etc. In the context of a class society, it is ludicrous to consider that all biophysical flows could circulate freely among all fund elements that actually belonged to different owners. The influence of the immaterial metabolism on material metabolism is a pending task for socio-metabolic quantitative analysis. However, I consider that the methodological developments of this thesis are a useful contribution to cope with this challenge.

1.2 The study of cultural landscapes as a footprint of social metabolism

The *Energy-Landscape Integrated Analysis* (*ELIA*) studies the relationship between social metabolism and landscape structure for the first time in an integrated and quantitative manner. We do this task by rethinking the agroecosystem pattern of flows from a cyclical conception that allows closing the whole biophysical turnover, and working with an accounting methodology that allows making spatial-explicit all the values accounted for.

The cyclic structure of flows drawn through graph modelling starts with the photosynthetic capacity (the current Net Primary Production that takes place in the system boundaries). Then, following the graph model, we can count the fraction of each energy flow that reaches a node and then is split into two, either to go outside through Final Produce or loop inside the agroecosytem to connect with another node of its energy network (except when there is a third waste path). The graph also includes the energy entries coming from outside that become interlinked with the rest of flows. In this way we avoid adding flows; the entire energy turnover can be closed without incurring in double counting the same flow; the energy temporarily stored within the agroecosystem is separated from the one dissipated outside; the pattern complexity can be assessed as information content; and all values can be counted in a spatial explicit manner. Importantly, all this relies on the previous results obtained by our energy balances of farm systems that for the first time bring to light the internal loops that remain within the agroecosystem, and increase its complexity. Without the novel methodology of energy balances summarized in the previous section all *ELIA* advances would have not been possible, or would be lacking a fund-flow reproductive vision of agroecosystems.

Another analytical step forward made thanks to the systemic approach of the agricultural metabolism adopted has been making energy balances spatially explicit, by linking the activity of the farming community with livestock metabolism and farmland-uses according to the services provided through the integration between the fund elements in the landscape. As a result, we can observe for the first time the joint effect of the agroecological functioning driven by farm social metabolism—i.e. its ability to emulate the natural processes of energy storage through the interrelations set among the various funds, and the resulting landscape functional structure allowed by these interrelations, which can be analysed through their patterns.

This allows a first approach to what the material conditions for farm-associated biodiversity are. We do this by means of a spatial explicit analysis of the internal accumulation of energy available for all agroecological food chains (food and feed for all living funds), and the equidiversity of land covers (habitat differentiation) in each cell of a grid in the landscape. In this way we can compare situations of different periods and territories and, by difference, to highlight in which cases better conditions occur. *ELIA* becomes a tool for comparative analysis. While the actual impact of these material conditions on farm-associated biodiversity remained as an hypothesis in the *ELIA* presented in this thesis, further researches have demonstrated its usefulness in order to assess it.

Therefore, *ELIA* is a methodology that connects for the first time the disciplines of social metabolism and landscape ecology. It becomes a fundamental step towards the landscape modelling of agroecosystems that can take into account the effect of agricultural activity on farm-associated biodiversity, with the objective of evaluating the progress towards new agroecological horizons.

1.3 Modelling agroecosystems as socio-ecological systems

Finally, I consider that the most relevant methodological contribution made in this thesis is the *Sustainable Farm Reproductive Analysis* (*SFRA*) model. This approach allows making the leap from the analysis of agricultural systems carried out so far, to its programming modelling. I consider it a first step towards a prospective-deliberative Social Metabolism, beyond an analytical one.

By using linear and non-linear optimization of flows and fund elements, this methodology allows identifying not only what should be the configuration of the uses that respond to social needs, but the entire fund-flow pattern that would allow having an organic farming with a sustainable metabolism. It can be applied to foresee how agroecosystems would perform either at plot, farm or landscape scales, allowing the definition and testing of *feasible*, *technically viable*, and *desirable* farm systems. Obviously it does so by simplifying things, as in any model. Yet it maintains a biophysically realistic reproductive approach by choosing the different units which are relevant to keep each fund alive. In addition, the possibility of incorporating non-linear programming in the second case study has allowed increasing the degrees of freedom of the model to address aspects such as landscape patterns. This opens a door to increase the complexity of these programming models, as long as they continue responding to coherent biophysical problems from an agroecological standpoint.

To develop this *SFRA* it has been necessary to link various disciplines: recovering the role of reproductive studies in the agrarian economy, connecting them with current research on landscape ecology and land-use planning, and incorporating them to a novel approach to programming modelling based on social metabolism.

Its usefulness has been proven as a historical tool for counterfactual analysis, as well as a prospective tool for land-use planning to generate agroecological scenarios from which deliberative processes can be established. In the first case, we have considered the study at farm level as a basis to compare the optimum situation with different desirable aims, i.e., minimizing land-use, minimizing labour requirements, or maximizing cash flow. This has allowed us to understand better the reasons behind land-use intensification in advanced organic farming, and to highlight its social and biophysical limits.

In the second case study we applied the *SFRA* model to a current situation to compare how strategies oriented to plan new agroecological landscapes can allow the recovery of organic metabolism in agricultural systems. I consider that this modelling quantitatively solves the leap of agroecological scale from plot level to the landscape one. This can be a key tool to guarantee: i) the closure of metabolic cycles; ii) the recovery of certain biocultural legacies of farm management; iii) an improvement in the material conditions for farm-associated biodiversity; and, iv) the facilitation of deliberative processes for a new socio-ecological transition towards more sustainable farm systems.

These are the first examples of what this methodological approach can give us. In spite of limitations I believe that through forthcoming improvements, and the consolidation of this tool by controlling the sources of uncertainty in the programming model, it can become robust enough to facilitate new social and political processes of transition to new agro-food regimes; while, at the same time, also help to deepen historical analysis of agrarian systems from a comparative perspective.

2. Socioecological transition from organic societies to industrial ones

This thesis was also aimed at deepening the knowledge that Environmental History has of the Socioecological Transitions experienced along the last century which have laid the foundations of many important sides of the current global ecological crisis. This has mainly been done, by providing the new methodologies developed from a systemic perspective, presented above, that seek to contribute to the study of certain processes which, despite having been noticed for a long time, have remained unassessed and not quantified so far. Focusing on the empirical results obtained in the case study of the Vallès County, and linking them with a novel integration of different ongoing debates in various disciplines, I will highlight seven aspects that appear to be the key drivers of this transition from advanced organic to industrial farming. However, there are some aspects (mainly from paragraphs 2, 3 and 5) which had already been partially or totally assessed in previous researches, when applying for the first time the socioecological balances, carried out by Cussó et al. (2006) and Tello et al. (2008).

1. *The impact of the global food regime on the satisfaction of local needs*. Throughout the study period, the farm system analysed changed from a situation c.1860 in which 69% of the food needs of the local population could be satisfied by the same agroecosystem, into another in 2009 in which it hardly could reach 16%, and where a huge livestock specialization prevails. The change in the local food coverage does not simply respond to the specialization as such. Before the arrival of the *Phylloxera* plague in Catalonia during the late 1880s, 36% of the Vallès study area was devoted to vine-growing. Thus farmers were able to maintain a regionally specialized agroecosystem in a certain balance with the satisfaction of local food needs. This does not happen at present. Cities are no longer the main consumers of the food produced in their surrounding territory. Conversely, global specialization and the overcoming of local and regional biophysical limits it entails, have turned farm systems into alien ones regarding the food needs of the people living in their own territory. In turn, while cities remain also alien to their surrounding landscapes in terms of agricultural flows, they continue to increase the pressure exerted upon them by linear infrastructures, and the expansion of built-up areas.

2. *Polarization of farming disturbance within a spatial redistribution of farmland uses*. The Green Revolution cannot be understood without the energy transition that led to the massive

diffusion and use of fossil fuels. Throughout the world, this process has involved a very significant increase of anthropic disturbances exerted on agricultural lands and soils. The substitution of organic fertilization practices and reuses of biomass by synthetic fertilizers, of certain ecosystem services by biocides, and of the animal draught force by tractor mechanization have greatly reduced the energy efficiency of farming. In our study area, cropland soils occupy less and less surface. On the one hand, abandonment of marginal lands not easy to mechanize has been combined with urban expansion. On the other hand, forest abandonment has decreased its contribution to the agroecosystem's products up to less than 15% of what it represented c.1860, while forestland has expanded into cropland left abandoned.

3. *An increasingly useless livestock subsystem from an agroecological standpoint*. During the 20th century livestock has progressively lost its former agroecological functions, while increasing its metabolic bite upon human-apt food resources. The change in livestock breeds, replacing those ecologically most adapted to local resources which did not compete with human nutrition, by others more productive in fattening feedlots, has meant an efficiency improvement in terms of kg of animal live weight being fattened per kg of consumed feed. But this has also implied a breakdown of its metabolic links with the rest of the agroecosystem. Before the socioecological industrial transition, the role livestock had was multiple: draught power, source of fertilizer, reappraisal of by-products, domestic heating and –in a complementary manner— food. Currently the latter is the only one at stake. Manure slurry has become a waste instead of a resource, due to the economic cost of handling it compared to synthetic fertilizers. Furthermore, due to the intensification of livestock production cycles, animal diets no longer makes profit from by-products—these being estimated less than 14% in aggregate terms compared to cereal grains used as feed and fodder. In short, livestock fattening has only just one function at present: providing meat, eggs and milk through a linear energy-inefficient bioconversion at the expense of human-edible resources.

4. *The vanishing of the territorial synergy.* An emerging property of agroecosystems, which was a key factor prior to the socioecological transition to industrial farming, is what our Catalan SFS research team has called land-use synergy which results from the integration among the different self-reproducing funds of agroecosystems. In past advanced organic farming this landscape efficiency allowed to lessen the land cost of sustainability, by means of keeping the various fund elements integrated and functioning as a whole instead of separately. Through reproduction models, I have been able to quantify the outcome of this land-use synergy: c.1860 it would allowed to reduce by more than 50% the total area required to nourish the farming community and livestock. In contrast, in 2009 this value has been reduced to around 6% due to the lack of linkages between conventional industrial agriculture and livestock fattening in feedlots and the current human diets. This is a clear decrease of landscape efficiency derived from the disintegration among livestock, agriculture and forest uses, which resulted in a linearization of metabolic fund-flow processes. Summing up, the lesser complexity of funds' linkages has led to a significant loss in the organic functioning of farm systems and the landscape efficiency it provides.

5. *From complex agro-silvo-pastoral mosaics to a simplified landscape that endangers farm-associated biodiversity*. Disintegration among agroecosystem funds has had a clear impact on the landscape. The loss of diverse land-use mosaics, together with the polarization of farming disturbances between land intensification and abandonment, has resulted in poor material conditions for farm-associated biodiversity. This emerging property of cultural landscapes is currently being hampered by a land cover pattern where, on the one hand, there is still a

certain variety of habitats in distinct agricultural areas where the level of farm disturbance has become very high—sometimes too high for the dispersal ability of many species to withstand them. On the other hand, forest and pasture areas have suffered a land cover homogenization that has meant a decrease in habitat differentiation, while large amounts of unharvested biomass are accumulated there. Instead of contributing to biodiversity, this process seem to only expand the populations of a small number of species due to the lack of habitat differentiation. The negative impact of linear infrastructures is added, by increasing habitat fragmentation and exerting a barrier effect against the ecological connectivity among landscape cells that have decreased by 38% from c. 1860 to 1999 in our study area. Although in this thesis I have not tackled biodiversity as such using data based on direct observations, the results obtained have verified how the material conditions for farm-associated biodiversity hosted in landscapes have been very significantly degraded throughout the socioecological transition from organic to industrial farm systems.

6. *Environmental load displacement does not save strong local impacts*. I have estimated that the current specialization of the Vallès study area in meat producing feedlots lies on a land imprint of feed imports of more than eight times the area locally cultivated in 1999. Beyond animal feeding supplied from inland Spain, most of these imports likely come from South Global countries. Obviously, this generates deep impacts on them that would be both socially and environmentally more worrying because of the existence of laxer laws and globally more asymmetrical power relationships than in Catalonia. Despite displacing a great deal of this unsustainable environmental load to those countries, important consequences to local agroecosystems are not avoided. The metabolic rift entailed by these huge feed imports also implies importing around eight times more nitrogen (N) than the one required by extractions in the cultivated soils of the Vallès study area yearly. This is a clear example of a resource out of place, i.e. of waste. We estimated that only few part of this manure slurry may end up performing a maintenance function for soil fertility.

7. *Social inequality as a driver of fund-flow intensification and globalization*. Last but not least, there is the role that social inequality has played as a driving force of the socioecological transition studied. After analysing the pressures exerted by farming social metabolism on the study area c.1860, I concluded that population density seemed not to be a major driver of land-use intensification. The population could still have been increased by 90% at best, as long as there had been an egalitarian redistribution of land. Conversely, vine-growing specialization was led by wealthy peasants and large landowners who offered long-lasting sharecropping contracts called *rabassa morta* in Catalan (as they only ended when the vines died) to landless peasants. As a result of this inequality, approximately 80% of peasant smallholder units had less than the land required to meet their family needs within their farms. This probably forced them to carry out land-use intensive practices, which did not mainly come from population pressure but from prevailing social institutions that legitimized this social inequality. A process of soil nutrient mining was probably underway due to this unequal agrarian class structure. It also forced many of these smallholders to enter the labour market in search of wages to supplement their small family incomes, a result that helped consolidate agrarian capitalism. This situation could have been overcome in the Vallès municipality of Sentmenat through an egalitarian access to land, a context where vineyards could still be increased to reach an estimated sustainable maximum extent of 66% of farmland. Thus, the role that inequality did play in land-use intensification becomes a key to understand the transition from organic to agro-industrial farm systems. The land grabbing exerted by a few wealthy owners forced the vast majority of smallholders to redouble their socio-metabolic efforts. In the mid-nineteenth century this process could already be considered a displacement of environmental burdens that took place between social classes of the same territory. Nowadays, the accumulation or social control of a large number of land

resources by a handful of transnational agribusiness also boosts the intensification of land-use, extractivism and unsustainability. This is mainly happening thanks to the international division of labour and corresponding trade value chains that allow expelling a part of the Global North unsustainability through the massive imports of feed produced in the Global South.

3. Challenges in the transition to agroecological landscapes

In order to start laying the foundations of a new economic model, I consider that, regarding agricultural aspects, the research advances carried out by our SFS project in agroecological landscapes can be very fruitful to help new forms of participatory public policies towards sustainability. Devising future scenarios of farming, and of possible agrifood chains, requires a multi-criterial deliberative process capable of dealing with multiple dimensions and scales. It should never be limited to any single aspect. However, having a reliable way of predicting how agroecological landscapes would look like depending on the main desired objectives adopted will be a very useful tool for decision-making processes.

The *SFRA* model has been tested to evaluate the potentials of change towards sustainable agroecological landscapes, compared to the current industrial agriculture. In the process of doing so, several problems have appeared that are worth taking up as challenges to debate and investigate in the light of a new socio-ecological transition. Many issues pointed out here require a deeper empirical analysis to corroborate them. But even at this initial stage, they help to outline lines of future research relevant to the task of helping agroecology advance from plot or farm-based levels to landscape scale.

First of all, we have found the limits of the closure of farming socio-metabolic cycles in relation to the soil biogeochemical processes. The precautionary principle applied to the controversial return of human excretion to the agroecosystem strongly limits the capacity to attain a totally reproductive system at landscape scale. Discarding humanure as a source to replenish soil nutrients could even reduce by 75% the potentially sustainable population that could be fed locally in the territory studied. This restriction is mainly due to the highest limits set by the Phosphorus cycle (P). A possible use of the P stock that exists in the soil would release this restriction by adopting a very long-term temporal scale.

Hence, we face a dilemma: either new procedures appear for a safe recovery of the nutrients contained in human excretion; or society will have to consider other kinds of soil fertility management which would be only nearly-sustainable, e.g. resorting to a mining process of the stock of P in the soil with a horizon of exhaustion of the order of thousands of years. Currently, from a purely agrarian strategy, while there are no new wastewater technologies, the real dilemma is to improve local agroecological systems by expelling unsustainability to other territories through environmental load displacements embodied into commercial flows; or to start a local consumption of the stock of nutrients in the soil in a clearly non-reproductive way (although it can be considered nearly-sustainable for a long time period).

Secondly, I have been able to verify the current capacity of agroecology to face the productivity gap between conventional and organic farming when evaluated at landscape level. In the case studied, the *SFRA* model has checked that if many agroecological land-use synergies are used, a new organic farming could provide a healthier diet with a similar amount of land than producing the same diet in an industrial agriculture. This result is obtained taking into account the recovery of various land-saving strategies that had been in operation in past advanced organic farming in the same territory, and now are part and parcel of its biocultural heritage. Among them, there stand out: i) the farm-integration of livestock, and especially ruminant animals as bio-converters of farmland resources which do not compete with human feed; ii) an active use of forestland as provider of soil nutrients for cropland, and of animal feeding for livestock; and iii) keeping land-use diversification strategies, such as crop rotations, associated crops and agroforestry.

Thirdly, I have verified that defining diets becomes a fundamental issue to determine what the potential of an agroecosystem to feed human population is. Choosing a healthy and sustainable diet is a basic objective when it comes to optimizing the uses of the land through the *SFRA* model. Beyond its benefits for peoples' health, a diet established with nutritionally equilibrated criteria and locally provided by an agroecological landscape would reduce the land required more than 50% compared to the current diet. This could guarantee the food maintenance of population densities that could exceed 150 inhab./km^2, a much higher one than the 70 inhab./km^2 that could be locally sustained with agroecological farming and the unhealthy food intake of the study area in 2009.

Fourthly, regarding landscape *SFRA* assessment, another very important determining factor is the recovery of cultural landscapes with agro-silvo-pastoral mosaics which were not relictual but functional. The integration among different land covers within agroecological landscapes we deem would probably allow improving and keeping an important farm-associated biodiversity, which is currently endangered. This is an emerging property of cultural landscapes that could enhance more conventional biodiversity conservation strategies. Among the examples of biodiversity improvement through wildlife-friendly farming we can mention the role of open pastureland spaces for butterflies, Mediterranean orchids and certain bees. In turn, the nearby presence of pollinators becomes a vital ecosystem service to keep the metabolic sustainability of complex cultural landscapes created by organic farming running.

Finally, I have verified that maintaining a commitment to a full local supply of all food needs implies a 30% reduction in the maximum agricultural productive capacity of the territory considered, because of the need to cultivate some products under lesser optimal conditions than in other places from which they could be imported (and, conversely, the possibility of making better use of local natural resources through specialization). However, a commercial specialization aimed at maximizing production would also require a dependence on commercial flows that would represent around 40% of the total provision of the local diet, and would result in land-use configurations less resilient to agro-climatic variability, to ecological disturbances, and to market price volatility. Without more empirical data obtained at different scales, it is difficult to infer further conclusions.

The trade-sustainability nexus is a problem that remains open. Leopold Pfaundler (1839-1920) suggested a general criterion to seek a balance between the biophysical pros and cons of trade. According to his approach, the solution should be in intermediate scenarios that take advantage of the specialization opportunities offered by different allocations of natural resources in different territories, taking into account at the same time the energy costs and the ecological impacts of trade. We assessed the range in between our case study could take the most advantage on one side of self-satisfying needs an on the other the maximum degree of openness. However, it still requires further research to achieve a specific proposal through linking different agroecosystems to reach a specific result.

4. Pending puzzles and barriers to be solved in Substantive Economics

A central scientific motivation of my thesis has been to contribute to a much needed Substantive Economics, where the conceptualization and accounting of labour and natural resources becomes de-commodified. The current scientific knowledge on the causes and consequences of the ongoing ecological crisis clearly indicates that a paradigm shift is necessary. The Strong Sustainability Science owes its birth to this recognition.

My thesis has been focused on the long-term change of biophysical patterns and agroecological processes of farm systems taken as an object of analysis. However, I have often faced the limits that relate them to other areas of the economy. The impact of mechanization in extractive activities, the relationship of agriculture with water metabolism, the role of forests in energy metabolism, are examples of the intersectionality among different study areas of the economic matrix of any current society. It has been sometimes difficult, especially in the study of industrial societies, to establish the theoretical limits and spatial boundaries of the analysis. Any economic proposal that wants to succeed, in the holistic sense of the word, must be aware of this intersectionality. Yet proposals on limited dimensions and scales are also needed, so as to confront them with these set of broader interactions in a process of ascending scientific construction.

In this last section I would like to underline the theoretical contributions made to the conceptual framework of Ecological Economics, and in particular to the Social Metabolism of agriculture. I divide them into two closely related aspects: what we understand as *structuring-information* in the agroecosystems; and how we can move forward in the search for innovative political proposals to overcome current unsustainable trends.

As explained, there are no agroecosystems without human intentions behind. The work incorporated into them, as in any other productive process, always responds to a specific objective. Goals are often not decided collectively, even though they may be. We consider that this *intentionality* is what ends up structuring the agroecosystem. However, in order for agricultural systems to be truly sustainable, the structure of their network of energy flows must be both ecologically *viable* and technologically *feasible*. Therefore, from a socio-metabolic point of view the *structuring information* is nothing more and nothing less than the pattern of flows that ensures the agroecological *viability* and technical *feasibility* necessary to achieve the socially adopted objectives to make the agroecosystems functioning.

Therefore *desirability* plays a fundamental role in shaping the structure and functioning of the farm systems that we currently have, as it happens in any attempt to advance towards more sustainable agroecological landscapes. To that aim the decision-making processes of agricultural policy, rural development and land-use planning have to be democratized, and this is why I am offering new models which can be used as a guide to foresee the functioning of new desirable agroecosystems. Humbly, I see this contribution as a small further step for reaching an Ecological Economics' framework to improve participation in the design and implementation of innovative agricultural and environmental public policies.

There is a need, and also an increasing capacity to generate multi-criterial tools that facilitate these deliberative processes, to which I have contributed in this thesis mainly with the *SFRA* model. The ultimate goal is to define a new framework for economic exchange relationships. In fact, institutional systems have a controlling role in market flows. They could drive them so as to ensure that they are carried out in an ecologically and socially sustainable manner, or quite the opposite. In order to lead the economic functioning towards more sustainable scenarios –provided that democratic processes establish this priority—, the current market pricing mechanism must be turned upside down.

The dominant neoliberal approach to the way markets currently work is that prices should establish both the *desirability* and the *cash viability* of any production process that is *technically viable*. Under this predominant view of supply and demand, the only optimization considered is the one that maximizes profits through cost-benefit analysis. Every assessment is made only in terms of money, and any ensuing biophysical impact on the metabolic exchange between society and nature is considered a mere externality. Although market decisions move constantly a large amount of materials and energy flows that have strong environmental impacts, they are only taken into account according to the relative prices dictated by markets and the opportunities for profit they can offer. As a result, economic processes driven by markets are blind to any biophysical and social dimension. Once this socio-environmental blindness has already led to a global ecological crisis, it is necessary to question its inherent inability to face the long-term feasibility of decisions that are taken exclusively under market criteria.

A key point here is that markets will never provide a true democratic social validation through single-minded decisions taken by individuals isolated from each other which are only based on relative prices and profit margins. The fact that almost everyone participates in markets as price takers (leaving aside the fact that some have market power to be price makers) cannot be interpreted as if this socio-ecologically blind mechanism might solve the problem of a community-wide preference aggregation (i.e. overcoming Arrow’s impossibility theorem). Only a deliberative democratic process can do so, addressing complex multidimensional sets of the people’s real preferences.

The *SFRA* programming model allows defining which sustainable pattern of farming biophysical flows should be established between society and nature, and how the network of flows set among the agroecosystem funds should look like, to generate a specific type of cultural landscape. New reproductive economic analyses could take these results, established in biophysical terms using the *SFRA* model, to find out the relative price structure between different types of goods, and between labour and capital, required to achieve those aims adopted democratically. This would establish the conversion factors between biophysical units and market values (prices, wages and profits) that would have to be modified, and to what extent. Then, society will have to choose the appropriate economic instruments of social and environmental policy to make the desired socioecological pattern *viable* also in market value terms. Individuals would continue to be price takers, but community-wide democratic processes would become price makers to reorient economic exchanges, and the corresponding biophysical flows, towards more sustainable and fairer deals.

This sets out a path that is far from simple. However, according to our proposals and results it can be scientifically viable to make public policy proposals aimed at facilitating the necessary socioecological changes through regulatory norms, taxes, land-use planning, economic planning, public spending and investment, and other forms of state intervention. All these are forthcoming tasks for a new Substantive Economics that would no longer consider as occasional market failures the overshooting of many vital social and ecological limits at global scale. On the contrary, it will interpret them as the starting point for a new framework of socioeconomic and political relationships.

CHAPTER 9. ONGOING AND FURTHER RESEARCH

Before finishing this PhD thesis, and despite having already done so in some parts of the conclusions, I want to group here several lines for future research, some of which are already being developed. They will be presented in four different sections: i) the potential of studying structuring information and improving the *ELIA*; ii) some internal improvements on the *SFRA* model that I deem necessary; iii) the introduction of new dimensions in *SFRA* itself; and last iv) some more general lines on how to advance towards Substantive Economics. Obviously, I can only briefly present here these possibilities, prioritizing what I consider most relevant to consolidate the lines of research on which this thesis has focused on.

1. Structure-information and the ELIA graph[50]

In the first *ELIA* proposal presented in Chapter 3 we considered how the pattern of flows which circulate in an agroecosystem can be analysed considering their cyclical nature by using graph modelling. In further developments, and within the collective debate in the SFS group in Barcelona, we improved this tool through bringing in the sub-cycle of the Farming Community. In Figure 9.1[51], we can see the new graph of energy flows proposed.

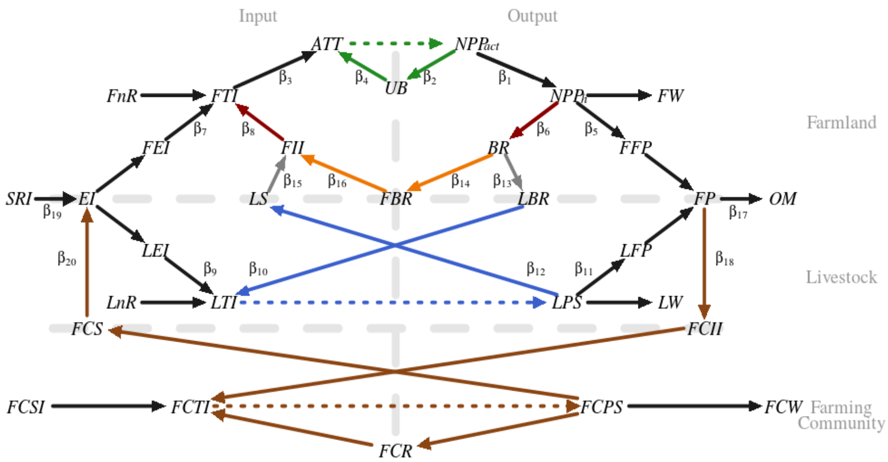

Figure 9.1. New graph model of the agroecosystem's energy flows with the Farming Community incorporated. Source: Our own.

We believe this way of characterizing the farming processes through the relationship set among funds can be very explanatory in order to highlight how agroecosystems are closer or not to the optimum distribution they may have. Thus, by comparing in traditional agrarian societies the share devoted to each subsystem, we can see if there were some type of constraints that determined stable relations among unharvested biomass and that devoted to farmland, livestock and the farming community.

[50] We are already developing this research together with Carme Font, Claudio Cattaneo, Joan Marull and Enric Tello. We have some preliminary results, which we present here.

[51] Variables: Actual Net Primary Production (NPP_{act}); Unharvested Biomass (*UB*); Harvested Net Primary Production (NPP_h); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input (*FEI*); Livestock External Input (*LEI*); Livestock Total Input (*LTI*); Livestock Produce and Services (*LPS*); Livestock Final Produce (*LFP*); Livestock Services (*LS*); Final Produce (*FP*); Agroecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*); Output Market (*OM*); Farm Community Internal Input (*FCII*); Farm Community Produce and Services (*FCPS*); Societal Renewable Inputs (*SRI*); Farm no Renewable Inputs (*FnR*); Livestock no Renewable Iputs (*LnR*); Farming Community Societal Inputs (FCSI); Farming Community Total Inputs (FCTI); Farming Community Services (FCS); Farming Community Reproduction (FCR); Farming Community Waste (FCW). β_i's are the incoming-outgoing coefficients.

Identifying these fractions for the various optimization cases proposed in Chapter 6, and the estimated flow structure of the Vallès in 1860 (Table 9.1), we observe that there is a certain distribution of flows that, although not clearly homogeneous, used to oscillate in relatively small ranges. In fact, if we compare these flow values with the proposed land-use distributions, we reach a very interesting conclusion (although still under discussion): that the differences in energy flows expressed by the Euclidean distances ranged between 0.08 and 0.25, while differences in land-uses distributions ranged from 0.29 and 0.78. We interpret this as a sustainability imperative: land-uses could be very different regarding *intentionality*, but the sustainability of the energy flows stemming in and out of them imposed that the intensity of these flows (GJ/ha) could only be limited to what an organic system would assume. In the same vein, different funds required similar investments no matter the intentionality of the farming community was. Therefore, whatever which land-use distribution existed, an organic farm system should only redistribute flows within its structure along a restricted range.

Table 9.1. Subsystems' weights and ranges in the graph c.1860. Source: Our own.

	Vallès 1860	RMU (intensive)	RPU (extensive)	MSS (cash)
Unharvested subsystem	0.387	0.255	0.286	0.271
Farmland subsystem	0.269	0.241	0.260	0.429
Livestock subsystem	0.204	0.277	0.286	0.205
Farming community subsystem	0.139	0.227	0.168	0.094

RMU: Reproduction Minimum Unit (intensive strategy); RPU: Reproduction Peasant Unit (extensive strategy); MSS: Maximum Sustainable Specialization (cash strategy).

On the other hand, in the initial *ELIA* we also proposed a first approach to the application of the information theory in the interaction between social metabolism and landscape patterns. This was the so-called *message-information*, and it was assessed using a Shannon Index on how equidistributed those flows were. This is an assumption that in research on ecological networks proved relevant in terms of setting a link with the thermodynamics and resilience of the systems (Ho and Ulanowicz, 2005; Kay et al., 2001; Ulanowicz, 2003, 2001). However, as I discussed in the theoretical development of the *SFRA* model (chapter 5), we consider that from the perspective of social metabolism, that seeks to understand the relations established between society and nature, the *structuring information* becomes more significant (Passet, 1996). We have identified this *structure-information* with the *intentionality* with which societies, or farming communities, distribute the flows in agroecosystems.

We consider that the Shannon Index applied to the graph model of energy flows, based on how equidistributed the flowing network is, should take maximum values when the distribution being accounted resembles the distribution resulting from satisfying a specific objective, *feasible* and *technically viable* and not when the equidistribution of flows is the highest. In this way, we believe that the indicator needed would give account of how the actual flow pattern resembles the one required to meet a given desirability.

This new indicator can be useful, along with the new graph, when it comes to defining possible agroecological horizons according to the objective adopted, observing the proximity of the actual configuration to the desired pattern. In addition, we could use some research done on ecological networks where several other indicators have been defined which could be relevant for inferring the ecological state of the socio-metabolic relationships assessed (Kay et al., 2001; Ulanowicz, 2001, 1997). For example, using this graph and novel indicators we will be able to introduce other aspects in the analysis of socio-metabolic profiles such as resilience to disturbances—a very relevant issue in the current situation of global environmental change.

2. Required improvements on SFRA

Although the *SFRA* model has already been improved in chapter 7, compared with the initial one used in chapter 6, I am aware that it still has to overcome some limitations. Here I list several aspects easy to introduce that would immediately improve the model without changing its fundamental structure. They were not included from the onset due to either lack of time, or because at the beginning I was not aware of their relevance.

1. *Incorporating empirically tested models in the approach of farm-associated biodiversity*. The approach to farm-associated biodiversity adopted in this thesis is only preliminary. We used the modified Shannon index for land cover equidiversity, while keeping a significant area of forest with low perturbation levels in a relatively arbitrary way. To improve this analysis more empirical-based data and indicators are needed. A research developed by the SFS Catalan Team can be key for future approaches (Marull et al., 2018). Using a model called Intermediate Disturbance Complexity Model, that uses as biodiversity predictor the modified Shannon index of land cover diversity multiplied by the HANPP (Vitousek et al., 1986), this study has found out that 58% of the total biodiversity currently observed in Catalonia is located in slightly disturbed forest areas, while 42% is associated to agro-silvo-pastoral mosaics farmed with intermediate disturbance levels. These results confirm the relevance of having areas with habitat differentiation and intermediate anthropic disturbances, together with low-disturbed natural protected areas. This is true for most taxa, with the exception of birds, which can withstand many disturbances by flying, provided they can find enough habitats and food resources. Incorporating into *SFRA* these empirically-tested model and indicators will allow improving the assessment of the material conditions for farm-associated biodiversity, beyond the simpler preliminary hypothesis used so far. Likewise, we should also differentiate among various forest covers so as not to underestimate their role in biodiversity maintenance.

2. *Contribute to the debate on the mechanization of agricultural activities*. So far we considered the mechanization of agricultural activities as something given, for which I have estimated in all scenarios similar labour intensities to the current ones. However, in order to have more realistic parameters we should modify this assumption by considering the different energy costs that exist in conventional management and in ecological farms. In addition, we could also estimate the cost of returning to animal traction in a post-peak oil scenario. Introducing into the model all these details and additional options will bring about new scenarios for a better deliberation.

3. *Analyse the potential contribution of forest biomass to energy metabolism*. The potential of forest biomass as an energy source could currently cover 9% of all energetic requirements of Catalonia (Codina and Koua, 2015; FAO, 2013; Institut Català de l'Energia, 2009). We can contribute to the debate on how to make a sustainable use of this resource by running new scenarios with differential consumption patterns of this biomass, considering as a socio-metabolic tension the competition between different land-uses in agricultural and forestry activities, and the ensuing trade-offs among their positive and negative environmental impacts.

4. *The links between agroecological landscapes, water metabolism and the emission of greenhouse gases (GHG).* These two very important sides of the current ecological crisis are not unrelated to the other dimensions considered so far, and can be linked with *ELIA* and *SFRA* models. We have made a very rough estimation for water uses in the prospective scenarios considered so far. GHG emissions have not been considered yet. Establishing

these links, and doing it in a more robust manner, are still pending tasks to be done in further *SFRA* studies. For both water balances and GHG emissions there are already clear methodologies to be applied, which we could introduce into our model (Aguilera et al., 2015; Madrid-López and Giampietro, 2015). While their intersectionality with the rest of sectors in the economic matrix is clear, we can also study them alone and see if the scenario obtained means an improvement or a worsening from the starting conditions. Likewise, we can set goals based on relative restrictions (e.g. reducing GHG of agriculture by 30%, according to criteria defined by global agreements to face Climate Change).

5. *Modelling the dynamics of the agroecosystem throughout the year*: This is something we have already introduced in the *SFRA* model for 1860, only in terms of labour, and that proved not difficult to do. We believe that it would be necessary, in addition of doing this for labour, to consider the seasonal availability of agricultural products in order to avoid overestimating the feed capacity of the agroecosystem. Especially for ruminants, which depend on pastureland, this seasonal check is very important.

3. New dimensions to consider for an SFRA as a useful tool for deliberative processes

Next we propose a second block of improvements that will affect the general structure of the model. Despite being more difficult, we believe that these changes can bring significant refinements when using *SFRA* modelling in deliberation processes of decision making. These advances would lead to a more versatile and more applicable *SFRA* model as well.

3.1 The unit of analysis

The scale of analysis used remains a general issue. In the first approach carried out c.1860, the analysis was based on the reproductive characteristics of the farm unit, while in the model of the year 2009 we have expanded its scope at landscape scale. However, taking into account the limitation of sources and the role of the Vallès case as our test bench, we have applied the *SFRA* model always keeping the four municipalities as a basic unit of analysis.

The *SFRA* is a socio-ecological model, not just agronomic or bioregional. In our view, the commitment to keep as unit of analysis water basins, certain topographic units or bioregions depending on the biotic composition only makes sense when they are representative of historical cultural interactions (Dodge, 1990). Therefore, from a socioeconomic point of view it is necessary to identify an appropriate agroecosystem scale that keeps a certain consistency in bioregional terms.

In this regard deeper studies and methodologies are needed, among them the proposal of considering ‘foodsheds’ as units of analysis stands out. These, however, tend to circumscribe the regions under study simply based on proximity to large cities or macro-regions (Desjardins et al., 2010; Meier and Christen, 2013; Peters et al., 2012; Van Kernebeek et al., 2016). In order to be able to maintain a suitable landscape scale where the closure of the majority of metabolic cycles would be feasible, and to maintain certain coherence from a socioeconomic perspective, we deem that we should not use larger areas of study such as whole provinces or autonomous regions within the Spanish state. For instance, to make comparable case studies larger than those we have adopted (for example, Catalonia), we should have to distinguish among several bioregions that exist from a socioecological and socioeconomic point of view, in order to compare them one a another and later extend the analysis to the entire area considered.

In the meantime what could be done is to introduce new, different scales. In the case of food flows, it would be consistent to analyse them at the scale of the whole agrifood chain.

However, at least in the current circumstances the closure of metabolic cycles may require a different scale of analysis, and the study of landscape patterns another one. Following the multi-scalar operation logic that MuSIASEM enables (Giampietro et al., 2013), we could define restrictions that only affect certain scales. This would be possible by using hierarchical optimizations (Zeigler et al., 2000).

3.2 Defining possible spatially explicit scenarios

Precisely the same tool mentioned in the previous section, hierarchical optimization, would allow to solve the problem of going beyond a single scale, with the possibility of having results spatially explicit. This is something that I started to test, but that due to lack of time I was unable to present in the thesis. I defined several internal cells within the analysed region (Figure 9.2) distributed according to proximity to urban areas. This would allow, after the non-linear optimization was carried out, a second hierarchical optimization of the possible distribution of the resulting land-uses.

Moreover, in order to be able to model how the landscape would look like, we could make use of cellular automata programming in this second optimization, which in land-use planning is a useful tool to foresee the outcome of a likely evolution of land covers (White et al., 1997).

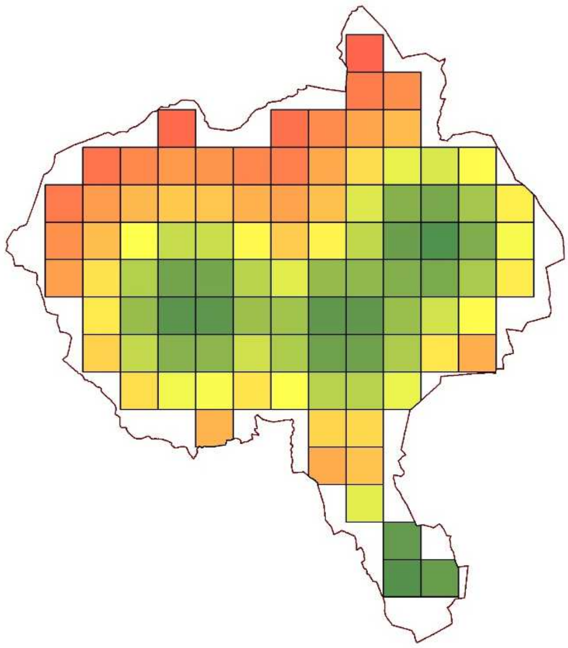

Figure 9.2. Cells distribution for hierarchical optimization on land-use distribution for the Vallès case study. Source: Our own.

3.3 Optimization can be done in many ways

A fact that we have remarked very often in this last part of this PhD thesis is the relevance of what I called *desirability*. This is not a mantra, but a firm conviction that this is key starting point to define a transition towards agroecological landscapes through participative-deliberative decision making processes.

In the cases applied so far we used simple optimization functions in which the objective was just one in each scenario. However, it must be borne in mind that from a community-wide or societal point of view there can be multiple objectives at stake. Therefore, in a deliberation process it is possible that people's decisions would consider multiple goals. Thus, multicriteria analysis is needed to carry out weighted optimization functions, which would end up resulting in landscapes that meet multiple objectives at the same time.

In addition, in the future we should deepen on which criteria we run the scenarios aimed at maximization of production. In Chapter 7 we assumed the metabolizable energy as a good proxy of the use value of food. Yet, as already said, this is something that remains open to be politically debated and scientifically deepened.

3.4 Network theory to connect agroecosystems

Last, in this thesis we have not been able to propose a solution to Pfaundler's dilemma on the socioecological balance between globalized trade and autarky. However, we state our support in favour of network theory applied to food systems as a possible further step towards connecting agroecosystems (Born and Purcell, 2006; Kneafsey et al., 2001). If multiple studies are available for different nearby agroecosystems, the next step will be to connect the nodes to see how from an aggregate standpoint we would be able to meet people's needs. The ultimate aim would be ensuring in this way the sustainability of the agroecosystems, while avoiding falling into local socioecological traps.

4. Advancing towards Substantive Economics

In the conclusions I raised a possible path for Strong Sustainability Science of agricultural systems, in order to lay the foundations for a Substantive Economics. However, the path of research is very long. As shown, the difficulties of the proposals made in this chapter have been growing section to section. Knowing that there lies a long road ahead, I believe it is necessary to mark certain goals that would require new scientific evidence as well as ample social deliberation.

If throughout this process we finally obtain a solid and robust SFRA, connecting the different scales of agroecosystems, the following steps to be considered towards the desired direction are two: i) to face the impact of all forms of societal inequality; and ii) to move from modelling scenarios to propose public policies through the analysis of market flows in money terms.

If we do not ground the analysis at the scale of farm units, and we do not take into consideration who owns the means of production (i.e. agricultural funds in socio-metabolic terms), we cannot see how the intangible metabolism affects the material functioning of agroecological landscapes. The societal blindness of our modelling would prevent us from taking into account how inequality would affect the future scenarios devised for a new socioecological transition. I consider that this is also a key factor for defining planning strategies towards sustainability, which ought to be tightly linked to social equity. A small step in this direction would be analysing current landownership distributions, to see if they hamper or facilitate the eco-functionality of the proposed prospective scenarios. In this regard, certain research currently being developed within the SFS group of Barcelona, led by Inés Marco, establishes solid methodologies and coherent empirical comparative data that allow to evaluate the impact of inequality by linking socio-metabolic and reproductive approaches (Marco et al., forthcoming). However, they have only been applied to past advanced organic agricultures so far.

In addition, we find in these novel researches that link socio-metabolic and socioeconomic inequalities a key to advance towards novel forms of economic valuation in a new Substantive Economics. Through the analysis of relative prices and subsistence prices proposed by these investigations, we could open a workable path from a reproductive Sraffian perspective to a definition of possible public policies that mitigate these impacts and facilitate the transition to more sustainable fairer future.

As we have said, we still cannot fully apply these new steps empirically. But we believe that there exists certain methodological basis to do so; and that, by going ahead in this research, they could provide helpful tools to contribute to address the current global ecological crisis. This is something that is becoming more necessary every day.

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ANNEX I. ASSUMPTIONS AND SOURCES FOR ENERGY BALANCES CONSTRUCTION

In this annex, we present the main assumptions, estimations and sources for the energy balances used in chapters 2, 3 and 4. We follow the hierarchial procedure explained in chapter 2 of the "*forced local fund sustainability assumption*" (sections 4.1 and 4.2). For this, we depart of the total produce estimates. Then, we calculate the biomass reused through the feed and nutrient balances for livestock and soil fertility respectively, and finally we estimate the external inputs, regarding the historical context and information from sources.

1. Total Produce estimates

1.1 Land Produce

Crop yields are taken from local sources (IACSI, 1879, Garrabou and Planas, 1998) and provincial averages (MAGRAMA Statistical Yearbook using an average between 1954 and 1958), and county and provincial averages for the latest period (INE, 1999). Water content and GCV are taken from Guzmán et al. (2014), except for hemp (Sacilik et al. 2003), vetches (Mansourifar et al., 2013) and grape juice (analysis made by Xavier Remesar and Mar Grasa in the Labouratory of the Department of Nutrition and Food Science; at the Faculty of Biology of the University of Barcelona).

By-product yields are taken from local or provincial sources when available (mainly grain straw and vine pruning). When date was unavailable, we used several complementary sources. For vegetable by-product yields, we used Guzmán et al. (2014); for fresh fruits and nuts pruning, Bilandzija et al. (2012); for cereal husk and stubble, Kernan et al. (1984); for hemp, Mutjé et al. (2008); for corn, beans, potatoes, vetches and lupins by-products, Unal and Alibas (2007); for rape and turnip seed by-products, Vázquez de Aldana et al. (2011); for olive tree by-products, Infante and Parcerisas (2013); for vine leaves, Kok et al. (2007); for grapevine pomace, Kavargiris et al. (2009). We used our own estimates for olive tree and strain replacements c.1860. For olive trees we estimated 400 kg per tree, 100 trees per hectare and a 300-year lifespan. For vineyards, we estimated 22 kg per vine, 3,000 vines per hectare and a 60year lifespan (Colomé, 2015). Water content and GCV were taken from Haberl (1995), except for water content of corn stalks and cobs (Lu et al., 2006), olive tree pruning water content (Carone et al., 2011) and GCV (Porceddu et al., 2010).

Table A1.1. Main Products, Yields, Water content and GCV (1860, 1956, 1999). Sources: Our own, adapted from sources quoted in the text.

	Main Products	Yields (kg/ha)			Water content (%)	GCV (MJ/kg)
		1860	1956	1999		
gardens	Vegetables	5,239	16,422	23,459	92.0	18.7
gardens	Fresh fruits	4,148	3,004	6,892	84.8	20.1
gardens	Nuts	525	-	1,250	4.4	25.0
irrigated	Wheat	1,146	2,549	5,907	14.0	18.3
irrigated	Barley	-	-	4,960	14.0	18.2
irrigated	Corn	1,093	2,431	-	14.0	18.5
irrigated	Hemp	1,199	-	-	7.9	17.6
irrigated	Potatoes	-	-	23,397	78.0	16.8
irrigated	Fodder	-	-	56,848	79.8	18.5
irrigated	Beans	951	1,127	-	15.0	18.0
rainfed	Wheat	1,109	1,231	2,795	14.0	18.3
rainfed	Associated Wheat*	1,017	-	-	14.0	18.3
rainfed	Corn	512	910	-	14.0	18.5
rainfed	Rye & Wheat mixture	736	-	-	14.0	18.1
rainfed	Rye& Oat mixture	-	1,188	-	14.0	18.1
rainfed	Barley	527	1,382	2,296	14.0	18.2
rainfed	Oat	-	-	1,752	14.0	18.8
rainfed	Fodder	6,754	-	16,479	66.7	18.5
rainfed	Potatoes	1,543	6,472	8,518	78.0	16.8
rainfed	Beans	731	406	-	15.0	18.0
rainfed	Vetches	798	-	-	80.0	20.7
rainfed	Lupins	658	-	-	14.0	20.7
rainfed	Legumes for feed	-	-	798	80.0	16.8
rainfed	Rape and Turnip seeds	-	-	2,700	78.0	26.7
woody crops	Olive oil	186	192	270	0.0	39.7
woody crops	Grape juice	1,164	3,779	6,355	83.1	17.2

* Associated wheat refers to wheat crops combined with others in the same land, in particular permanent crops like olive trees, along trees or vineyards.

Table A1.2. By-products: Yields, Water content and GCV (1860, 1956, 1999). Source: Our own, adapted from sources quoted in the text.

By-products			Yields (kg/ha) 1860	1956	1999	Water content (%)	GCV (MJ/kg)
gardens	Vegetables	Leaves, stems, straws & weeds	5,342	16,641	23,771	88.0	18.0
	Fresh fruits	Fresh tree pruning	1,170	1,170	2,879	6.5	17.1
		Tree replacement	625	625	4,133	30.0	17.1
	Nuts	Fresh tree pruning	1,170	1,170	1,779	6.5	17.1
		Tree replacement	625	625	2,938	30.0	17.1
irrigated	Wheat	Straw	1,798	2,973	6,492	14.0	17.8
		Husk	504	1,121	2,599	14.0	17.8
		Stubble	83	184	427	14.0	17.8
	Barley	Straw	-	-	4,816	14.0	18.2
		Husk	-	-	2,182	14.0	18.2
		Stubble	-	-	359	14.0	18.2
	Corn	Stalks & Cobs	1,672	3,720	-	7.9	17.1
	Hemp strains	Hurds & shives	1,354	-	-	10.0	17.6
	Potatoes	Stems & Leaves	-	-	3,833	92.0	18.0
	Beans	Bean straw	1,379	2,273	-	85.5	17.0
rainfed	Wheat	Straw	1,783	2,705	3,072	14.0	17.8
		Husk	500	541	1,230	14.0	17.8
		Stubble	82	89	202	14.0	17.8
	Associated Wheat	Straw	1,147	-	-	14.0	17.8
		Husk	321	-	-	14.0	17.8
		Stubble	53	-	-	14.0	17.8
	Corn	Stalks & Cobs	783	1,392	-	7.9	17.1
	Rye & wheat mixture	Straw	1,154	-	-	14.0	18.1
		Husk	324	-	-	14.0	18.1
		Stubble	53	-	-	14.0	18.1
	Rye & oat mixture	Straw	-	3,362	-	14.0	18.1
		Husk	-	522	-	14.0	18.1
		Stubble	-	86	-	14.0	18.1
	Barley	Straw	826	3,022	2,230	14.0	18.2
		Husk	232	608	1,010	14.0	18.2
		Stubble	38	99	166	14.0	18.2
	Oat	Straw	-	-	1,596	14.0	18.0
		Husk	-	-	771	14.0	18.0
		Stubble	-	-	127	14.0	18.0
	Potatoes	Stems & Leaves	784	2,912	3,833	92.0	18.0
	Beans	Bean straw	4,503	649	-	80.0	17.0
	Vetches	Vetches straw	593	-	-	80.0	17.0
	Lupins	Lupins straw	4,101	-	-	80.0	17.0
	Legumes for feed	Legume's straw	-	-	1,157	85.5	17.0
	Rape and Turnip seeds	Rape Straw	-	-	13,500	5.9	19.3
woody crops	Olive trees	Olive tree pruning	1,628	372	2,524	29.2	19.6
		Olive tree browsing	543	113	-	28.0	19.6
		Tree replacement	133	133	1,779	29.2	19.6
		Olive oil pomace	822	94	1,192	40.2	22.0
	Vineyards	Vine pruning	1,342	564	4,255	40.9	18.8
		Strain replacement	1,100	1,100	840	40.9	18.8
		Vine leaves	1,250	1,250	-	60.6	19.0
		Grapevine pomace	496	1,024	496	59.4	21.8

We estimated forest and pasture produce through different sources, because it has not been possible to find reliable historical sources. In order to reduce uncertainty, we adopted the mentioned criteria of sustainable extractions (chapter 2). First, using MIRABOSC data (CREAF, 2007) we identified the average productivity of a forest depending on its main species composition. For 1860, and considering the qualitative information from historical sources (Garrabou and Planas 1998), we assumed that extraction was equal to productivity, because the pressure on forests was very high due to domestic firewood consumption and charcoal making. Conversely, we know that in 1956 and 1999, because of the energy and forest transition, the use of firewood and wood for construction declined dramatically. For 1956, we used the average between statistical data on provincial extraction (average 1954-1958), and a value found in the Historical Archive of the Vallès County for 1956. For 1999, we used data from provincial extraction (MAGRAMA 2009), assuming a similar pressure on forest resources in the Vallès area for each dominant species. Finally, regarding grazing extraction, as will be highlighted in further sections, what matters is to have a livestock density below the maximum allowed, given the pasture productivity available. So we depart from a potential maximum productivity of 900 kg dm/ha (Olea and Miguel-Ayanz, 2006), and we then check that not all of it is consumed.

1.2 Livestock Produce

We estimated animal produce per animal c.1860 using Cussó et al. (2006). We re-estimated wool productivity data (1.5 kg per unit/year), and goat milk productivity (0.94 liters per day during 3 months) from local sources (IACSI 1879). For 1956, we considered animal produce per head equal to that of c.1860, although milk and eggs produce per head came from the Agricultural Census (MAGRAMA, 1963) where provincial data was available. For 1999, the Agricultural Census includes detailed information about livestock composition. Given that in an industrial breeding system most animals lived less than one year, we included an animal feeding life cycle analysis to estimate feeding demand and livestock productivity over one year. For that purpose, we considered the reproductive cycle of each species (fertility ages and period, number of broods in a year). To estimate how many were sacrificed in each age group, and the slaughter weight per animal, we consulted the Slaughter Survey 2004, with provincial data, and maintained the criteria of livestock reproduction (a number of individuals from younger stages should be kept from slaughter to replace older ones). For dairy cows, we estimated a produce of 7,198 liters/head/year (García and Larrull, 2001). We considered that sheep and goat milk was consumed by suckling lamb and kids, and therefore did not end up as produce milk for human consumption. We took the number of eggs per hen (261) from Catalan sources (García and Larrull 2001), and egg weight (60 gr) from the Annual report of the agri-food industry in Catalonia (Generalitat de Catalunya, 2000). Water content and GCV were taken from Haberl (1995).

2. Agricultural Inputs: Biomass Reused and External Inputs

The share of the total biomass produced in the agroecosystem that was reused within its borders was also calculated assuming the *forced local fund sustainability assumption*. Accordingly, we first estimated the biomass reused for livestock feeding and then the corresponding one used for closing nitrogen cycle in cultivated soils.

2.1 Biomass Reused

2.1.1 *Livestock-Barnyard Biomass Reused*

Accurately accounting how livestock were or were not properly fed is relevant in order not to overestimate the external flows of animal husbandry. We based our methodology on a simple bottom-up model from animal feed requirements to the dung composition, assuming maximum efficiency on feeding and taking into account the several losses among the processes due to bioconversion and decomposition. From livestock-barnyard data, we calculated feed requirements in accordance with the main activity and age of each type of animal. Energy requirements were estimated from Church (1984) or from several reports written by the National

Research Council of the USA but also checking for 1860 with consumption rations proposed in IACSI (1879). The next step was to define feed sources, their contribution in terms of metabolic energy and, when they had to be provided from local sources, their availability. In past organic systems, and still during the mid-twentieth century, diet was adapted to a variety of available sources (i.e. grain, forages, crop by-products), while current consumption is adapted to planned diets based mainly on grains. We used only some physiological limitations considering historical and current data on organic livestock breeding. For instance, for certain feed typologies (i.e. alfalfa hay), no more than the maximum share could be included in their diets. As well, animals did not all consume the same type of feed (i.e. feeding cows with acorns made no cultural sense). On the other hand, current feeding includes other typologies which have to be imported from abroad, which we estimated from Flores and Rodríguez-Ventura (2014). There is few information on current feed rations. However, after checking those proposals with average apparent consumption and regional reports we deem they are fairly confident to the actual ones (Babot et al., 2011; Seguí et al., 2012). First, we allocated all the sources from the agroecosystem that could be supplied, under the maximum allowed for nutritional criterion from FEDNA (2010). If this animal feed was not enough for locally supply it or was no produced within the agroecosystem, energy in transport was considered. We calculated the national average apparent consumption of each product, the region or country of origin, the distance from its main commercial harbour and, depending on the type of transport, an assumed energy expenditure in terms of GJ/t·km following Pérez Martínez and Monzón (2008). The embodied energy of feed also includes energy consumption for its processing (Cooperativas Agro-alimentarias 2010). Besides ensuring the endosomatic requirements of metabolic energy, livestock maintenance also required other biomass and energy flows. In organic agriculture this was mainly stall bedding, estimated from Cascón (1918) and Soroa (1953).

Then, in order to assign the different feed sources in historical balances (c.1860 and 1956), we follow a cascade top-down process: we first allocate the better feed available for each type of livestock prioritizing working animals over the rest. Then we follow filling the animal feed ratios resorting to the resources of lower nutritional quality up to the quantities needed according to the live weight and number of heads. Before taking a decision, we check that the resulting mix became nutritionally equilibrated, and palatable.

2.1.2 *Soil Nutrient Balance*

In order to carry the soil nutrient balance, we only focused in Nitrogen (N) as a first approach. In further analysis (chapters 6 and 7), we will include Phosphorus (P) and Potassium (K) as they are also key as macronutrients for the sustainability of agricultural activities. Also, based on a previous studio done c. 1860 in the same area by Tello et al. (2012), N presented an estimated imbalance of 6.8%, while K imbalance was 6.3% and P seemed to present some surplus. Therefore, we deem that it was key at least to asses in this first approach the N.

A general framework on how to estimate nutrient balances in historical perspective can be found in González de Molina et al. (2010). We estimated N extracted through harvesting by taking the N composition of all the products and by-products given by Soroa (1953), CESNID (2003), Mataix (2002) and Moreiras-Valera et al. (1997). We estimated potential looses of soil N for basal denitrification, denitrification associated to organic and inorganic amedments, leaching, athmospheric deposition and non symbiotic fixation (Hofstra and Bouwman, 2005; Galloway et al., 1994; Holland et al., 1999; IPCC, 2006b; Junta Consultiva Agronómica, 1916; Loomis and Connor, 1992; Gathumbi et al., 2002; Wichern et al., 2008; Tello et al., 2012). The anthropogenic ones are related to seeds and irrigation. Data on irrigation without pumping is taken from the Junta Consultiva Agronómica (1919) and, after the introduction of fuel motors, we estimated through water balances. We carried out this balance using sources on rainfall and evapotranspiration (Gázquez, 2005) and crop coefficients of water consumption (Allen et al., 2006).

From this pre-balance we obtained the total needs in N as an annual average. These are the requirements for fertilization that must be satisfied through fertilization practices. In terms of fertilizing practices, first we identified different nutrient sources and their contemporary importance. After the Green Revolution, the main source is synthetic fertilizer, although organic amendments still played a role. In past organic or mixed industrial-organic farming, the most common fertilizer was livestock manure, which we estimated due to the scant historical data available. Based on the modelled animal diet, we performed a mass balance to estimate the total amount of dry excretes and check them with historical sources (IACSI, 1879). The difference between the Gross Calorific Value (GCV) and the Metabolic Energy (ME) accounts for all the energy excreted either as solid droppings, or methane emissions due to enteric fermentation (IPCC, 2006a). For the N composition of excreta we also made a balance between the estimated consumption and taking into account the part that is upkeep or lost through bioconversion process (Brito et al., 2006; IPCC, 2006; Jørgensen et al., 2013; Kohn et al., 2005), checking the results with current and historical sources. For current data we check data with ASAE (2000).

However, not all the excreta was available for fertilization, so we deducted the losses due to collection factors according to Cascón (1918) data. Then we included losses during the composting process based on IPCC data (2006b), while weight losses come from Michel et al. (2004). We also included humanure, since we know it was highly valued in Catalonia used until the end of the 19th century (Tello et al., 2012), calculated through Gotaas (1956). There were also other organic amendments in 1860 that did not come from animals or humans, like burying vegetal crop by-products which we also consider.

Once all N sources and requirements are known, we established how N demand was met through a hierarchical process, starting from the most reliable sources and ending with the most uncertain ones. Inorganic fertilizers, if they existed, were the first to be accounted, followed by manure and humanure and finally the inclusion of re-ploughed biomass. In the second and third time points, burying biomass was still a fertilizing method used, together with manure or dung slurry application. Although the results of nutrient balances are not explicitly analyzed, this process has been necessary to calculate the required *Farmland Biomass Reused* (*FBR*) expressed in energy values.

Before finishing this analysis on the soil nutrient balances, we want to notice another relevant source of *Farmland Biomass Reused*. Circa 1860, historical sources give notice of another kind of relevant practices called at the time *formiguers* in Catalan (a series of small charcoal kilns burnt and then incorporated into the soil). We could not integrate them into the Nitrogen balances, because of its null contribution in terms of N. Yet they were strongly appreciated probably due to its weed-killing and disinfectant effect on the soil cover, and by also incorporating some P and K through ashes among other beneficious effects (Olarieta et al., 2011). We deem this practice was mainly done due to scarcity of other fertilizing sources (Garrabou and Planas, 1998; Mestre and Mestres, 1949). After finding that there was fairly enough N for closing this nutrient cycle at farm community aggregate level, we consider likely that it would had been not necessary to rely significantly on these *formiguers.* It is important to keep in mind that, because of the '*forced local fund sustainability assumption*', here we are assessing the most optimal situation for this balance. However scarcity of fertilizing biomass at farm level could make *formiguers* much more necessary in farms lacking better options. Therefore, variations of *formiguers*' requirements cannot be observed unless research is undertaken at household level. As no quantitative data is available in the area, we used a rough estimation following some of the assumptions made in Tello et al., (2012) according to which a quarter of the available biomass in woodland and scrubland was used in this way, given that this amount was not competing with firewood needed as a fuel at home or as charcoal.

2.2 External Inputs

External Inputs include very different typologies of energy flows coming from outside the agroecosystem. They can either come from the farming community or from the rest of society.

2.2.1 *Farming Community Inputs*

This is the labour that farming community puts into the agroecosystem. Although it represents a small share of the total energy throughput, labour has a great effect on the way the agroecosystem is managed and the landscape appears. Humanure and domestic residues are the other category of farm community input that were relevant in the first two data points.

2.2.1.1 Labour

We deduced the agricultural population from the Population Register (1860) and Agricultural Censuses (1956 and 1999). Pluriactivity of rural family members (including manufacturing) and flexibility of household structures c.1860 and 1956 made it difficult to determine a reliable agriculture population. We corrected the official data through an estimation of the required population to reproduce the agroecosystem. This estimation was based on the required working days per hectare of cropland, distinguishing among different crops, woodland and livestock densities (IACSI 1879, Garrabou and Planas 1998).

In accordance to the *SFS* international research project, we proposed a mixed methodology for assessing Labour Energy Flows (Tello et al. 2015) that includes endosomatic and exosomatic energy accountancy (Lotka 1956) based on the 'total energy of food metabolized while working' (Fluck 1992). This methodology starts by calculating the Gross Calorific Value (GCV) of the dietary intake of male adults within an average food basket consumption c.1860 taken from local historical research done by Cussó and Garrabou (2001, 2007, 2012), and other authors (Colomé 1996; Nicolau and Pujol 2005). For 1956 and 1999, we took statistical data from the average Catalan food consumption (INE 1969; DARP 1998). Details on diet changes are specified in chapter 4. Over this period, total endosomatic energy intake per person has been stable at between 12 and 13 MJ/labourer/day. We calculated the total energy content of food intake by taking into account the hours worked (a yearly average of 8 hours a day) and the intensity of the activities related to agricultural tasks and other human activities (coefficients that range from 1 for sleeping to 7 for more intense agricultural tasks). This reduced the yearly energy content of human labour to 7 to 9 MJ/labourer/day for 240 days of work.

This energy accountancy of labour is consistent with the farmer standpoint adopted, and avoids treating peasants as livestock or slaves who were only fed to work. This approach makes the accountancy sensitive to farmers' time allocation among labour, other non-agricultural tasks, domestic chores and leisure. Shifting the sustainability assessment from this local farm system scale to a wider societal scope would entail adopting a wider reproductive accounting to include all energy requirements by all members of this local community, whether agriculturally active or not (Tello et al. 2015).

We included the embodied energy of these food baskets when some of their ingredients came from outside the local community. We used national averages for international food trade. We obtained the percentage of imports over apparent consumption for each product from the Statistical Yearbook of MAGRAMA, which provides information about domestic production, imports and exports, other uses, and apparent (human) consumption. Data on the proportion of each type of transport used (maritime, railroad, road and air transport), and energy consumption associated to each type of freight was calculated according to Pérez Neira et al. (2014) and Simón et al. (2014). Then we made an assessment of embodied energy that included the expenditure of internal transports and the energy spent in packaging-processing, retail outlets and preservation and preparation of food at home. For that aim we relied on the estimates of the Spanish agri-food system in the 1950s and the 2000s (Infante-Amate and González de Molina 2013; Infante-Amate et al. 2014). Including the embodied energy of diets, changes to the embodied energy of Labour remained stable during the period (3,610-4,350-3,176 GJ respectively), although the number of labourers declined (2,057-1,154-250 people). Labour energy flow rose from 1.8 GJ per labourer c.1860, to 3.8 and 12.8.

2.2.1.2 Domestic residues and humanure

Farmers used organic household residues and human excreta to close nutrient cycles before the Green Revolution. Farmers fed organic household residues to livestock, which we estimated using average production of residues from the non-edible part of diets (Farran et al., 2004) and applied this to the entire population of the case study area. For the 1999 time point, this flow was not considered, because livestock were fed in feedlots and domestic animals had disappeared from households.

Humanure is a source of nutrients for the soil. In 1860 and 1956, prior to the introduction of water closets in all households, humanure was composted together with animal dung and was mainly applied to vegetable gardens. It has not been accounted for the 1999 time point. The recovered share of human excreta was estimated from the part of the agrarian population, applying the information available in Gootas (1956).

2.2.2 *Agroecosystem Societal Inputs (ASI)*

The flows coming from the rest of society were of a very different nature. We have accounted for five different categories of flows: seeds, feed, machinery, synthetic fertilizers/biocides and direct energy consumption. All of these flows are the result of the Green Revolution, and appear for the first time in the 1956 data point. Circa 1860 for sure there were some flows from society towards the agroecosystem as tools, but we did not approach them as we considered them as a minor flow.

We estimated the seed imported in or 1956 as the difference between total seed requirements in the case study area and the estimated productivity of local seed-oriented farms (using information derived from the 1962 census for the Barcelona province). In 1956, feed imports were still at a minimum, but they rapidly grew thereinafter. With data only available at the Spanish level, we estimated an average of 34kg/LU500/yr in 1956 (which would reach nearly 300kg/LU500/yr only seven years later). Although there were still pastures and cropland residues in excess with respect to the livestock available, we did not include them. Had we decided to include them, the energy balance would not have changed, since feed imports constituted only 68GJ, that is 0.09% of the External Inputs). Section 2.1.1 shows how they have been calculated for the 1999 time point.

For 1956, we extrapolated the machinery available and the fertilizer and biocide used from the 1962 provincial census. We have calculated the machinery and fertilizer/biocide use per area of cropland, and adapted it to the case study cropland area. Since the conditions in 1956, at the beginning of the Green Revolution, were quite different from those in 1962, we determined the annual growth rate of these external inputs from the Agriculture Ministry sources (Ministerio de Agricultura 1954, 1959 and 1963). We obtained data on the existing machinery in the four municipalities studied from the 1999 Agricultural Census, which shows machines owned exclusively by farms. Information from the 1999 Agricultural Census provides the number of seeders, trailers, fertilizers distribution tanks and fertilizer centrifuges. In addition, each tractor includes a cultivator, a harrow and a roller. For direct fuel consumption and embodied energy in machinery, fertilizers and biocides we used Aguilera et al. (2015).

To estimate fertilizer applications c.1999 we used the standards proposed by the Ministry of the Environment and Rural and Marine Affairs (García Serrano et al. 2010) and regional sources on total consumption from census (INE, 1999). Considering that fertilization depends on the yield level, we adapted the ratios proposed to the crop yields of our case study. For vineyards we used the Guide to Good Agricultural Practice for wine exploitations.

Direct energy consumption included pumping for irrigation (1956 and 1999 data points) and infrastructure heating for livestock husbandry (1999 data point only). For 1956, we applied an irrigation energy input of 0.5 GJ/ha/year based on Aguilera et al. (2015). For 1999, we calculated a water balance using system efficiency on water distribution (ACA 2014), and information on the share of different distribution systems of water (INE 2000), in order to obtain the total water consumption. Using data on energy consumption for water disposal on agriculture (Hardy et al. 2012) and the energy efficiency from primary energy to electricity (Barracó et al. 1999), we estimated the total embodied energy for irrigation.

Finally, energy use increased with livestock in feedlots and the diffusion of new varieties unsuited to some climatic conditions, whether from fuel or electricity. We used energy studies from different species of livestock (as the breeding conditions vary a great deal across animal typologies). For pigs, we used Lavola (2008); for cows and cattle, Bartolomé et al. (2011) and Irimia et al. (2012); for sheep and goats, Gil and del Pino (2011); for hens, broilers and other poultry, Fundacion Entorno (2006). We transformed these energy values into primary energy demand using conversion and efficiency factors from Barracó et al. (1999), and added the embodied energy for transport used (Pérez and Monzón 2008) weighted by the provenance of oil (FECYT 2002).

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ANNEX II. LINEAR OPTIMIZATION PROGRAMME OF THE SFRA c.1860

We present below the complete linear optimization programme used in chapter 6. To this end, first we draw on the main variables that define the size of the farm. Then we explain the assumptions and boundary conditions of the three funds considered: Domestic Unit (DU), livestock and soil. Subsequently, we specify the constraints given by biophysical conditions as well as cultural factors, presenting them according to the fund they correspond to. Finally, the objective functions are shown in the fourth section.

The time frame considered to run the programme is a whole year. This does not contradict a dynamic view of the agroecosystem functioning. Farmers' decisions are ever changing over time, and so do the natural processes they are coproducing with. Hence, flow interactions among these funds will be different from one year to another. The data taken to specify the variables, parameters and constrains of the linear programming model are average values that usually averaged the oscillations of the last five years. Yet, in order to ensure sustainability for the years to come the needs of these funds had to be met within those average values of the annual flows considered.

1. Main variables

Initially, we define one variable for each potential land-use registered in the *Estudio Agrícola del Vallès* of 1874 (Garrabou and Planas, 1998). Thus, we begin with the 22 variables presented in Table A2.1. This table also includes the soil quality in which each crop or land-use grew. To facilitate the interpretation of the results, instead of presenting 22 variables in the text we used crop rotations. We classified these 22 variables into seven groups: vegetables and fruits (gardens and orchards), irrigated rotation, rain-fed herbaceous rotation, rotation with dryland olive groves, vineyards, pasture and forest.

Table A2.1. Main variables. Source: Our own.

	Land-use	**Variable**	**Soil Quality 1**	**2**	**3**
Vegetable gardens	Vegetables	X_1	■		
	Fresh fruits	X_2	■		
	Nuts	X_3	■		
Irrigated	Wheat	X_4	■	■	■
	Corn	X_5	■	■	■
	Hemp	X_6	■	■	■
	Beans	X_7	■	■	■
Rain-fed annual crops	Wheat	X_8	■	■	
	Associated wheat	X_9	■		
	Corn	X_{10}		■	
	Rye & wheat mixture	X_{11}		■	■
	Barley	X_{12}			■
	Fodder	X_{13}		■	
	Potatoes	X_{14}	■	■	
	Beans	X_{15}	■		
	Vetches	X_{16}			■
	Lupines	X_{17}			■
Wood crops	Olive oil	X_{18}	■	■	■
	Grape juice	X_{19}	■	■	■
Other uses	Fallow	X_{20}	■	■	■
	Pasture	X_{21}	■	■	■
	Forest	X_{22}	■	■	■

.

Obviously, for these and for all the defined variables we set their limits, as all of them must be positive numbers as indicated in Eq.1.

$$X_i \geq 0 \text{ (Eq. 1)}$$

2. Funds and boundary conditions

Once the main variables are defined, we have to characterize the dimension of the soil fund (in terms of surface area) by setting the assumptions and boundary conditions that affect the size of the funds. We consider boundary conditions to be the dimension of DU and livestock, while the optimization will be regarding the total surface of farmland. This is reasonable for the domestic unit (DU), as its composition was a socio-cultural condition, but not for livestock density[52]. Therefore, we will have to double check whether in an optimized scenario it would be better to increase or decrease the livestock component. In further methodological developments, this issue will be solved using non-linear optimization.

[52] The dimension of the Domestic Unit depended on the available farmland surface, and was also defined by social traditions and conditions. Indeed, if we run the model asking for the minimum surface required to reproduce an agroecosystem, the dimension of Domestic Unit will always be one average person.

2.1 <u>Domestic Unit (DU)</u>

From the 1860 municipal population census of Sentmenat we obtain the average domestic structure, counting both family and non-family members (servants), of the 197 farms of which we have specific information on their composition. Average was 5.08 people per DU, median was 5 people, and 4 people the modal. We will take 5 people as representative of the Domestic Unit (DU).

Once we analysed the 30 DU with 5 individuals, their modal composition included a girl between 0, a boy from 5 to 10, a man between 18 and 60, a woman between 18 and 60, and a man over 60 years old. This will be our average DU, and its structure affects in our *SFRA* model the consumption of food (regarding each type of diet), the work capacity, and the monetary requirements for clothes and shoes (as will be seen later in terms of constraints).

This DU structure fits the Consumers/Workers ratio that existed at municipal level. Yet, in order to avoid an overestimation of farmland capacity, and to extrapolate results at municipal level, we need to verify as well that this composition corresponds to the maximum requirement of surface throughout the live family cycle. Thus, we calculate the *Minimum Reproduction Unit* (*MRU*; i.e., the most variable scenario regarding this boundary condition) for the five stages of the life cycle that we defined in Table A2.2. The modal composition presented above corresponds to stage 2.

Table A2.2. Scenarios of evolution of the family structure; *W* indicates woman and *M* man. Data in years

	Family members				
Stage	**1 (*W*)**	**2 (*M*)**	**3 (*W*)**	**4 (*M*)**	**5 (*M*)**
S1	-	-	20	24	-
S2	2	7	30	34	65
S3	12	17	40	44	-
S4	22	-	50	54	-
S5	-	-	60	64	-

Source: Our own, based on the sources detailed in the text.

Once we run the *MRU* model in these 5 stages, the resulting profile in terms of required land surface is the one indicated in Figure A2.1. As can be seen, stage 2 was the one that required the greater surface. Therefore, regardless of whether this stage is taken to represent the evolution at municipal level, the result for all the scenarios will be suitable for the whole family cycle (that is, a complete generation).

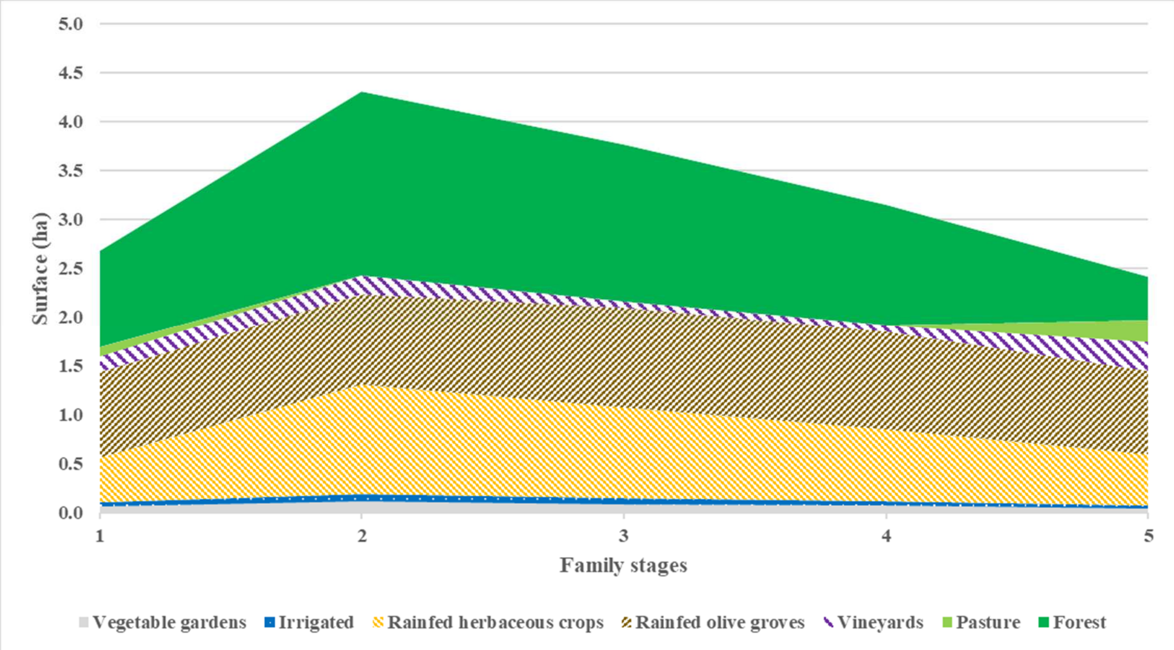

Figure A2.1. Evolution of the surface required in MRU according to the family stage. Source: Our own, based on the sources detailed in the text

In order to be able to extrapolate the results at municipal scale, we have to take into account the different DU compositions within the whole population. Therefore, we weighted the results based on the number of people in the UD. For that purpose, we define the *Z* parameter, which is an integer value according to the number of individuals in the farm. As indicated above, at farm scale analysis we use as a reference *Z*=5. Notwithstanding, when extrapolating the potential development at municipal level results are weighted according to the distribution of frequencies for each composition of DU. Frequency distribution in Sentmenat c.1855 is presented in Figure A2.2.

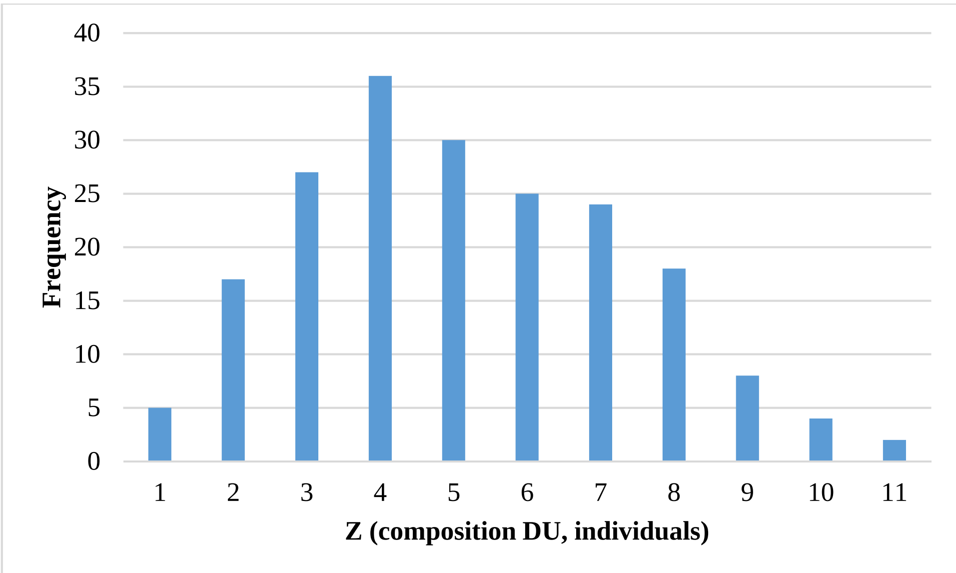

Figure A2.2. Frequency of DU according to number of individuals for Setnmenat c.1860. Source: Our own, based on the sources detailed in the text.

2.2 Livestock

As indicated in chapter 6, we distinguish between two types of domestic animals: meat and dairy producing animals, and draught animals. We base their dimension on the other two funds. Meat and dairy producing animals, or consumption animals, depend on the size of the DU (Z), while draught animals depend on the amount of land to be ploughed and tilled (cropland area) according to the prevailing farm management in the Vallès County at that time (Roca, 2007).

For consumption animals we consider that a family of 5 people had 1 rabbit, 2 chickens, 2 hens and 1 pig (Marco et al., 2017). We included ovine and caprine heads as well into these consumption animals. At municipal level, according to the livestock census of 1860, there were 2,835 units, which once distributed among DUs represented 1.6 units/DU. We rounded up that value to 2 animals/DU, which would be sheep as it was the most common meat consumed in those rural areas.

For draught animals we consider that smallholder farms shared mules (the predominant ones according to the livestock census of 1860), meaning that their feeding was proportional to the farmland area possessed (Roca, 2007). Since Sentmenat had an standardized weight of draught animals of 115.8 LU500, if we divide this among the 1,757 ha of cropland area we get 0.1011 mules/ha. We define a parameter M that indicates the estimated livestock density endowment (in terms of mule sharing; Eq.2). Therefore, we multiply M by the total surface of the farm.

$$M = 0.1011(X_1 + X_2 + X_3 + X_4 + X_6 + X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{18}) \text{ (Eq. 2)}$$ [53]

2.3 Soil fund

The funds considered to reproduce the agroecosystem are, as mentioned: domestic units (DU), domesticated species (livestock), and non-domesticated species. Within those large categories, soil fund has some difficult properties when dealing with fund-flow analysis of social metabolism. We consider soil as the thin layer between geological materials and the ground where plants are able to grow. It includes a lot of biota that behaves as non-domesticated species performing a vital role as biomass and humus decomposers. At the same time, this living soil is the main structure were plants can root and live, where they can take nutrients and water to bio-convert solar radiation into biomass. Therefore, soil is a key fund regarding water and nutrients metabolism. This is why it is so relevant to assess its reproducibility. However, as a living layer full of organisms, it has several properties that we would have to consider in order to capture its sustainability.

In order to make a workable approach, and dealing with the weak information we have from historical sources, we have to inevitably limit the way we face its complexity in our socio-metabolic assessment. We will only consider two main features from soil fund-flow agro-ecological functioning: nutrient cycles and water. Even so, we do not have proper information for water to assess its metabolism. Therefore, we will make a rough assumption for its modelisation considering that irrigated land could be maintained over time.

Regarding nutrient cycles, they contribute to keep soil fertility. In turn, we can split this fertility into physical, chemical and biological fertility. This involves again a complex set of relationships. Nevertheless, in order to simplify this assessment through a fund-flow model approach, we exclude both physical and biological fertility from the study. This means assuming that the physical-structural and biological dimensions of fertility would have been guaranteed, at

[53] As can be seen on the total surface area cultivated, neither X_5, X_7 nor X_{18} appear in the formula. The reason is that their areas are accounted in other uses or vice versa, as indicated in section 3.1 of this Annex.

least to a certain degree, if biogeochemical cycles were addressed through organic amendments and with proper conservation practices available c.1860. Hence, in this first approach we define the conditions of reproducibility only through soil chemical fertility assessed by means of macro-nutrients (N-P-K) cycles, as explained in section 3.3 of this supplementary material.

This approach has some other important assumptions. What we are dealing to when only assessing the nutrient cycles, is not really the chemical fertility system as a whole. Chemical fluxes from one year to another are highly affected by the physical and biological conditions of soils. Nutrients shift from non-bio-available to bio-available, or vice versa, depending on several factors. However, here we will only take into account the effect of nutrient inputs and outputs from the soil. Therefore, we are not analysing nutrients dynamics inside soil, considering that any input, at some point, will be mineralized and available for the plant nutrition requirements of forthcoming years. Therefore, we are taking a point of view of biogeochemical fluxes assessment. What we assess is whether there were enough nutrients or not for satisfying the average demand stemming from the extractions that took place in cropping areas. Indeed, even if we wanted to analyse these soil-plant dynamics in a more complex way, historical sources do not allow for that. The use of too many technical estimates would be probably biasing the results, and analysing this at municipal level would make no sense given that these factors are site-specific at plot level. Therefore, we consider that under these circumstances limiting our scrutiny of soil reproducibility to N-P-K balances makes sense. Later on we will explain how we assess these nutrient balances.

Another aspect regarding soil is that, as a fund, it is a fundamental part of the process of biomass production from one year to another. Therefore, as we do not consider vegetables as a fund (they are incorporated into the product, as they are the product itself), we relate farm yields to this soil fund.

To this aim, we assume in our reproductive model that data on land productivity provided by historical sources and current statistics respond to a static equilibrium. Therefore, as long as farmers ensured nutrients replenishment, land productivity would have been kept steady. Land productivity data has been taken from the *Estudio Agrícola del Vallès* of 1874 (Garrabou and Planas, 1998), and the estimates of all its by-products through ratios compiled in Guzmán et al., (2014), as indicated in Table A2.3. Data is about yields, once the required seed for the coming year was subtracted.

Before finishing this section, we want to make a semantic consideration. The soil has another important feature: is the only agroecosystem fund that can be represented spatially (unlike the farming domestic units or the livestock). Therefore, when we assess the dimensions of the surface area existing for the whole municipalities considered, and its constraints, we will include them into the whole restrictions for the soil fund.

Table A2.3. Registered land productivity and estimated by-products according to soil quality, in kg/ha, moisture and direction of flow (to which fund each flow went). DU indicates Domestic Unit, L to livestock and S for soil fertility. Source: Our own, based on the sources detailed in the text.

	Crop or land-use	Product	Q1	Q2	Q3	M(%)	Direction
Vegetable gardens	Vegetables	Vegetables	5,070			92	DU
		Straw	5,342			81	L
	Fresh fruits	Fruits	4,148			85	DU
		Firewood	2,475			30	DU
	Nuts	Dry fruits	525			4	DU
		Firewood	2,847			30	DU
Irrigated	Wheat	Grain	1,242	1,023	731	14	DU
		Straw	2,889	2,433	1,825	14	L+S
	Corn	Grain	1,348	1,075	802	14	L
		Stalks	1,044	835	627	8	L
	Hemp	Fibre	1,213	1,104	996	8	DU
		Stalks	1,477	1,354	1,231	10	L
	Beans	Beans	1,078	853	640	15	DU+L
		Straw	1,695	1,378	1,060	20	L
Rain-fed annual crops	Wheat	Grain	1,169	877		14	DU
		Straw	2,737	2,129		14	L+S
	Associated wheat	Grain	877			14	DU
		Straw	1,521			14	L+S
	Corn	Grain		501		14	L
		Stalks		783		8	L
	Rye & wheat mixture	Grain		424	636	14	DU
		Straw		1,176	1,617	14	L+S
	Barley	Grain			439	14	L
		Straw			1,096	14	L+S
	Fodder	Fodder		6,754		72	L
	Potatoes	Potatoes	1,679/1,250	1,215		20	DU
		Straw	1,020/784	765		20	S
	Beans	Beans	658			15	DU+L
		Straw	1,060			20	L+S
	Vetches	Vetches			658	20	L
		Straw			954	20	L+S
	Lupines	Lupines			585	20	L
		Straw			954	20	L+S
Woody Crops	Olives	Olive oil	273	202	141	0	DU
		Browsing	796	590	413	28	L
		Pomace	1,205	893	625	59	L
		Firewood	1,628				DU+S
	Vines	Grape juice	2,142	1,683	918	83	DU
		Pomace	912	717	391	40	L
		Firewood	2,442				DU+S
		Leaves	1,250				S
Extensive uses	Pasture	Pasture	3,947			62	L
	Forest	Firewood	5,438	4,078	2,719		DU+S
		Pasture	1,523			62	L
		Oak acorns	187				L

3. Constraints

In order to define the constraints that determined both biophysical and cultural practices, it is necessary to establish a series of secondary variables. Being the main variables land surfaces, each secondary variable is going to be a product or by-product per unit of land-use.

For each product and by-product we define a number of possible directions (*j*), e.g. farmers used cereal straw to feed livestock, as stall bedding, or for burying it on cropland to maintain soil fertility. The magnitude of flows in each direction is also the result of the optimization, while $X_{i,j}$ represents a fraction of total surface of land-use (Eq.2).

$$X_i = \sum_{j=1}^{j=n} X_{i,j} \; on \; X_{i,j} \geq 0 \text{ (Eq.2)}$$

Thus, there will be as many secondary variables as directions any flow of biomass can take, reaching 128. With these, we define both general and specific constraints.

General constraints fix the relationship between the total area of a land-use, and the directions each product or by-product obtained in this use can take. These constraints all take a similar configuration, as indicated in Eq.3 (where X_i is the surface of a specific use (along X_1 and X_{22}), and $X_{i,j}$ the product ratio of this surface X_i which is going in the direction *j*).

$$X_i = \sum_{j=1}^{j=n} X_{i,j} \; where \; X_{i,j} \geq 0 \text{ (Eq.3)}$$

It is also necessary to define specific restrictions, which are the ones that determine the arrival directions of flows. That is, where these $X_{i,j}$ flows were allocated to meet the needs of specific funds. For example, the sum of all feed devoted to pigs must be equal or greater than their energy requirements. And then, these flows can take different configurations depending on the needs of each fund to be satisfied.

Then, taking all kind of constraints, we define the requirements of minimum and maximum flows which allow each of the three funds to be reproduced (minimum for inputs, and maximum for outputs of the fund).

DU is the central element that maintains and reproduces the agroecosystem through labour. To ensure its stability we consider three fundamental input constraints: *i*) obtaining sufficient food, estimated through contemporary diets; *ii*) having enough fuel in the form of firewood and oil for lighting; and *iii*) cash requirements to meet expenses of clothing, footwear, tools and housing, as well as municipal and royal taxes. Therefore, we consider basic human material needs as determined *ex-ante* and not regarding farmers' well-being (Harrison, 1975). Notwithstanding, as long as we are setting a threshold for the farming family reproduction, not on how to organize the farm counting without restrictions on means of production, we consider this demand to be inelastic. Moreover, unless otherwise stated, we consider the land farmed as farmers' property—i.e. without having to pay land rents or parts of fruits through tenancy contracts, as we are trying to infer how society could rule without inequality.

Regarding outputs, we set a maximum amount of monthly labour taking into account farming seasonality , including all requirements of the farm components (cropland, livestock and reproducing the DU itself). The capacity to work also depended on the DU composition, distributed according to age and family role considering as well the domestic care work (Marco et al., forthcoming). Finally, we consider as returns from DU to the agroecosystem both human excrete and domestic waste.

With respect to livestock, we distinguish between draught animals and other livestock, given their different roles (Roca, 2007). Both groups were fed mainly with products coming from cropland and extensive areas (using products and by-products), although there was also a smaller flow coming from DU as domestic waste recycled through poultry and pig feeding. Their diets were flexible, fixing certain basic physiological criteria. They also required a certain amount of litter as stall bedding. Furthermore, livestock was a supplier of food but also fertilizer for the soil and, as working animals, draught force.

To analyse flows affecting the biogeochemical cycles, we define nutrients requirement resulting from the balance of cultivated land in terms of nitrogen, phosphorus and potassium. We base our methodology for estimating these cycles on the proposal made by González de Molina et al. (2010) and Tello et al. (2012), with a similar proposal as followed in Annex I, but including P and K nutrient cycles. We consider that these nutrients were restored through fertilization practices such as animal manure, humanure, and burying biomass from forest or crop by-products. We also fix sustainable exploitation of firewood from forest and brushwood. Note then, that we will only implement nutrient balances to cropland.

Likewise, the prevailing system of crop rotations became one of the main cultural factors given. Finally, we consider the soil and climate features of the site specifically associated with soil fertility, taking into account a suitable distribution of soil qualities, the amount of water available for irrigation, and using typical yields of crops for both products and by-products.

3.1 Constraints of soil quality and rotation systems

We start with the constraints that affect the agrological capacities of the cultivated land at municipal level, taking the site-specific cultural practices into account. For this section, we use the information given in the municipal land-use register (*Amillaramiento*) of 1859 on the extent of each soil quality, as well as the crop rotation systems described in the *Estudio agrícola del Vallés* of 1874 (Garrabou and Planas, 1998).

3.1.1 Distribution of soil quality in the municipality

For land-uses that appear in more than one quality, we define general restrictions for irrigated wheat (characterized by X_4), dryland wheat (X_8), rye & wheat mixture (X_{11}), potatoes (X_{14}), olive tree groves (X_{18}), vineyards (X_{19}) and forest (X_{22}), which we present in equations 4 to 10.

$$X_4 = X_{4(1a)} + X_{4(2a)} + X_{4(3a)} = X_{23} + X_{24} + X_{25} \text{ (Eq.4)}$$ [54]

$$X_8 = X_{8(1a)} + X_{8(2a)} = X_{26} + X_{27} \text{ (Eq.5)}$$

$$X_{11} = X_{11(2a)} + X_{11(3a)} = X_{28} + X_{29} \text{ (Eq.6)}$$

$$X_{14} = X_{14(1aH)} + X_{14(2aH)} + X_{14(1aO)} = X_{30} + X_{31} + X_{32} \text{ (Eq.7)}$$

$$X_{18} = X_{18(1a)} + X_{18(2a)} + X_{18(3a)} = X_{33} + X_{34} + X_{35} \text{ (Eq.8)}$$

$$X_{19} = X_{19(1a)} + X_{19(2a)} + X_{19(3a)} = X_{36} + X_{37} + X_{38} \text{ (Eq.9)}$$

$$X_{22} = X_{22(1a)} + X_{22(2a)} + X_{22(3a)} = X_{39} + X_{40} + X_{41} \text{ (Eq.10)}$$

[54] Regarding irrigated land, we only define variables X_{23} to X_{25}, which we will use to define all products and by-products of irrigation, using the proportions set out in section 3.1.2. This avoids the generation of more than nine variables that would complicate the linear programming further.

The following are the specific equations corresponding to the first and second soil quality surfaces, so that their distribution does not overestimate the productive capacity of each type of land unit in the territory. This allows the results obtained as yields per unit of land to be extrapolated at municipal scale (Eq.11-12).

$$X_1 + X_2 + X_3 + 2X_{23} + X_{26} + X_9 + X_{30} + X_{32} + X_{15} + X_{36} + X_{39} = \frac{541}{2781}(X_1 + X_2 + X_3 + X_4 + X_6 + X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{19} + X_{21} + X_{22}) \quad \text{(Eq.12)}$$

$$2X_{24} + X_{27} + X_{10} + X_{29} + X_{13} + X_{31} + X_{37} + X_{40} = \frac{706}{2781}(X_1 + X_2 + X_3 + X_4 + X_6 + X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{19} + X_{21} + X_{22}) \quad \text{(Eq.12)}$$

Here it is important to explain a relevant assumption regarding soil quality. We assumed that each soil quality registered by crops is interchangeable to other uses. While this could be more or less reliable for dryland crops and vines, it is less suitable for a change from forest to rain-fed crops. Indeed, from a historical perspective, land intensification in the area was mainly driven by the emphyteutic *rabassa morta* contracts. There, forest or brushwood areas where leased to poor farmers who had to clear them and plant vineyards. Very often those areas where in steep lands, and farmers were forced to build terraces so as to protect them from erosion. Fieldwork done in a neighbouring municipality by Olarieta et al., (2008) recorded that around 43% of cropped area required *landesque capital* investments in the form of terraces and soil conservation practices. Therefore, the assumption that steep forest areas could be cropped despite their agrological low value for certain crops seems to be reasonable in a context of those land-use intensification practices carried out in a rather socially unequal rural society. Hence, in mid-nineteenth century the prevalence of crops located in marginal areas thanks to enormous labour investments made on terraces, allows to assume in our modelling that other crops could also be grown on them (Olarieta et al., 2008). However, in order to ensure the reliability of results we will make a double check with the slopes assumed to be cropped and their agrological suitability as well (CGI, 2010; Olarieta et al., 2008; Rodriguez Valle, 2003). For further *SFRA* improvements it would be better to directly consider suitability as a constraint.

3.1.2 Crop rotation in irrigated land

The rotation for irrigated lands implied tilling more than a crop a year. Wheat (X_4) was followed after harvested, within the same year, by corn (X_5) sown in half of the land, while the other half was left in fallow (X_{20}). The same happened after hemp (X_6) and beans (X_7) for the second year. Thus, the total irrigated area will be expressed by the sum between X_4 and X_6, amounting X_5, X_7 and X_{20} the same surface as the former. We do not count as total surface the latter, because crop is produced within the same space although at different moments along one year. We indicate the relationship between these surfaces in the restrictions of Eq.10 to 13.

$$X_4 = X_6 \quad \text{(Eq.10)}$$

$$X_5 = \frac{1}{2}X_4 \quad \text{(Eq.11)}$$

$$X_7 = \frac{1}{2}X_6 \quad \text{(Eq.12)}$$

$$X_{20} = \frac{1}{2}X_4 + \frac{1}{2}X_6 = X_4 \quad \text{(Eq.13)}$$

3.1.3 Crop rotation for herbaceous dryland

In the herbaceous dryland there was a rotation for each soil quality. In the first one there was a biennial rotation of wheat and beans; in the second one it was of wheat and forage, and in the third of rye & wheat mixture and vetches (Eq.14-18).

$$X_{15}=\frac{1}{2}X_{8(1a)}=\frac{1}{2}X_{26} \text{ (Eq.14)}$$

$$X_{30}=\frac{1}{2}X_{8(1a)}=\frac{1}{2}X_{26} \text{ (Eq.15)}$$

$$X_{13}=\frac{1}{2}X_{8(2a)}=\frac{1}{2}X_{27} \text{ (Eq.16)}$$

$$X_{31}=\frac{1}{2}X_{8(2a)}=\frac{1}{2}X_{27} \text{ (Eq.17)}$$

$$X_{16}=X_{11(3a)}=X_{29} \text{ (Eq.18)}$$

3.1.4 Crop rotation of herbaceous grains intercropped with olive trees

The cultivation of olive trees was associated to various grains intercropped in between the rows of trees according to the soil quality (Eq.19-23). Land productivities of the original historical sources contemplated that farmers cultivated olive trees and other herbaceous crops simultaneously, as an associated silvoarable farming. This means that both perennial and annual crops were grown on the same land at the same time, so total olive groves' rotation area will be either X_{18} or the sum of all the associated crops. .

$$X_{9}=\frac{1}{2}X_{18(1a)}=\frac{1}{2}\cdot X_{33} \text{ (Eq.19)}$$

$$X_{32}=\frac{1}{2}X_{18(1a)}=\frac{1}{2}\cdot X_{33} \text{ (Eq.20)}$$

$$X_{10}=\frac{1}{2}X_{18(2a)}=\frac{1}{2}\cdot X_{34} \text{ (Eq.21)}$$

$$X_{11(2a)}=\frac{1}{2}X_{18(2a)} \rightarrow X_{28}=\frac{1}{2}X_{34} \text{ (Eq.22)}$$

$$X_{12}=\frac{1}{2}X_{18(3a)}=\frac{1}{2}\cdot X_{35} \text{ (Eq.23)}$$

$$X_{17}=\frac{1}{2}X_{18(3a)}=\frac{1}{2}\cdot X_{35} \text{ (Eq.24)}$$

3.2 Constraints for livestock breeding

Regarding livestock feeding, the model begins from the energy requirements of each type of animal accounted as metabolizable energy (ME). The energy needs of animals are primarily estimated from Church (1984), as well as using other secondary sources (Brenes et al., 1978; Burden, 2012; Giménez, 1994; National Research Council, 1989; IACSI, 1879) from which we estimate the requirements shown in Table A2.4.

Table A2.4. Animal energy requirements. Source: Our own, based on the sources detailed in the text.

	Annual requirements (MJ/year)
Mules	19,076
Sheep	2,393
Hens	544
Chickens	411
Rabbits	317
Pigs	5,956

We therefore identify which resources were suitable for feeding each animal, following the criteria indicated below:

- Straw and stubble: Includes wheat stump, hoof and stubble (from dryland, irrigated, associated to olive tree groves and mixed with rye), and the same with barley. We consider all animals suitable for consuming straw, with the exception of pigs, poultry and rabbits.
- Grain: A part of the main production was destined to animal feeding. Included barley, corn and legumes (dryland and irrigated beans, vetches and lupines). It was suitable for all animals.
- Horticultural by-products: We estimate its composition from a mixture of the leftovers of various vegetables (pumpkin, beans, lettuce, turnips, tomatoes and carrots). They were used to feed pigs, poultry and rabbits.
- Pomace of vine grapes and olives: Farmers also used pomaces for feeding pigs
- Olive tree browsing: These were the tender shoots of olive trees, which farmers used to feed herds, mainly of pigs.
- Fodder: Draught animals, as well as sheep, complemented their feeding with such kind of production. However, sometimes also pigs could take advantage from them.
- Domestic residues: They were the basis for the feeding of chickens, hens, rabbits and pigs.
- Oak acorns from forest: In the case of pigs, we consider that a relevant part of its feeding came from grazing in oak forests.
- Grazing in pastures and forests: Sheep, but also draught animals, where fed using grazing lands.

In order to know the contribution in terms of metabolizable energy of each possible kind of feed, Table A2.6 shows its contribution per kg in dry and per animal. When some cells appear empty it means that this was an unsuitable feed, or not commonly used for the specific animals considered.

Table A2.5. Metabolizable energy values (MJ/kg of dry matter) regarding kinds of feeds and species

		Pigs	Poultry	Rabbits	Sheep	Mules
Straw and stubble	**Cereals**					0.72
	Leguminous					1.44
Grain	**Barley**	3.06	2.80	3.10		3.30
	Corn	3.39	3.18	3.15		3.46
	Legumes		2.60	3.05		3.12
Horticultural residues		1.05	0.51	1.07		
Olive oil pomace		0.71				
Grapevine pomace		0.71				
Olive tree browsing		0.48				
Forages		1.71			1.36	1.36
Domestic residues		1.25	1.00	1.50		
Oak acorns		2.08				
Pasture					2.15	1.46

Source: Our own, based on the sources detailed in the text.

In order to calculate the distribution of feed, it is necessary to define new secondary variables that are associated to the multiple directions that each flow can take. Domestic residues, which do not come from any land-use but from the DU, will be distributed among pigs, poultry and rabbits. Since in this case they are not associated with any land surface, the sum of secondary variables is equal to 1, as shown in Eq. 25, where values represent a proportion of the total household waste.

$$X_{23} + X_{24} + X_{25} = 1 \text{ (Eq.25)}$$

From here, all the rest of feed came from land-uses, so all the associated secondary variables representing all the directions that a flow could take will be less or equal to the surface of the specific use. This inequality allows for the existence of a surplus if feed does not match with livestock. We thus generated the following variables (Eq. 26-45).

$$X_{26} + X_{27} + X_{28} \leq X_1 \text{ (Eq.26)}$$
$$X_{29} + X_{30} + X_{31} + X_{32} \leq X_{12} \text{ (Eq.27)}$$
$$X_{33} + X_{34} + X_{35} + X_{36} \leq X_5 \text{ (Eq.28)}$$
$$X_{37} + X_{38} + X_{39} + X_{40} \leq X_{10} \text{ (Eq.29)}$$
$$X_{41} + X_{42} + X_{43} \leq X_{13} \text{ (Eq.30)}$$
$$X_{44} + X_{45} + X_{46} + X_{47} \leq X_7 \text{ (Eq.31)}$$
$$X_{48} + X_{49} + X_{50} + X_{51} \leq X_{15} \text{ (Eq.32)}$$
$$X_{52} + X_{53} + X_{54} \leq X_{16} \text{ (Eq.33)}$$
$$X_{55} + X_{56} + X_{57} \leq X_{17} \text{ (Eq.34)}$$
$$X_{58} + X_{59} \leq X_{21} \text{ (Eq.35)}$$
$$X_{60} + X_{61} \leq X_4 \text{ (Eq.36)}$$
$$X_{62} + X_{63} \leq X_8 \text{ (Eq.37)}$$
$$X_{64} + X_{65} \leq X_9 \text{ (Eq.38)}$$
$$X_{66} + X_{67} \leq X_{11} \text{ (Eq.39)}$$
$$X_{68} + X_{69} \leq X_{12} \text{ (Eq.40)}$$
$$X_{70} + X_{71} \leq X_7 \text{ (Eq.41)}$$
$$X_{72} + X_{73} \leq X_{15} \text{ (Eq.42)}$$
$$X_{74} + X_{75} \leq X_{16} \text{ (Eq.43)}$$
$$X_{76} + X_{77} \leq X_{17} \text{ (Eq.44)}$$

$$X_{78} + X_{79} \leq X_{14} \text{ (Eq.45)}$$

Once the variables are defined in terms of productivities, moisture and energy content of each feed, we proceed to perform the specific restrictions of animal feeding for each species. In some cases, we include physiological limitations based on the maximum recommended shares in the diet of certain kinds of products (FEDNA, 2010).

3.2.1 Pigs feeding

For pigs the maximum consumption of alfalfa should be 15%. Therefore, this limits its contribution in the total diet, as indicated in Eq.46.

$$13{,}530X_{70} \leq 0.15 \cdot 1191 \cdot Z \text{ (Eq.46)}$$

We indicate the restriction for feeding in Eq.47.

$$1{,}628X_{22} + 13{,}530X_{70} + 4{,}172X_{33} + 2572X_{34} + 1800X_{35} + 1111X_{36} + 873X_{37} + 476X_{38} + 97 \cdot Z \cdot X_{42} + 4{,}459X_{45} + 4{,}834X_{51} + 16{,}443X_{55} + 13{,}112X_{59} + 9{,}783X_{63} + 6{,}111X_{67} \geq 1191 \cdot Z \text{ (Eq.47)}$$

3.2.2 Poultry feeding

Given the type of feeding traditionally used for chickens and hens, all kind of potential feeds can be consumed at will. Therefore, the only restriction is total feeding, as shown in Eq.48.

$$77.66 \cdot Z \cdot X_{43} + 2{,}183X_{46} + 4{,}423X_{48} + 15{,}424X_{52} + 12{,}301X_{56} + 9{,}177X_{60} + 5{,}733X_{64} + 9{,}968X_{71} + 7{,}887X_{75} + 5{,}918X_{79} + 6{,}084X_{83} + 4{,}882X_{87} + 5{,}091X_{90} \geq 382 \cdot Z \text{ (Eq.48)}$$

3.2.3 Rabbits feeding

In the same vein as poultry, we define for rabbits the total equation of feeding indicated in Eq. 49.

$$116 \cdot Z \cdot X_{44} + 4{,}548X_{47} + 4{,}897X_{49} + 15{,}279X_{53} + 12{,}185X_{57} + 9{,}090X_{61} + 5{,}678.56X_{65} + 11{,}693X_{72} + 9{,}252X_{76} + 6{,}942X_{80} + 7{,}137X_{84} + 5{,}717X_{88} + 5{,}972X_{91} \geq 63 \cdot Z \text{ (Eq.49)}$$

3.2.4 Sheep feeding

For sheep, we set a limit on fodder consumption, due to the problems that it can cause to ruminant animals. We set it according to the criteria of FEDNA (2010), as shown in Eq. 50. Eq. 51 is the restriction for total consumption.

$$10{,}761X_{69} \leq 0.35 \cdot 957 \cdot Z \text{ (Eq.50)}$$

$$17{,}580X_{93}+5{,}206X_{95}+10{,}761X_{69} \leq 957 \cdot Z \text{ (Eq.51)}$$

3.2.5 Mules feeding

We define several restrictions for mules. First, on the one hand, the inclusion of the *M* parameter requires fixing a restriction according to which the pasture consumption is less than the total consumption of feed, as indicated in Eq.52. On the other hand, fodder cannot account for more than 45% of diet (Eq.53), and cereal straw must reach a maximum of 25% (Eq.54). Finally, we present total restriction for mules feeding in Eq.55.

$$\frac{9162X_{94}+3535X_{96}}{19076M} \leq 1 \text{ (Eq.52)}$$

$$10{,}761X_{68} \leq 0.45 \cdot 19{,}076 \text{ (Eq.53)}$$

$$7{,}485X_{97} + 6{,}303X_{99} + 4{,}708X_{101} + 7{,}091X_{103} + 5{,}515X_{105} + 4{,}582X_{107} + 3{,}045X_{109} + 4{,}189X_{111} + 3{,}302X_{113} \leq 0.25 \cdot 19{,}076 \quad \text{(Eq. 54)}$$

$$11{,}937X_{94} + 3{,}535X_{96} + 10{,}770X_{68} + 5{,}213X_{50} + 16{,}782X_{54} + 13{,}384X_{58} + 9{,}984X_{62} + 6{,}238X_{66} + 11{,}961X_{73} + 9{,}465X_{77} + 7{,}101X_{81} + 7{,}301X_{85} + 5{,}848X_{89} + 6{,}109X_{92} + 7{,}485X_{97} + 6{,}303X_{99} + 4{,}707X_{101} + 7{,}091X_{103} + 5{,}516X_{105} + 4{,}582X_{107} + 3{,}046X_{109} + 4{,}189X_{111} + 3{,}302X_{113} + 8{,}170X_{115} + 6{,}642X_{117} + 5{,}109X_{119} + 5{,}109X_{121} + 4{,}598.25X_{123} + 4{,}598X_{125} \geq 19{,}076 \quad \text{(Eq.55)}$$

3.2.6 Stall bedding

It is also necessary to consider the amount of crop by-products needed to make stall beds for livestock. Using Soroa (1953) as historical source, we assume that mules required 2 kg of stall bedding per day, 0.2 kg/day for sheep, and 1.5 kg/day for pigs and. From UPAE (2011) we assume for poultry and rabbits 1.25 kg/year. This supposes an average of 730 kg/year for a mule, and 700 kg/year for the rest of animals. In terms of *M* and *Z* parameters, this would be expressed as 730*M* + 140**Z*. We consider that these beds came from either hemp or corn stalks, or straw from wheat and barley harvest. We show the restriction in Eq.56.

$$2{,}889X_{98} + 2{,}433X_{100} + 1{,}825X_{102} + 2{,}737X_{104} + 2{,}129X_{106} + 1{,}521X_{108} + 1{,}176X_{110} + 1{,}617X_{112} + 1{,}096X_{114} + 2{,}521X_{23} + 2{,}189X_{24} + 1{,}858X_{25} + 783X_{10} \geq 730M + 140Z \quad \text{(Eq.56)}$$

3.2.7 Capacity to work from draught animals

We use data on the working capacity of draught animal power assuming an average working period of 220 days/year. Sources are the same ones used for labour in section 3.4.3, adapted to those agrarian activities which require draft power for ploughing, transport or other uses. Thus, the resulting equation is equation 57, in terms of workdays.

$$22.9X_1 + 8.9X_2 + 8.9X_3 + 13.4X_4 + 8.3X_5 + 22.9X_6 + 4.4X_7 + 13.4X_8 + 14X_9 + 8.3X_{10} + 14X_{11} + 14X_{12} + 5.7X_{13} + 5.5X_{14} + 4.4X_{15} + 5.7X_{16} + 14.6X_{17} + 8.9X_{18} + 4.2X_{19} \leq 220M \qquad \text{(Eq.57)}$$

3.3 Constraints for nutrient cycles

With respect to the flows needed for closing the nutrient cycles, we divide the whole cropland surface among 5 different crop systems, mainly based on crop rotations. These were: orchards and fruit trees, irrigated crops, herbaceous dryland crops, associated crops in olive tree groves, and vineyards. We consider three different kinds of cultural practices for fertilization, which were used for one or more of the different crop systems:

- Application of humanure: We consider that its application was limited to vegetable gardens, irrigated crops and herbaceous dryland, which were located on the lands closest to the farmhouse.
- Application of animal manure with its corresponding beds: These were applied in all crops except for vegetable gardens and fruit tree orchards where we assume they were not necessary.
- Burying biomass: It is known that the burial of biomass was a common practice, and it was done both for all dry crops and in vineyards.

We characterize those practices regarding its fertilization potential, in terms of the main macronutrients (nitrogen, phosphorus and potassium) content.

3.3.1 Humanure

Based on information on the composition of excrements and urine of human excreta (Gootas, 1956), and considering a family unit of 5 people, we estimated the amount of potential nutrients provided. Therefore, total available nitrogen was 27.6 kg. However, according to the IPCC (2006), approximately 50% out of these 27.6 kg N has to be subtracted as losses during the composting process, which represents a remaining value of 13.8 kg N (or 2.8*Z kg N). In relation to phosphorus and potassium, if we consider losses of 0.3% for phosphorus and 20% for potassium, there would be a total of 9.9 kg of P (or 2*Z kg P) and 5.3 kg of K (or 1.1*Z kg K).

3.3.2 Animal manure

Animal manure comprises two different phases: On the one hand animal excreta, and on the other hand stall beds on which this excreta remains. It is a rather complex issue to decide the composition of animal feeding, given that the actual collection of excreta depended on the number of days animals grazed. We assume that all the flows of feeding were obtained at municipal scale in 1860 (Marco et al., 2017). Thus, we consider the amount of excreta, moisture and grazing days, and its composition in N, P and K in kg of fresh matter taken from a brief review on sources including ASAE (2000), Cascón (1918) and the resulting values from the feed balance and the ratios of animal uptake in nutrients consumption. Assuming that livestock was 100% of the days of a year grazing, only 45% of excreta could be collected by means of locking the animals in pens at night (Cascón, 1918). Hence, the actual factor of manure application was also determined by considering their grazing period.

For the case of mules, and given its relevance and multiple possibilities of their feed intake, we generate a *P* parameter in order to define the percentage of manure collected from the total. This *P* depends in turn on a parameter *D*, which is the number of grazing days. We express the relation among those parameters in equations 58 and 59.

$$P = 1 - \frac{0.55 \cdot D}{365} \qquad \text{(Eq.58)}$$

$$D = \frac{9{,}162X_{94} + 3{,}5351X_{96}}{19076M} \cdot 365 \qquad \text{(Eq.59)}$$

Based on this information, we proceed to calculate the total amount of animal excreta obtained in terms of kg of N, P and K. We also have to consider the nutrients contribution obtained from stall bedding. Its average composition in nutrients was estimated to be 0.51% in N, 0.08% in P, and 0.50% in K. Thus, and depending on the distribution of cattle according to *M* and *Z*, the contribution in terms of the different nutrients is considered to be 4.45*M + 0.85*Z kg for nitrogen, 0.57*M + 0.11*Z kg for phosphorus and 3.65*M + 0.70*Z kg for potassium.

Thus, from the sum of excreta and stall beds we obtain that, for nitrogen its contribution was 31.5*P*M + 4.5*M + 6.5*Z kg, for phosphorus 7.5*P*M + 0.6*M + 1.8*Z kg, and for potassium 26.2*P*M + 3.7*M + 3.8*Z.

We also assumed, according to our historical sources, that animal manure was not allways used after composting process (Garrabou and Planas, 1998). Then we calculated the total contribution of nutrients taking into account that this composting process entailed a loss of 50% of its nitrogen content, 0.3% in phosphorus, and 20% in potassium. Applying these losses, we obtain the total final manure contribution for different nutrients shown in equations 60 to 62.

$$18.4PM + 2.6M + 3.8Z\ kg\ of\ N \qquad \text{(Eq.60)}$$

$$7.5PM + 0.6M + 1.8Z\ kg\ of\ P \qquad \text{(Eq.61)}$$

$$21.8PM + 3.1M + 3.8Z\ kg\ of\ K \qquad \text{(Eq.62)}$$

3.3.3 Burying of biomass

This fertilizing practice affected three groups of different crop systems using part of the by-products obtained from certain land-uses. While in the herbaceous dry land crops, associated or not with olive trees, peasants buried the leftover straw, vine leaves were either used for animal feeding or buried in the vineyards. We also take into account that for nitrogen these practices entailed 20% of N losses, as stated by IPCC (2006).

3.3.4 Defining secondary variables

For all those forms of fertilization that came from the same source (that is, of the same crop or the same bioconverter), and then were divided between two or more groups of crops, it will be necessary to set new secondary variables. We were are aware this proposal of distribution could limit at some point the potential of development for the model, which could have limitations when a land-use distribution scenario have polarized values. However, after having analysed all the scenarios and results we comproved that these assumptions (where the nutrient sources are devoted to) were not affecting the results.

Thus, humanure is divided between vegetable gardens and fruit tree orchards, irrigation and herbaceous dry land, and the sum of its distribution has to equal 1 (Eq. 63).

$$X_{127} + X_{128} + X_{129} = 1 \qquad \text{(Eq.63)}$$

Regarding animal manure, we divide it between all crop systems with the exception of vegetable gardens and fruit tree orchards. In the same vein as with human manure, the sum of the variables has to equal 1 (Eq.64).

$$X_{130} + X_{131} + X_{132} + X_{133} = 1 \qquad \text{(Eq.64)}$$

The pruning of olive trees (X_{18}) was distributed either for burying into the soil (X_{134}) or as firewood (X_{135}), as equation 65 expresses.

$$X_{134} + \ X_{135} = X_{18} \qquad \text{(Eq.65)}$$

In vineyards, pruning was either used to be burnt at home (X_{136}) or to bury it in irrigated or vineyard land (X_{137} + X_{138}). In turn, these flow directions had to either reach the total area covered by vineyards (X_{19}) or less than it, since the amount of usable vineyard wood pruning was restricted and it could also be sold (section 3.4.2), as expressed in equation 66.

$$X_{136} + X_{137} + X_{138} = X_{19} \qquad \text{(Eq.66)}$$

Finally, a relevant source for nutrient imports towards cropland was forest. We consider that woodland biomass could either be burnt for heating and cooking at home, or for burying it into cultivated soil. These burials of forest biomass flows could be carried out in the crop systems of herbaceous dryland, associated to olive tree groves, or in vineyards. Since wood productivities in forestland were a function of soil quality, we define several variables for each destination and soil qualities (Eq. 67-69).

$$X_{139} + X_{140} + X_{141} + X_{142} = X_{39} \qquad \text{(Eq.67)}$$

$$X_{143} + X_{144} + X_{145} + X_{146} = X_{40} \qquad \text{(Eq.68)}$$

$$X_{147} + X_{148} + X_{149} + X_{150} = X_{41} \qquad \text{(Eq.69)}$$

To run everything off, we calculate the replenishment requirements for each land-use through nutrient balances, mainly following the criteria proposed by González de Molina et al. (2010). The results are presented in Table A2.6. Here, we estimated fluxes for atmospheric deposition, non-symbiotic fixation, symbiotic fixation, seeds, irrigation, volatilization, denitrification and leaching, following the same criteria as in Annex I.

Table A2.6. Requirements in terms of N, P and K (kg/ha) for the different land-uses, regarding its soil quality. Source: Our own, based on the sources detailed in the text.

	Soil Quality	N	P	K
Vegetable gardens		51.0	3.4	11.4
Fresh fruits in orchards		8.3	-2.1	-4.8
Nuts		26.6	0.2	3.0
Irrigated wheat	1	42.4	6.1	15.3
	2	34.2	4.9	11.8
	3	23.3	3.2	7.2
Irrigated corn	1	28.0	4.0	8.9
	2	21.9	3.1	6.8
	3	15.9	2.2	4.7
Irrigated hemp	1	45.8	-0.0	0.7
	2	41.8	-0.3	-0.1
	3	37.8	-0.5	-1.0
Irrigated beans	1	-23.2	5.4	20.3
	2	-21.6	4.0	15.0
	3	-19.6	2.6	9.6
Wheat	1	41.4	6.3	17.2
Beans		-4.6	3.6	13.9
Potatoes		13.4	1.3	10.1
Wheat	2	30.5	4.6	12.5
Fodder		24.6	4.7	26.8
Potatoes		9.7	0.8	6.6
Rye & wheat mixture	3	21.5	3.2	8.6
Vetches		-1.0	2.3	15.0
Associated wheat to olive trees	1	27.4	3.7	11.0
Potatoes		17.7	1.6	10.1
Corn	2	14.8	1.6	3.9
Rye & wheat mixture		21.4	2.8	8.4
Barley	2	18.7	2.1	10.5
Lupines		2.6	4.1	6.1
Olive oil	1	25.4	3.1	7.5
	2	21.3	2.7	6.4
	3	17.9	2.4	5.4
Vineyard	1	13.2	1.1	10.1
	2	10.5	0.7	8.6
	3	6.0	0.2	6.0

3.3.5 Fertilization in vegetable gardens and fruit tree orchards

Considering N-P-K replenishment needs, and assuming that farmers only used humanure to fertilize these plots, restrictions for each nutrient are those indicated in Eq.70-72.

$$51X_1 + 8.3X_2 + 26.6X_3 \leq 2.8 \cdot Z \cdot X_{127} \quad \text{(Eq.70)}$$
$$3.4X_1 - 2.1X_2 + 0.2X_3 \leq 2 \cdot Z \cdot X_{127} \quad \text{(Eq.71)}$$
$$1.4X_1 - 4.9X_2 + 3X_3 \leq 1.1 \cdot Z \cdot X_{127} \quad \text{(Eq.72)}$$

3.3.6 Fertilization in irrigated crops

In this crop rotation, we consider that peasants added humanure, animal manure, or wood from vineyards to be buried. For the first flows we have already defined its composition. For the case of vineyard pruning, its contribution will correspond to its composition, except for the case of nitrogen where we discounted 20% lost through volatilization, as indicated in equations 73 to 75.

$$2{,}442\ kg \frac{pruning}{ha} \cdot \frac{2\ g\ N}{1\ kg\ pruning} \cdot \frac{1\ kg\ N}{1000\ g\ N} \cdot \frac{80\ kg\ N\ effective}{100\ kg\ N} \cdot X_{137} = 3.9X_{137}\ kg\ N/ha \quad \text{(Eq.73)}$$

$$2{,}442\ kg \frac{pruning}{ha} \cdot \frac{0.17\ g\ P}{1\ kg\ pruning} \cdot \frac{1\ kg\ P}{1000\ g\ P} \cdot X_{137} = 0.4X_{137}\ kg\ P/ha \quad \text{(Eq.74)}$$

$$2{,}442\ kg \frac{prunning}{ha} \cdot \frac{2.49\ g\ K}{1\ kg\ pruning} \cdot \frac{1\ kg\ K}{1000\ g\ K} \cdot X_{137} = 6.1X_{137}\ kg\ K/ha \quad \text{(Eq.75)}$$

Therefore, the composition of fertilizers used for irrigated land resulted from a balance of the different nutrients between soil replenishment needs and contributions of humanure, animal manure, or biomass buried. Since the ratio between crops is known, the total requirements for each rotation are calculated based on the quantity of land surface by soil quality. The requirements for each nutrient are presented in equations 76 to 78.

$$90.4 \cdot X_{23} + 76.2 \cdot X_{24} + 59.3 \cdot X_{25} \leq 2.8 \cdot Z \cdot X_{128} + 18.4 \cdot P \cdot M \cdot X_{130} + 2.6 \cdot M \cdot X_{130} + 3.8 \cdot Z \cdot X_{130} + 3.9 \cdot X_{137} \quad \text{(Eq.76)}$$

$$10.8 \cdot X_{23} + 8.2 \cdot X_{24} + 5.1 \cdot X_{25} \leq 2 \cdot Z \cdot X_{128} + 7.5 \cdot P \cdot M \cdot X_{130} + 0.6 \cdot M \cdot X_{130} + 1.8 \cdot Z \cdot X_{130} + 0.4 \cdot X_{137} \quad \text{(Eq.77)}$$

$$30.7 \cdot X_{23} + 22.6 \cdot X_{24} + 13.3 \cdot X_{25} \leq 1.1 \cdot Z \cdot X_{128} + 21.8 \cdot P \cdot M \cdot X_{130} + 3.0 \cdot M \cdot X_{130} + 3.2 \cdot Z \cdot X_{130} + 6.1 \cdot X_{137} \quad \text{(Eq.78)}$$

3.3.7 Fertilization in herbaceous dryland rotation

For fertilizing these crops farmers used animal manure and straws. Thus, we calculate leftover wheat straw, also from rye & wheat mixture (third soil quality), beans (dryland and irrigated land) and from vetches. In Table A2.7 we show the resulting formulas for each product and nutrient.

Table A2.7. Contribution of burying biomass of the different nutrients in the herbaceous dryland rotation. Source: Our own, based on the sources detailed in the text.

	Composition (g/kg)			Contribution (kg/ha)		
	N	P	K	N	P	K
Dryland wheat	4.8	1.0	5.2	$10.5(X_{26}-X_{103}-X_{104})$	$2.6(X_{26}-X_{103}-X_{104})$	$14.3(X_{26}-X_{103}-X_{104})$
				$8.2(X_{27}-X_{105}-X_{106})$	$2.0(X_{27}-X_{105}-X_{106})$	$11.1(X_{27}-X_{105}-X_{106})$
Rye & wheat mixture	4.8	1.0	5.2	$6.2(X_{29}-X_{111}-X_{112})$	$1.6(X_{29}-X_{111}-X_{112})$	$8.5(X_{29}-X_{111}-X_{112})$
Irrigated beans	10.4	1.7	8.9	$14.1X_{116}$	$2.8X_{116}$	$15.1X_{116}$
				$11.5X_{118}$	$2.3X_{118}$	$12.2X_{118}$
				$8.8X_{120}$	$1.8X_{120}$	$9.4X_{120}$
Dryland beans	10.4	1.7	8.9	$8.8X_{122}$	$1.8X_{122}$	$9.4X_{122}$
Vetches	10.4	1.7	8.9	$7.9X_{124}$	$1.6X_{124}$	$8.6X_{124}$
Potatoes	4.9	0.7	3.6	$4X_{30}$	$0.7X_{30}$	$3.6X_{30}$
				$3X_{31}$	$0.5X_{31}$	$2.7X_{31}$

We also calculated the amount of nutrients that farmers could import from forest to cropland. Since productivities varied according to soil quality, we consider the range of possible imports they had. Thus, we obtain the contributions per hectare of buried forest biomass shown in Table A2.8.

Table A2.8. Potential nutrients contribution of forest biomass in kg/ha regarding soil quality

	Associated variable	**N**	**P**	**K**
1st Soil quality	X_{140}	13.1	1.6	14.1
2nd Soil quality	X_{144}	10.4	1.2	10.6
3rd Soil quality	X_{148}	7.0	0.8	7.1

Source: Our own, based on the sources detailed in the text.

Based on the potential nutrient contribution of biomass, together with animal manure, humanure and the potential contribution of nutrients coming from forestland, and matching them to the cropland needs, we set restrictions for the three different nutrients in each crop (Eq.79-81).

$$41.5X_{26} + 30.6X_{27} + 21.3X_{29} + 24.7X_{13} - 4.6X_{15} - 1X_{16} + 13.4X_{30} + 9.7X_{31} \leq 10.5(X_{26} - X_{103} - X_{104}) + 8.2(X_{27} - X_{105} - X_{106}) + 6.2(X_{29} - X_{111} - X_{112}) + 14.1X_{116} + 11.5X_{118} + 8.8X_{120} + 8.8X_{122} + 7.9X_{124} + 4X_{30} + 3X_{31} + 2.8ZX_{129} + 18.4PMX_{131} + 2.6MX_{131} + 3.8ZX_{131} + 13.1X_{140} + 10.4X_{144} + 7.0X_{148} \qquad \text{(Eq.79)}$$

$$6.3X_{26} + 4.6X_{27} + 3.2X_{29} + 4.7X_{13} + 3.6X_{15} + 2.3X_{16} + 1.3X_{30} + 0.8X_{31} \leq 2.6(X_{26} - X_{103} - X_{104}) + 2.04(X_{27} - X_{105} - X_{106}) + 1.55(X_{29} - X_{111} - X_{112}) + 2.8X_{116} + 2.3X_{118} + 1.8X_{120} + 1.8X_{122} +$$

$$1.6X_{124} + 0.7X_{30} + 0.5X_{31} + 2ZX_{129} + 7.5PMX_{133} + 0.6MX_{133} + 1.8ZX_{133} + 1.6X_{140} + 1.2X_{144} + 0.8X_{148} \text{ (Eq.80)}$$

$$17.2X_{26} + 12.5X_{27} + 8.6X_{29} + 13.9X_{13} + 10.1X_{15} + 12.5X_{16} + 6.6X_{30} + 15.0X_{31} \leq 14.3(X_{26} - X_{103} - X_{104}) + 11.1(X_{27} - X_{105} - X_{106}) + 8.5(X_{29} - X_{111} - X_{112}) + 15.1X_{116} + 12.2X_{118} + 9.4X_{120} + 9.4X_{122} + 8.6X_{124} + 3.6X_{30} + 2.7X_{31} + 1.1ZX_{129} + 21.8PMX_{131} + 3.0MX_{131} + 3.2ZX_{131} + 14.1X_{140} + 10.6X_{144} + 7.1X_{148} \text{ (Eq.81)}$$

3.3.8 Fertilization of olive tree groves associated to a dryland crop rotation

In this case, apart from the animal manure provided, biomass was also buried. We estimate it could have come from leftovers of wheat straw, rye & wheat mixture straw of second soil quality, potatoes residues, lupines straw, and the remains of olive tree pruning. We can therefore calculate its fertilization potential. Table A2.9 shows the results for each product and nutrient.

Table A2.9. Contribution by burying biomass of different nutrients in the olive tree groves associated to dryland crop rotation

	Composition (g/kg)			Contribution (kg/ha)		
	N	P	K	N	P	K
Associated wheat	4.8	1	5.2	5.5(X_9-X_{107}-X_{108})	1.5(X_9-X_{107}-X_{108})	8(X_9-X_{107}-X_{108})
Rye & wheat mixture	4.8	1	5.2	4.5(X_{28}-X_{109}-X_{110})	1.1(X_{28}-X_{109}-X_{110})	6.2(X_{28}-X_{109}-X_{110})
Potatoes	4.9	0.7	3.6	3.1X_{32}	0.6X_{32}	2.8X_{32}
Lupines	5.0	0.5	1.3	3.8X_{126}	0.5X_{126}	1.2X_{126}
Olive trees	7.5	1.3	3.2	12.1X_{134}	2.6X_{134}	6.5X_{134}

Source: Our own, based on the sources detailed in the text.

Therefore, the restriction corresponding to fertilization of this crop rotation is the matching of the replenishment needs with the soil amendments of animal manure and burying biomass (Eq.82-84).

$$27.4X_9 + 14.9X_{10} + 21.4X_{28} + 18.8X_{12} + 17.8X_{32} + 2.6X_{17} + 25.4X_{33} + 21.4X_{34} + 17.9X_{35} \leq 5.8(X_9 - X_{107} - X_{108}) + 4.5(X_{28} - X_{109} - X_{110}) + 3.1X_{32} + 3.8X_{126} + 12.1X_{134} + 18.4PMX_{132} + 2.6MX_{132} + 3.8ZX_{132} + 13.1X_{141} + 10.4X_{145} + 7.0X_{149} \text{ (Eq.82)}$$

$$3.7X_9 + 1.6X_{10} + 2.8X_{28} + 2.1X_{12} + 1.6X_{32} + 4.1X_{17} + 3.1X_{33} + 2.7X_{34} + 2.4X_{35} \leq 1.5(X_9 - X_{107} - X_{108}) + 1.1(X_{28} - X_{109} - X_{110}) + 0.6X_{32} + 0.5X_{126} + 2.6X_{134} + 7.5PMX_{132} + 0.6MX_{132} + 1.8ZX_{132} + 1.6X_{141} + 1.2X_{145} + 0.8X_{149} \quad \text{(Eq.83)}$$

$$11.0X_9 + 3.9X_{10} + 8.4X_{28} + 10.5X_{12} + 10.1X_{32} + 6.1X_{17} + 7.5X_{33} + 6.4X_{34} + 5.5X_{35} \leq 7.9(X_9 - X_{107} - X_{108}) + 6.2(X_{28} - X_{109} - X_{110}) + 2.8X_{32} + 1.2X_{126} + 6.5X_{134} + 21.8PMX_{132} + 3.0MX_{132} + 3.2ZX_{132} + 14.1X_{141} + 10.6X_{145} + 7.1X_{149} \quad \text{(Eq.84)}$$

3.3.9 Fertilization of vineyards

Apart from the contribution of nutrients from animal manure, we also consider in this case burial of vines pruning as well as the possible entry of nutrients from forest biomass. Therefore, restrictions corresponding to nutrients replenishment are those indicated in equations 85 and 87.

$$13.2X_{36} + 10.5X_{37} + 6X_{38} \leq 18.4PMX_{133} + 2.6MX_{133} + 3.8ZX_{133} + 3.9X_{138} + 13.1X_{142} + 10.6X_{146} + 7.1X_{150} \quad \text{(Eq.85)}$$

$$1.1X_{36} + 0.8X_{37} + 0.3X_{38} \leq 7.5PMX_{133} + 0.6MX_{133} + 1.8ZX_{133} + 0.4X_{138} + 1.6X_{142} + 1.2X_{146} + 0.8X_{150} \quad \text{(Eq.86)}$$

$$10.1X_{36} + 8.6X_{37} + 6X_{38} \leq 21.8PMX_{133} + 3.0MX_{133} + 3.8ZX_{133} + 6.1X_{138} + 14.1X_{142} + 10.6X_{146} + 7.1X_{150} \quad \text{(Eq.87)}$$

3.3.10 Total irrigated surface and total farm surface

In order to ensure the adequacy of results to the edaphic capabilities we include two additional boundary conditions. For this purpose we consider that the whole irrigated area that existed, according to the municipal land tax register sources of Sentmenat, was the maximum possible irrigated land under those cultural practices and available technologies. So, the amount of land-used with this irrigated crop rotation has to represent in the farm-type considered the same percentage as at the municipal level. With a total surface of 42.54 ha over the 2,781 ha of farmland, that proportion was 1.5% as shown in equation 88.

$$X_4 + X_6 \leq 0.015 * (X_1 + X_2 + X_3 + X_4 + X_6 + X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{19} + X_{21} + X_{22}) \quad \text{(Eq.88)}$$

We also consider another restriction to ensure that the total area determined in the *MSS* scenario fits the local conditions at that time. This constraint will only be applied when analysing the *MSS* scenario. By dividing the total area among the population in the municipality we obtain Eq.89.

$$X_1 + X_2 + X_3 + X_4 + X_6 + X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{19} + X_{21} + X_{22} = 1.65 * Z \text{ (Eq.89)}$$

3.4 <u>Constraints for maintaining the Domestic Unit</u>

3.4.1 Food intake

When accounting for diets we will only consider food agroecosystems provided (that is, we exclude fish). Additionally, as already mentioned above, the model assumes that farmers could be free to obtain a perfect agrosilvopastoral mosaic to attain their self-sufficiency, as a counterfactual scenario to be contrasted with the actual situation in which they depended on exports, imports and the volatility of relative prices.

Indeed, historical sources confirm that most products included in the local diet came from the Vallès County. Peasant diets included mainly cereals, potatoes, legumes, oil and wine, with some products of animal origin (Cussó and Garrabou, 2000). Following the criteria of Marco et al. (forthcoming) we obtained an estimated average consumption for the average family unit of 5 people. Diet was mainly based on bread consumption, and potatoes to a lesser extent, contributing 70% and 12% respectively to daily intake. We show the results in Table A2.10.

Table A2.10. Food intake needs by our DU along a year

	Per DU (kg/day)	Per year and DU (kg)	Per year and person (kg)	Total consumption (kg/Z)
Bread	2.42	88.3	176	147
Olive oil[55]	0.06	22.9	4.5	12.5
Wine	0.40	146.8	29.4	29.4
Legumes	0.12	43.5	8.7	8.7
Potatoes	1.59	580.2	116.	116
Vegetables	0.86	315.3	63.1	63.1
Fresh fruit	0.14	50.5	10.1	10.1
Nuts	0.07	25.2	5.1	5.1
Meat	0.13	45.7	9.1	9.1

Source: Our own, based on the sources detailed in the text.

Therefore, crop distribution in a self-reproductive farm had to ensure that farmers could meet these nutritional needs. For all entry variables we set restrictions based on satisfying the human nutrition requirements, shown in equations 89 to 96. In them we assume a conversion factor of bread-wheat flour as 0.83 kg of flour/kg of bread. Finally, a percentage of shells, unserviceable parts and losses from cooking was considered to set the difference between data per year and person of direct food consumption, and total consumption in legumes, potatoes, vegetables, fruit, nuts and meats. Thus, they were the edible part. For that reason, yields of equations 90 to 94 are smaller than the values of productivity per hectare.[56]

$$1{,}242\cdot X_{23} + 1{,}023\cdot X_{24} + 731\cdot X_{25} + 1{,}169\cdot X_{26} + 877\cdot X_{27} + 585\cdot X_{9} + 424\cdot X_{28} + 636\, X_{29} \geq 147\cdot Z \quad \text{(Eq.89)}$$

$$273\cdot X_{33} + 202\cdot X_{34} + 141 X_{35} \geq 12.5\cdot Z \quad \text{(Eq.90)}$$

$$2{,}142\cdot X_{36} + 1{,}683\cdot X_{37} + 918\cdot X_{38} \geq 29.4\cdot Z \quad \text{(Eq.91)}$$

$$851.62\cdot X_{74} + 673.87\cdot X_{78} + 505.60\cdot X_{82} + 319.82\cdot X_{86} \geq 8.7\cdot Z \quad \text{(Eq.92)}$$

$$5069.59\cdot X_{1} = 63.1\cdot Z \quad \text{(Eq.93)}$$

$$1214.75\cdot X_{30} + 1250.5\cdot X_{31} + 1679.28\cdot X_{32} \geq 116\cdot Z \quad \text{(Eq.94)}$$

[55] The model includes the use of oil for illumination. According to our estimates, based on population data given by Garrabou (1,686 people), we estimated the local oil consumption for food and a total dietary consumption. This was 8,833 litres out of the 23,827 litres of apparent consumption in the municipality. The difference (14,994 litres) is divided between the number of certificates of the same source (347). We obtain an annual consumption of 43.20 litres/DU, that is a daily consumption of 0.118 litres/UD or 0.108 kg/UD we added in the food consumption data in the last column.

[56] Edible values are 79% in legumes, 82% in potatoes, 79% in vegetables and fresh fruits and 42% in nuts (Farran et al., 2004).

$$4147.5 \cdot X_2 = 10.1 \cdot Z \text{ (Eq.95)}$$

$$525 \cdot X_3 = 5.1 \cdot Z \text{ (Eq.96)}$$

For meat we calculated that with the estimated livestock density our DU obtained the total of 46 kg a year of meat required for an average farm at that time, according to the historical sources available.

3.4.2 Firewood for heating

It is also necessary to take into account that there were restrictions on the provision of firewood and wood. So we obtained the partial restriction to the exosomatic firewood consumption by this rural community based on an estimated consumption of 1.56 kg of wood fuel per inhabitant per day, following the criteria of Marco et al. (forthcoming). The sources of this flow could be forests (X_{139}, X_{143}, X_{147} amounting 5,438, 4,078 and 2,719 kg/ha respectively), from pruning of fruit and nut trees (X_2 and X_3, 2,475 and 2,847 Kg/ha respectively), from olive trees (X_{135}; 1,997 kg/ha), or the part of vine shoots that had not been used yet (X_{136}; 2,442 kg/ha)—as indicated in Eq. 97.

$$2475 \cdot X_2 + 2{,}847 \cdot X_3 + 1{,}997 \cdot X_{135} + 5{,}438\ X_{139} + 4078\ X_{143} + 2{,}719\ X_{147} + 2{,}442 \cdot X_{136} \geq 569 \cdot Z \text{ (Eq.97)}$$

3.4.3 Labour

In terms of labour, the restriction was that working capacity of the family did not exceed the labour needs of all the farms in the municipality. To calculate this we took, on the one hand, data on labour requirements for crops, forest and livestock maintenance (Garrabou and Planas, 1998). On the other hand, to calculate human labour capacity we used a monthly accounting to guarantee that there were no seasonal bottlenecks throughout the year.

a) Monthly labour capacity

We calculated the working capacity in the farm-type considered by estimating the ability of the 5 people taking gender and age into consideration. This implied a total availability of 580 workdays throughout a year. At monthly level, this meant an average of 9.7*Z workdays per month. However, we decided to consider the working capacity also based on the variation of hours of sunlight along the year. We calculated total hours of sunlight per day, based on latitude data and solar radiation functions. The latitude for Sentmenat is 41.6101 degrees. Once calculated, we obtain a correction factor for the duration of a day, by means of the factor 9.7*Z, as can be seen in Table A2.11.

Table A2.11. Weighting factors concerning total hours of sunlight. Source: Our own, based on the sources detailed in the text

	Daily hours of sunlight	Factor	Available workdays (*Z)
January	9.4	0.8	7.6
February	10.4	0.9	8.4
March	11.7	1.0	9.5
April	13.2	1.1	10.6
May	14.4	1.2	11.6
June	15.0	1.3	12.1
July	14.7	1.2	12.0
August	13.6	1.1	11.0
September	12.2	1.0	9.9
October	10.8	0.9	8.7
November	9.6	0.8	7.7
December	9.0	0.8	7.3
	12.0	1.00	9.7

.

b) Monthly requirements by crop

We calculated requirements for each crop on a monthly basis by weighting the annual data given in *Amillaramientos del Vallès* with the monthly distribution patterns detailed in Garrabou et al. (1992). The available data contains monthly workdays per hectare for the Counties of Empordà (1850-1870, 1930-1936), La Segarra (1880-1890), Vic (1830-1840, 1880-1890, 1930-1950) and El Penedès (1903-1907), all of them in Catalonia. We present this data in Table A2.12.

Table A2.12. Monthly requirements in workdays/ha

	Month												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
Vegetable gardens	6.1	6 1	8 5	13.6	15.3	15.3	18.8	18.8	17.0	10.0	6 8	6.1	142.4
Fresh fruits	0.0	3 3	0 0	0.0	0.0	1.9	1.9	5.3	5.3	0.0	0 0	0.0	17.7
Nuts	0.0	3 3	0 0	0.0	0.0	1.9	1.9	5.3	5.3	0.0	0 0	0.0	17.7
Wheat	0.0	4 9	8 7	2.4	0.0	4.8	14.1	3.9	1.9	5.3	3 4	0.0	49.5
Corn	0.0	4 2	7 3	1.0	9.1	7.2	0.0	4.4	1.9	8.3	0 0	8.7	52.0
Hemp	18.2	0 0	26 1	5,3	3.3	3.3	3.3	3.3	14.4	13.8	40 1	62.6	193.7
Beans	9.2	9 1	0 0	9.1	0.0	10.6	4.8	0.0	12.8	0.0	8 0	1.5	65.1
Wheat	0.0	4 9	8 8	2.5	0.0	4.8	14.2	3.9	2.0	5.4	3 4	0.0	50.0
Associated wheat	0.0	5 0	9 0	2.5	0.0	4.9	14.5	4.0	2.0	5.5	3 5	0.0	51.0
Corn	0.0	4 2	7 3	1.0	9.1	7.2	0.0	4.4	1.9	8.4	0 0	8.8	52.3
Rye & wheat mixture	0.0	6 2	9 7	4.2	0.0	4.2	9.6	3.4	2.9	4.7	3 5	0.0	48.3
Barley	0.0	2 1	4 2	2.1	0.0	4.7	14.3	14.7	3.0	2.5	0 4	0.0	48.1
Fodder	5.2	5 2	5 7	0.0	8.6	4.4	7.4	5.9	3.9	3.9	0 0	0.0	50.2
Potatoes	0.0	0 0	14 9	0.0	6.4	6.4	0.0	0.0	35.5	10.6	5 2	0.0	79.0
Beans	9.2	9 1	0 0	9.1	0.0	10.6	4.8	0.0	12.8	0.0	8 0	1.5	65.1
Vetches	9.2	9 1	0 0	9.1	0.0	10.6	4.8	0.0	12.8	0.0	8 0	1.5	65.1
Lupines	9.2	9 1	0 0	9.1	0.0	10.6	4.8	0.0	12.8	0.0	8 0	1.5	65.1
Olive trees	6.8	0 0	14 9	14.9	12.2	5.4	0.0	0.0	0.0	0.0	0 0	27.1	81.2
Vineyards	0.0	0 0	5 1	13.1	4.7	5.0	0.6	0.0	1.8	12.0	1 1	0.0	43.4

Source: Our own, based on the sources detailed in the text.

Regarding the care of livestock, there is a minimum of 35.5 workdays/year per mule and 27.87 workdays/year for the rest of livestock for a Z=5. On a monthly basis this will mean 3*M and 0.5*Z.

We add to these labour requirements the ones required by cropland fertilization, according to each type of fertilizing management, and using estimates from Soroa (1953). However, not all fertilization tasks took place in the same months. Thus, they are distributed as follows, based on cultivation schedules defined in Garrabou et al. (2012):

- For vegetable gardens and fruit tree orchards farmers fertilized in February and August (Eq. 99 and 100)

$$0.06Z\frac{X_{127}}{2} \text{ (Eq.99)}$$

$$0.06Z\frac{X_{127}}{2} \text{ (Eq.100)}$$

- In the irrigated rotation, they fertilized in February before sowing hemp (Eq. 101)

$$0.06ZX_{128} + 0.41PMX_{130} + 0.06MX_{130} + 0.08ZX_{130} + 4.34X_{137} \text{ (Eq.101)}$$

- For herbaceous dry rotations, according to the winter cereal cycle we assumed one fertilization in September, and another in March for corn (Eq. 102 and 103)

$$0.06Z\frac{X_{129}}{2} + 0.41PM\frac{X_{131}}{2} + 0.06M\frac{X_{131}}{2} + 0.08Z\frac{X_{131}}{2} + 4.87 \cdot (X_{26} - X_{103} - X_{104}) + +3.79 \cdot (X_{27} - X_{105} - X_{106}) + 3.79 \cdot (X_{29} - X_{111} - X_{112}) + 3.02 \cdot X_{116} + 2.45 \cdot X_{118} + 1.89 \cdot X_{120} + 1.89 \cdot X_{122} + 1.70 \cdot X_{124} + 1.81X_{30} + 1.36X_{31} \quad \text{(Eq.102)}$$

$$0.06Z\frac{X_{129}}{2} + 0.41PM\frac{X_{131}}{2} + 0.06M\frac{X_{131}}{2} + 0.08Z\frac{X_{131}}{2} + 12.09X_{140} + 9.07X_{144} + 6.05X_{148} \text{(Eq.103)}$$

- Within olive tree groves associated to a herbaceous rotation, considering that for burying remains of pruning it was necessary to have the ground not sown yet we assumed one fertilization in August (Eq. 104)

$$0.41PMX_{132} + 0.06MX_{132} + 0.08ZX_{132} + 2.04 \cdot (X_9 - X_{107} - X_{108}) + 2.09 \cdot (X_{28} - X_{109} - X_{110}) + 1.70 \cdot X_{126} + 1.39 \cdot X_{32} + 3.59 \cdot X_{134} + 12.09X_{141} + 9.07X_{145} + 6.05X_{149} \text{ (Eq.104)}$$

- Finally, in vineyards, biomass burying was done after pruning in May (Eq. 105)

$$0.41PMX_{133} + 0.06MX_{133} + 0.08ZX_{133} + 3.67 \cdot X_{19} + 4.34 \cdot X_{138} + 12.09X_{142} + 9.07X_{146} + 6.05X_{150} \text{ (Eq.105)}$$

Therefore, we express the labour associated with the entire maintenance of the agroecosystem for each month as shown in equation 106, taking as example the month of June.

$$15.3X_1 + 1.9X_2 + 1.9X_3 + 4.8X_4 + 7.2X_5 + 3.3X_6 + 10.6X_7 + 4.8X_8 + 4.9X_9 + 7.2X_{10} + 4.2X_{11} + 4.7X_{12} + 4.4X_{13} + 6.4X_{14} + 10.6X_{15} + 10.6X_{16} + 10.6X_{17} + 5.4X_{18} + 5X_{19} + 3 * M + 0.5 * Z \leq 12.1 * Z \qquad \text{(Eq.106)}$$

3.4.4 Monetary requirements

As a source to establish other economic necessities of our DU, we mainly used a study carried out on reproduction expenses of a rural DU in Catalonia in a context of wine-growing specialization (Colomé, 2015). For clothing and footwear Colomé proposes an average annual cost for an adult man of about 30 *pesetas*. Using the proposed factors on age for the whole family, this implies a total of 109.2 *pesetas* per DU, or 21.8*Z *pesetas*. For housing expenses, in order to pay the annual rent a peasant family would need the equivalent of about 36 workdays in the Catalan Penedès County in 1872. We considered that the average agricultural wage was around 72 *pesetas* (Colomé, 1996). However, at Catalan level another average has been set at around 85 *pesetas* (Vicedo et al., 2002). Summing up, expenses associated with the maintenance of the DU will be 21.8**Z* + 85 pesetas. Also as part of the maintenance of the DU we considered the cost of keeping and replacing the equipment of farm implements in order to use them in a sustainable manner. In this case, a study also cited by Colomé (1996) fixed the cost of amortization of farm implements in the municipality of Santa Margarida i els Monjos (Alt Penedès County) at 2.04 *pesetas*/ha, a value that we will be taken as a reference in our case. The annual cost of maintenance of the barrel and cellar for wine producing is estimated at 19.9 *pesetas*, according to Colomé (1996).

With regard to tax burdens, we consider the costs of paying the royal land, housing and livestock cadastral taxes, and the municipal ones. Regarding the seigneurial censuses paid to the

Marquis de Sentmenat, although it is true that some of them continued to be paid even at that time or even later, due to their devaluation through price inflation we considered them to be anecdotal. According to the *Distribution of Personal Wealth in Real Estate Ownership of 1852 in the Barcelona Province* (Library of the University of Barcelona, reference 146-1-II/13), in Sentmenat the cadastral taxes paid ranged on average 15% of taxable liquid incomes estimated (with a R^2 of 0.9996). The municipal taxes were accounted as a surcharge on this royal one, in such a way that surely ended up representing a direct tax burden of 20% of agricultural incomes calculated through the taxable liquid values set in the cadastre.

So as to identify the relationship set between the types and qualities of land and the tax burden paid, we made a multiple regression analysis relating the crop surface data of the 1859 municipal land register (*Amillaramiento*) and the taxable liquid incomes determined by the cadastre. The correlation had a R^2 value of 0.745. The resulting equation is the one presented in Eq. 107.

$$7.2(X_1 + X_2 + X_3 + X_4 + X_6) + 20.3(X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17}) + 7.5X_{19} + 5X_{22} \quad \text{(Eq.107)}$$

Likewise, we carried out a regression analysis on the valuation of the taxable liquid according to livestock owned. We get that a mule was computed as 34 *reales* of additional taxable income, a pig as 7.9, and a sheep as 1.3 (after 1869, 1 Spanish *peseta* = 4 *reales*).

To sum up, total costs of the monetary restriction are estimated as indicated in equation 108.

$$105 + 22 * Z + 7.15(X_1 + X_2 + X_3 + X_4 + X_6) + 20.3(X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{18}) + 7.5X_{19} + 5X_{22} + 1.7 \cdot M + 0.1 \cdot Z \quad \text{(Eq.108)}$$

Once the most basic monetary needs are satisfied, we calculated the total contribution of the farm surplus in monetary terms. For this, we estimated the potential sources of money that came from each crop. Given the approximate value of this restriction, we decided only to contemplate the surplus of the main products, and not what could be obtained from the sale of minor items such as straw (which had a small value). We obtained prices mainly from the *Estudio Agrícola del Vallés* of 1874, and through them we specified the possible incomes shown in Eq. 109.

$$(5067 \cdot X_1 - 64Z) \cdot 1.1 + (1679X_{30} + 1215X_{31} + 1250.5X_{32} - 116Z) \cdot 0.11 + (1242X_{23} + 1023X_{24} + 731X_{25} + 1169X_{26} + 877X_{27} + 585X_9 + 424X_{28} + 636X_{29} - 118 \cdot Z) \cdot 0.31 + (1348 \cdot (0.5X_{23} - X_{52} - X_{53} - X_{54} - X_{55}) + 1075 \cdot (0.5X_{24} - X_{56} - X_{57} - X_{58} - X_{59}) + 802 \cdot (0.5X_{25} - X_{60} - X_{61} - X_{62} - X_{63}) + 501(X_{10} - X_{64} - X_{65} - X_{66} - X_{67})) \cdot 0.29 + (1213 \cdot X_{23} + 1104 \cdot X_{24} + 996 \cdot X_{25}) \cdot 0.9625 + (1078 \cdot (0.5X_{23} - X_{71} - X_{72} - X_{73} - X_{74}) + 853 \cdot (0.5X_{24} - X_{75} - X_{76} - X_{77} - X_{78}) + 640 \cdot (0.5X_{25} - X_{79} - X_{80} - X_{81} - X_{82}) + 658(X_{15} - X_{83} - X_{84} - X_{85} - X_{86})) \cdot 0.42 + 439 \cdot (X_{12} - X_{48} - X_{49} - X_{50} - X_{51}) \cdot 0.20 + 6{,}754 \cdot 0.28 \cdot (X_{13} - X_{68} - X_{69} - X_{70}) \cdot 0.08 + 560 \cdot (X_{16} - X_{87} - X_{88} - X_{89}) \cdot 0.15 + 585 \cdot (X_{17} - X_{90} - X_{91} - X_{92}) \cdot 0.15 + (273X_{33} + 202X_{34} + 141X_{35} - 12.46 \cdot Z) \cdot 1.24 + (2142X_{36} + 1683X_{37} + 918X_{38} - 29.37 \cdot Z) \cdot 0.12 + 1627(X_{19} - X_{136} - X_{137} - X_{138}) \cdot 0.01 \quad \text{(Eq.109)}$$

4. Objective functions

In this last section we show the objective functions that run our model. These are three: total surface minimization, or intensive optimum (Eq.110); minimizing total labour required, or extensive optimum (Eq.111); and maximizing the land allocated to vineyards or monetary optimum (Eq.111).

$$min(X_1 + X_2 + X_3 + X_4 + X_6 + X_7 + X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{19} + X_{21} + X_{22}) \text{ (Eq.110)}$$

$$min(1044.6X_1 + 365.5X_2 + 365.5X_3 + 361.8X_4 + 360.4X_5 + 1513.2X_6 + 291.7X_7 + 365.5X_8 + 372.8X_9 + 361.8X_{10} + 353.1X_{11} + 351.6X_{12} + 365.5X_{13} + 557.7X_{14} + 300.5X_{15} + 277.8X_{16} + 358.2X_{17} + 593.6X_{18} + 304.8X_{19} + 7.3X_{21} + 79.8X_{22} + 3PM + 0.4M + 0.6Z + (4.9(X_{26} - X_{103} - X_{104}) + 3.8(X_{27} - X_{105} - X_{106}) + 2.0(X_9 - X_{107} - X_{108}) + 2.1(X_{28} - X_{109} - X_{110}) + 3.8(X_{29} - X_{111} - X_{112}) + 3.0X_{116} + 2.5X_{118} + 1.9X_{120} + 1.9X_{122} + 1.7X_{124} + 1.7X_{126} + 1.8X_{30} + 1.4X_{31} + 1.4X_{32} + 3.6X_{134} + 4.3(X_{137} + X_{138}) + 9.9(X_{140} + X_{141} + X_{142}) + 7.1(X_{144} + X_{145} + X_{146}) + 4.24(X_{148} + X_{149} + X_{150}) + 2.22X_{19} + 1.45X_{22}) \cdot 7.3 + 259PM + 40Z) \text{ (Eq.111)}$$

$$max(X_{19}) \text{ (Eq.112)}$$

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ANNEX III. NON-LINEAR OPTIMIZATION PROGRAMME OF THE SFRA FOR 2009

In these supplementary materials we present the variables and assumptions of the nonlinear optimization model. Similarly to the supplementary materials presented in Annex II, we will divide the model into the following sections: definition of variables and their constraints, boundary conditions, general and specific restrictions, objective functions and sensitivity analysis of the *SFRA*.

Given the volume of variables and restrictions of our model, in this case we will not present the restrictions followed by their explanations, but a general reasoning of the most relevant assumptions of the *SFRA*. Finally, we include the optimization program. As we will see, there we reorganize the boundary conditions and constraints in a more comprehensive way than the one Annex II.

1. Main variables and their constraints

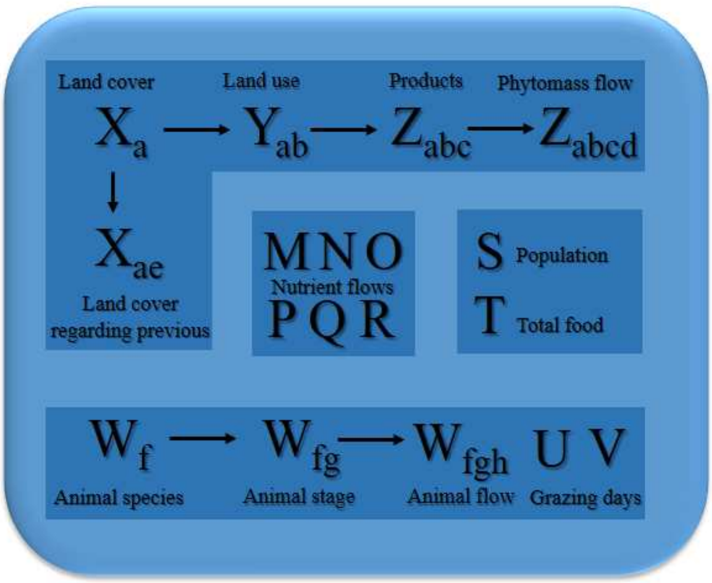

Figure A3.1. Variables in the SFRA for 2009. Source: Our own.

In order to set the structure of the model, we first define the variables and the relations among them. Given the complexity of developing a socioecological model, with the experience of the first *SFRA*, and following the structure of funds, we define 3 groups of variables: for population (S, T), for livestock (U, V, W) and a last one for soil fund (M, N, O, P, Q, R, X, Y, Z).

For the population fund, we define S and T. Their units correspond to number of inhabitants the first and MJ of metabolizable energy (ME) the second. Regarding livestock, the variables W, U and V represent individuals of animals the first one and days the next two. And lastly, variables X, Y and Z are surface units (hectares), while variables M to R refer to kg of nutrient per ha.

While V, W, X, Y and Z represent subgroups of variables, M to U are unique variables. This is why the first ones present subscripts[57]. Arrows in Figure A3.1 indicate hierarchical relationships between variables. This implies some first restrictions that refer to the links between hierarchical variables in form of equality as it can be seen in Eq. 1. Thus, any flow in the agroecosystem is registered by a Z_{abcd} or a W_{fgh}. The first ones, Z_{abcd}, are representative of a proportional amount of some specific product (Z_{abc}) that comes from a land use (Y_{ab}) which is part of some cover (X_a). Therefore, its units are in terms of surface area. For the latter, W_{fgh}, they

[57] These subscripts take consecutive integer values. In order to identify a variable that is part of a hierarchical structure, each subscript indicates its position with respect to its previous variable. For example, for variable Z_{64212} subscripts read as a = 6, b = 4, c = 2 and d = 12, which means that it belongs to cover X_6 (forest), land use Y_{64} (oak forest with slope less than 60%, pasturable), by-product Z_{642} (grass of this forest) and specifically to flow 12, which is the flow of pasture devoted to feed animal stage W_{411}, which are adult sheep for meat production.

reflect an amount of some flows coming from livestock (W_{fgh}) that depart from an animal stage (W_{fg}) and therefore belongs to a species (W_f). In this case, then, units are number of individuals.

$$\sum_{b=1}^{b=n} Y_{ab} = X_a \quad \text{(Eq. 1)}$$

Indeed, we set some constraints to guarantee that the surface of a given cover (X_a) equals the sum of all the surfaces of this one (X_{ae}). The same happens with animals (W_f) with which we set an equality with the sum of all animals in different stages of development (W_{fg}). From these associations, we obtain a total of 198 constraints.

2. Boundary conditions

Boundary conditions are those thresholds that are set as pre-fixed and which determine the limits of the *SFRA* through assumptions about its own development for each fund. Below, we list some of the assumptions we already presented in section 4.1.1 of chapter 7.

2.1 Society and Agrarian community

With respect to the society fund, we consider the population structure as a boundary condition. This determines the nutritional needs according to age and gender.

From data from population census of 2009 (IDESCAT, 2009a), we obtain the age pyramid in Figure A3.2, which presents a clear regressive type, typical of those countries which are considered economically developed. These weights for age and gender will define the average nutritional needs.

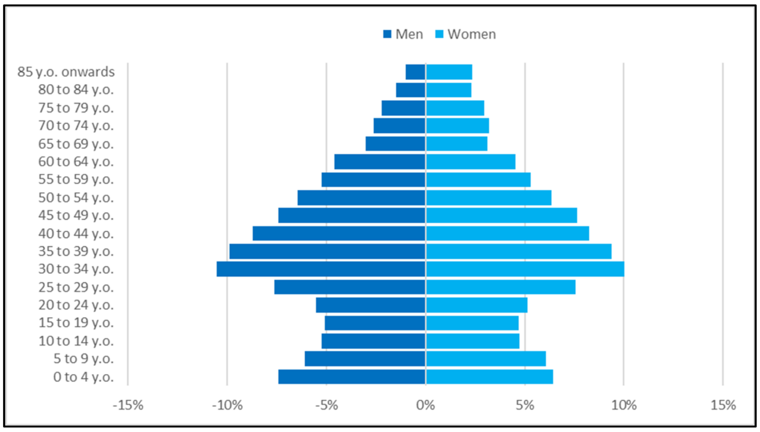

Figure A3.2. Age pyramid for the 4 municipalities of the case study from census of 2009. Source: Our own based on IDESCAT (2009)

We estimate the energy need according to the information of requirements by FAO (2004). We need to define what energy requirements are, based on the level of habitual physical activity, as well as average human weights per age class. Thus, we use data of the National Health Survey (Ministerio de Sanidad, 2014). These results are also different according to gender. Average weights at state level come from EUROSTAT (2009). Results of daily energy requirements by age categories are those shown in Table A3.1.

Table A3.1. Daily energetic requirements by age category (Kcal/day) and gender for the study area in 2009. Sources: Our own, calculated from FAO (2004) and Ministerio de Sanidad (2014).

	Men	**Women**
0 to 4 y.o.	897	820
5 to 9 y.o.	1,619	1,510
10 to 14 y.o.	2,470	2,250
15 to 19 y.o.	3,151	2,313
20 to 30 y.o.	2,999	2,245
30 to 59 y.o.	2,716	2,113
60 y.o. onwards	2,344	1,890

From weighting the results of Table A3.1 with the distribution of age classes and gender of Figure A3.1, we obtain an average requirement of daily metabolizable energy of 2,256 kcal/day. This will be the reference value in the analysis of diets, explained in section 3.1.1.

On the other hand, regarding the agrarian community, we considered that labour requirements are similar to the current ones, given the high level of mechanization. Therefore, we use labour intensities based on information of labour cost per hectare from farm surveys (Xarxa Comptable Agrària de Catalunya, 2010). According to this, the Agricultural Working Units (AWU) per surface unit or head of livestock are those indicated in Table A3.2. Based on these data, it is possible to calculate the amount of work required for each scenario and, thus, to estimate the total number of required workers[58]. However, it is necessary to point out that under agroecological management, these figures would not be exactly the same, e.g. it is imperative to minimize ploughing as a necessary condition for the maintenance of physical and biological soil fertility, so the use of machinery would be reduced anyway (Altieri, 1999).

Table A3.2. Labor requirements for surface or livestock unit considered in SFRA for 2009. Source: Adapted from XCAC (2010).

	AWU/ha
Vegetables	0.291
Fresh fruits	0.184
***Montcada* wheat**	0.014
Chickpeas	0.010
***Spelt* wheat**	0.014
Lentils	0.010
Mustard	0.010
Triticale	0.014
Fenugreek	0.010

	AWU/ha
Barley	0.009
Potatoes	0.098
***Fava* beans**	0.010
Olive groves	0.036
Almond groves	0.025
Vineyards	0.056
Pastures	0.007
Forest	0.002

	AWU/unit
Chickens	0.00020
Hens	0.00004
Porcine	0.00050
Meat sheep	0.00200
Milk sheep	0.00400

58 This total number of AWUs will not be equal to the total necessary people because seasonal information is not available. Thus, the total need of AWUs will be known, but it may be concentrated at a specific time span of the year.

2.2 Livestock

As indicated in section 4.1.1 of chapter 7, we select three different animal species for livestock: chickens and hens, pigs and sheep. We choose them because they are representative of the three categories defined in the development of the *SFRA*.

Nevertheless, we also base this selection on functional and representative reasons for our agroecosystem: Pigs are the most consumed animals in current diets; chickens are the second ones and although they are not the only ones producing eggs, theirs have a prevalence of 98%. Finally, we select sheep because of their ability for grazing heavily scrubbed lands -something cows can't do- which allows them to take advantage of forest resources which have been abandoned for a long time and makes them necessary, at least in the early stages of grassland recovery (Taüll, 2007). However, it is important to point out that sheep for milk production cannot graze in forest because of their difficulty when moving on the undergrowth.

Therefore, based on these three types, we define the cycles and relationships between the different life stages of animals. These cycles will allow setting general restrictions for livestock. Variables referring to same species are related in their different stages as shown in Eq.2, where W_{fg} is a phase *g* for the species *f*, W_{fg0} is the reference stage (usually a reproductive stage) and parameter *a* is the ratio of individuals between W_{fg} and W_{fg0} (number of individuals of the W_{fg} stage per unit of reference animal W_{fg0}).

$$W_{fg} = a \cdot W_{fg0} \quad \text{(Eq 2)}$$

Below we present flow diagrams between different stages for the considered species.

2.2.1 Stage relations between hens and chickens

Figure A3.3 represents the life cycle for hens, extracted from the recommendations of regional organic poultry (Pont Andrés, 2009). It is divided in three main phases: Initially, there is a process of chicks' growth, divided into three stages according to different energy requirements. From the 21st week, laying begins, but full production is not given until the 41st week. This process lasts until the 79th week during which they start an induced moulting process so that they can continue laying approximately until the 120th week, when they are sacrificed. As it is not a mammalian animal, its reproduction is simple and therefore we do not consider incubation process of eggs.

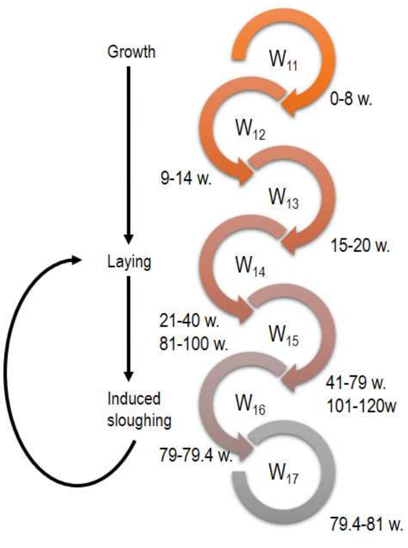

Figure A3.3. Life cycle for hens considered.
Source: Our own.

In relation to chickens, we show their cycle in Figure A3.4. It is even simpler than the previous one, with only three different stages taken from a study on organic poultry (UPAE, 2010). In the initial phase, up to the 4th week, they consume initiation grains. Until the 9th week, when they make the most growth. The last stage lasts for 7 weeks in which they have, again, different requirements.

As it can be seen, hens and chickens are defined with two different variables of species (W_1 and W_2), because they have completely different cycles from birth.

Thus, based on the temporal relationships that exist between the different stages, for both hens (W_{11}-W_{17}) and chickens (W_{21}-W_{23}), we define general constraints that determine the proportion of animals there must be in each stage throughout an annual cycle.

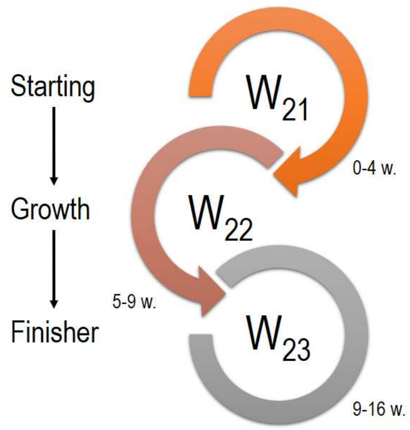

Figure A3.4. Life cycle for broilers considered. Source: Our own.

2.2.2 *Stage relations for pigs*

For pigs, the difference with respect to the needs of poultry is that they are mammalian animals and, therefore, have two different lines of development: pigs that are going to fattening and those sows that will serve as pregnant sows. Moreover, we consider some breeding pigs. In Figure A3.5 we show the relations among them, assuming that farms are carried out under closed cycle. We use data extracted from Pino de Delàs & Vila Camps (2005) i Vila Camps (2007).

Each pregnant sow has about 18 surviving piglets/year. Regardless of their destination, during the first 7 weeks they stay together, the piglets being mainly fed from breast milk, and gradually being given solid foods. Between these first two phases, they grow from less than 7 kg/piglet to approximately 23 kg. Once they reach the desired weight, most of them (17.8 out of 18) go to the fattening line, while only 0.2 remain as replacement sows. Moreover, we also estimate that a farm requires one breeding pig for every 20 sows in order to perform natural service. It will remain in the W_{35} phase once it is adult, throughout its remaining life span.

Regarding pigs that go through fattening line, they pass two stages of only 3 weeks the first and 4 the second. As a result, they gain from 23 to 50 kg in the first stage and from 50 to 110 kg (final-of-live-weight) in the second.

In relation to pregnancy sows, they must reach 40 weeks before the first insemination, so there are two stages of controlled fattening, reaching in the first one from 23 to 50 kg and then from 50 to 130 kg of live weight. Once there, they are performed different insemination cycles, up to 4 years, conformed by a gestation cycle (34 weeks), breastfeeding (12 weeks) and 6 weeks between weaning and new insemination.

From this information, general restrictions for pigs are set, taking into account these time proportions between each phase, and the proportion of piglets that are used for fattening or as replenishment sows.

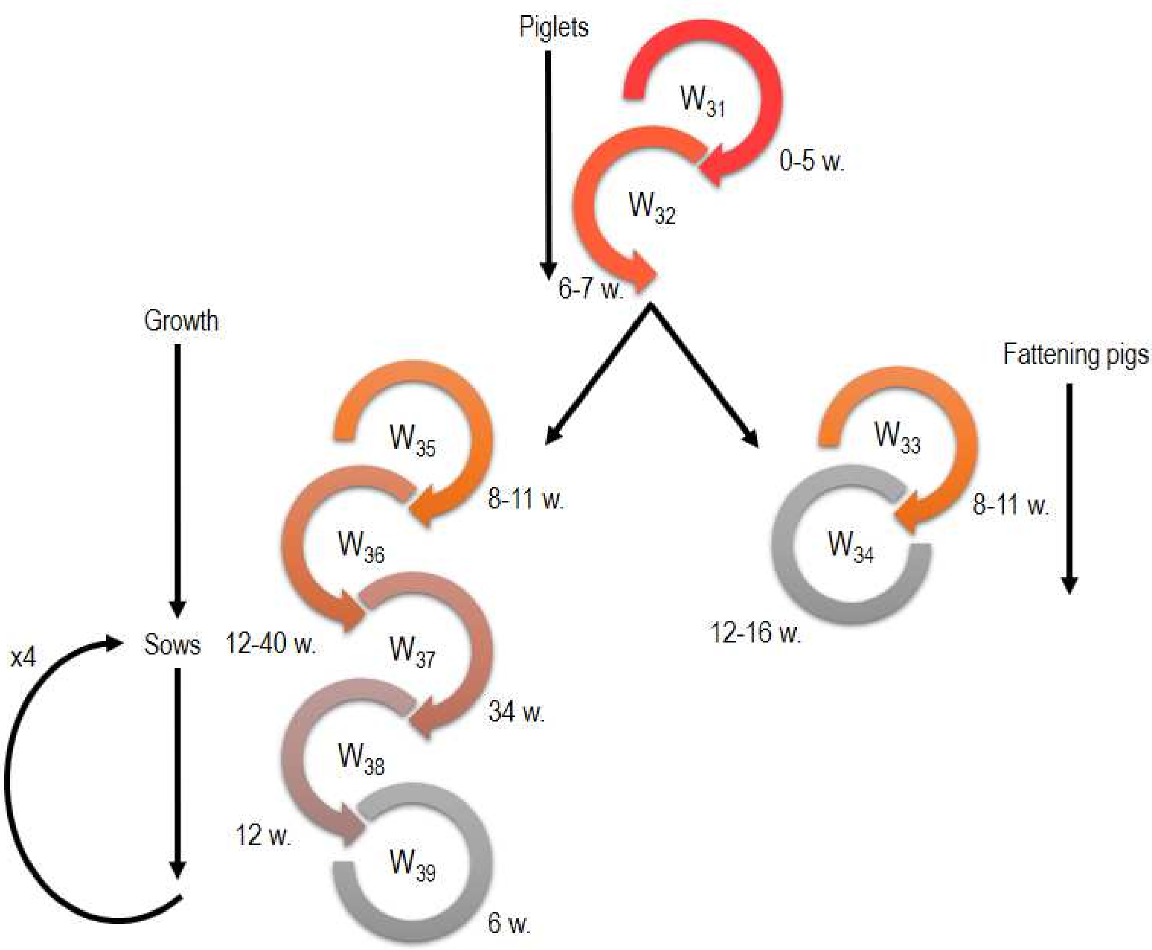

Figure A3.5. Live cycle for pigs considered. Source: Our own.

2.2.3 Stage relations for sheep

Finally, we present the different stages for ovine, which, as it will be seen, are quite similar to those of pigs. However, cycles are noticeably different, as it can be seen in Figure A3.6. We take the presented data from Milán Sendra & Caja López (2014).

Each breeding sheep (W_{411} or W_{412}) has a delivery of one or two lambs per year , what makes an average of 1.3 lambs per year and breeding sheep. Most of them are directly destined to sale, but some of them are kept for sheep replenishment or to become muttons. For sheep, we consider an approximate life span of 8 years, whereas for muttons it is only of 2 years. Approximately, one mutton is necessary for each 25 sheep.

Lambs for sale are milk-fed for 5 weeks until they reach an approximate weight of 10.5 kg. From there, they begin to eat food until the 11th week, when they weigh about 20 kg and they are sold on market. On the other hand, the small part destined to become muttons (approximately 2%) must have a later phase of growth up to 50 kg. Then, they live up to the 2nd year.

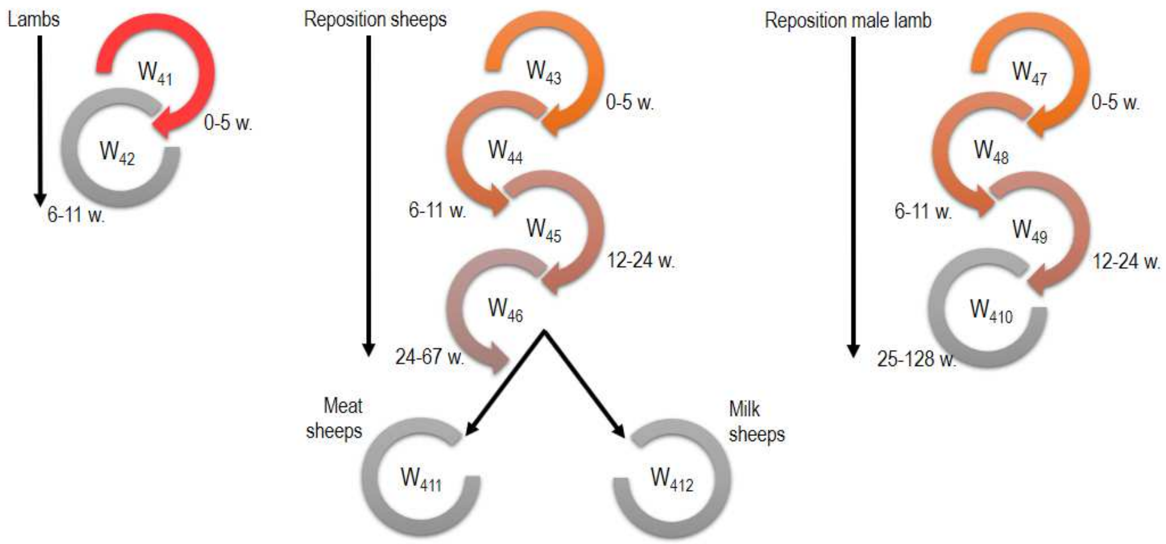

Figure A3.6. Live cycle for sheep considered. Source: Our own.

In terms of replacement sheep, which should be 15% of those born, they undergo a growth process of 24 weeks. This consists of 3 phases, similar to those of the mutton. On the 67th week, they are already fertile. Once they have delivered, we consider two different handles. If they are for meat, once the lambs have been discarded they are dried and they can continue eating on forest grass (W_{411}). Instead, if they are meant to produce milk (W_{412}), their diet will be more demanding and they will not be able to graze in forests.

2.3 Soil fund

Lastly, we present the two boundary conditions for soil fund: agrarian surface and possible crops, with their respective yields. Therefore, we are assuming the same consideration for total surface and yields as in the previous *SFRA*. We deem that as soil is the only fund with territorial expression, we infer to this the boundary conditions and constraints of the whole surface. This is why we also connect soil fund to farm-associated biodiversity, as we will later see. As well, as it is through soil that plants can grow, we refer yields to this fund.

2.3.1 Surface affected by agrarian metabolism

Regarding soil fund, the main boundary condition is the total agrarian surface an area has. We take data of 2009 on composition of land uses, indicated in Table A3.3. As you can see, the four municipalities have a total area of 11,996 ha, of which 2,266 are urban, infrastructures, riverbeds or rocky outcrops. All of them are unsuitable for agricultural purposes. It is obvious that in urban areas there may be some urban gardens or green areas, but we consider these do not intervene in a significant way, for now, in the whole agrarian metabolism.

Table A3.3. Land covers for 2009 in the Vall. Source: Adapted from CREAF (2009)

	Associated variable	Surface (ha)
Irrigated land	X_1	279.5
Dryland herbaceous crops	X_2	1,546.3
Olive and almond groves	X_3	274.7
Vineyards	X_4	15.4
Pastures	X_5	206.4
Forests	X_6	7,406.9
Agrarian inert uses	X_7	2,266.6
		11,995.7

For irrigation areas, we determine some boundary conditions for water metabolism. We want to approach that the exploitation of aquifers does not exceed a sustainable volume of extraction. However, there is little information available and in this *SFRA* we do not deepen into it. Therefore, we take a rough approach, which may be a starting point for future researches.

According to data of the Besòs aquifer (which includes a large part of municipalities of the Vallès Occidental and Oriental counties, with presence in more than 30 municipalities), the quantitative level of extraction in 2004 was 46 % (ACA, 2004). This means that it would surely be possible to increase the irrigated area in a sustainable way. Therefore, and as an approximate estimation, we consider irrigated surface could increase to 100% exploitation, while maintaining the share of water consumption for agriculture in relation to other uses. However, in view of future studies, we would like to estimate real necessary volumes at basin scale and their interaction with other non-agrarian metabolisms.

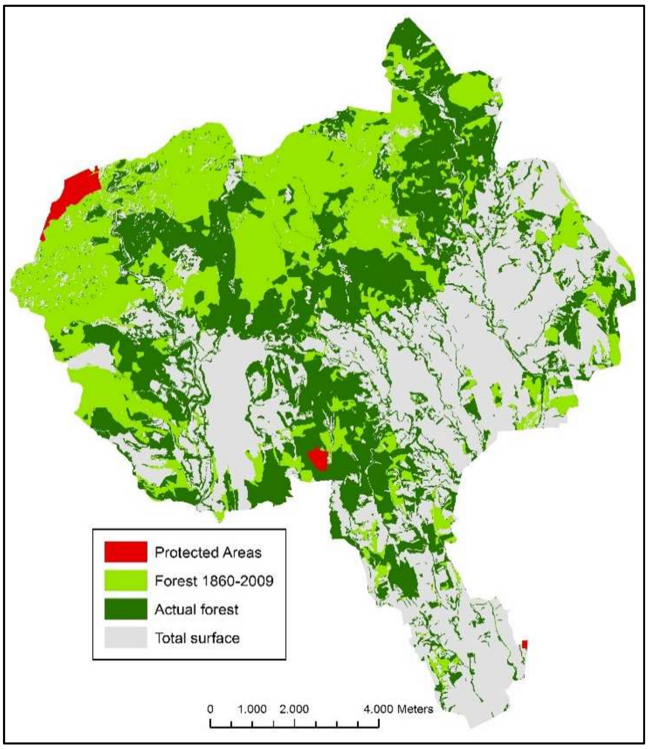

Figure A3.7. Protected areas and long-term forest map for the case study area in 2009. Source: Our own, adapted from DGPAMN (2017) and Tello et al. (2004)

In relation to the rest of uses, we cannot consider absolute freedom of uses transformation. Either because of the high impacts this might suppose on the natural environment, or because of technical unsuitability of cropping in some areas. For all of them, we will latter set restrictions in relation to slope and crop suitability.

In order to restrict the impact of human activities on environment, we consider necessary to protect some parts of the forests, both from the point of view of their conservation and their intrinsic value[59]. We assume, first, that those habitats that are relevant to protect will be those that already have protection figures. But also, we believe it is important to take into account those forests with long permanence as a first boundary condition on the maximum cropping surface that could be reached[60].

Thus, as it can be seen in Figure A3.7, we identify which areas have legal protection figures through the corresponding map (DGPAMN, 2017), as well as those forests with a long history, which have been identified as forest both in maps of land uses of 1860, 1956 and 2009 (CREAF, 2009; Tello et al., 2004). Thus, we obtain a total amount of 3,752 hectares of forest, which we believe that should not be reduced. This sets the threshold for the expansion of

[59] As we will note later this is not against taking a perspective of *land sharing strategy*. That is, we believe that a balance between human disturbances and maintenance of the ecological functionality of the territory is necessary. Nevertheless, we understand that the balance is between having the entire territory with human activity or completely polarizing activity only in a few agricultural spaces (Marull et al., in press; Tello and González de Molina, 2017)

[60] As indicated in Chapter 7, this is a strong and decisive assumption we made in the model. Defining which forest regions must be protected requires both processes of deliberation and scientific studies in relation to the intrinsic value of each forest plot. However, we presume this is a conservative approach, which would probably lead to lower values of potentially cropping areas.

agricultural activity, together with surfaces that do not intervene in agricultural terms, and those forests with slopes above 30%. In total, there are about 7,407 ha we propose to be kept as forest.

2.3.2 Crops and crop yields

As it has been said, as it happens with the animal selection, in this case we take crops which are representative of the range of possibilities within this agroecosystem. For irrigated areas, we consider farmers should only grow vegetables or fresh fruits. However, when analysing land use distributions for 2009 we observe irrigated crops of fodder or even cereal. We base this constraint on the principle indicated by Tuson (2011), according to which irrigated land is not justified for crops that can correctly grow in dryland, when this does not entail too low yields.

In relation to herbaceous crops, we defined three rotations, already explained in section 4.1.1 of Chapter 7. This led us to define general restrictions for rotations ensuring that the surface of a crop must be equivalent to those that follow it. There are 12 different crops, so this means 12 general rotation restrictions.

For woody crops, we propose olive trees, vineyards and almond trees. The current amount of oil consumed comes in 71% from olive (MAGRAMA, 2009), and the wine can only be produced with the vineyard. On the other hand, many woody crops produce nuts. We take the almond tree as representative condition for almond tree as regards to nuts as in the case of dry crops or animals.

On the other hand, for these woody crops and fruit trees, we want to make profit from the advantages of their associated crops (Eichhorn et al., 2006; Malézieux et al., 2009), as it was done on the same Vallès at least until the middle of 19th century (Garrabou and Planas, 1998). Thus, we propose intercropping an herbaceous cover of oats and vetches, as it could be done by others such as pea fodder, *vicia ervilia* or other cereals and legumes (Pastor, 2001; Pulido et al., 2006; Xavier Fontanet Roig., 2012). It is a good resource for grazing and it prevents them from entering into competition with fresh fruit, olives, vines or almonds in critical phases of fruit development. Finally, we will consider the improvement of pastures through planting seed mixtures of species (alfalfa, scab, dactylis and ray-grass) to increase their pastoral value and reduce their nitrogen requirements.

Lastly, one of the latest assumptions that affects the *SFRA* as a boundary condition are yields. These are very variable from one year to another, as we will see in the last sensitivity analysis. However, for the reference model, we will use the data available for 2009.

The largest part of yields correspond to estimations based on information from the agricultural census of 2009 (IDESCAT, 2009b), adapted to conditions of organic cultivation. We adapt yields from the gap identified in exhaustive revisions of comparative data between conventional and organic agriculture (De Ponti et al., 2012; Seufert et al., 2012). Therefore, we take a conservative approach regarding the potential of this management, taking into account that the diversification of practices can reduce the gap, or even overcome it (Ponisio et al., 2015). For crops with no regional information, we use data from a nearby ecological agricultural park or empirical studies in close regions with homologous Mediterranean conditions (Consorci de Gallecs, 2010; Tuson, 2009). Lastly, we obtain by-products yields with a ratio of main product, based on the database generated by Guzmán et al. (2014), but also with specific studies for each crop (Bilanzdija et al., 2012; Jankowski et al., 2014; Kok et al., 2007; Maiti et al., 2007; Sáez-Bastante et al., 2016; Wadhwa and Bakshi, 2013). Table A3.4 shows the estimated average yields for each product and by-product. As it can be seen, in forests there are two types of different pasture yields, which are in fact associated with the canopy cover ratio (> 30% or <30% respectively). Data on feasible grazing yields in forest is adapted from Taull (2007) and Taüll &

Baiges (2007), according to which livestock density[61] within forest ranges from 0.1-0.3 LU500/ha, under Mediterranean conditions.

Table A3.4. Yields and variables for different crops considered in the *SFRA* for 2009. Source: Our own, adapted from different revisions mentioned in text.

Crop or land use	Product	Yield
Vegetables (Y_{11})	Vegetables	25.725
	Crop residues	20.580
Fresh fruits (Y_{12})	Fresh fruit	11.622
	Wood	2.470
	Pasture	1.000
***Montcada* wheat (Y_{21})**	Grain	2.860
	Straw	4.487
	Stubble	206
Chickpeas (Y_{22})	Chickpeas	461
	Straw	668
***Spelt* wheat (Y_{23})**	Grain	2.844
	Straw	4.462
	Stubble	205
Lentils (Y_{24})	Grain	631
	Straw	915
Mustard (Y_{25})	Grain	998
	Straw	2.041
Triticale (Y_{26})	Grain	2.339
	Straw	3.670
	Stubble	168
Fenugreek (Y_{27})	Grain	876
	Straw	1.271
Barley (Y_{28})	Grain	1.795
	Straw	2.817
	Stubble	129

Crop or land use	Product	Yield
Potatoes (Y_{29})	Potatoes	7.826
	Stems & leaves	3.522
***Fava* beans (Y_{20})**	*Fava* beans	975
	Stems & leaves	1.413
Olive groves (Y_{31})	Olive oil	244
	Olive oil pomace	1.078
	Olive tree browsing	712
	Wood	2.443
	Pasture	1.282
Almond groves (Y_{32})	Almonds	624
	Husk and shell	1.454
	Wood	1.627
	Pasture	1.282
Vineyards (Y_{41})	Grapevine juice	6.395
	Grapevine pomace	3.453
	Leaves	1.925
	Wood	2.442
	Pasture	1.282
Pastures (Y_{51})	Pasture	2.136
***Pine* forest (Y_{61}- Y_{62}-Y_{65})**	Wood	3.500
	Pasture	1.500-1.850
***Holm oak* forest (Y_{63}- Y_{64}-Y_{66})**	Wood	2.800
	Pasture	1.500-1.850

These are field yields for the year 2009. However, from a reproductive point of view, it is also necessary to consider the amount of seed devoted to production for following years. These requirements are discounted for vegetables, cereals, legumes and potatoes, based on several sources (Consorci de Gallecs, 2010; Sáez-Bastante et al., 2016; Soroa, 1953; Tuson, 2009). In Table A3.6 we show the considered values.

For grassland, it is also relevant to take into account a dynamic problem; since they are not available proportionally distributed throughout the year. As already noted in chapter 7, we consider transhumance as an appropriate historical management for this temporary scarcity of grasslands on planes with the corresponding reverse on mountains. Therefore, real densities would double the considered ones but only for half of the year; thus, the resulting effect on an annual scale would be similar. However, in further models, it would be convenient to consider

[61] We represent the units of livestock density in LU500, which are livestock units equivalent to a 500 kg of animal.

temporalities of different flows and agrarian processes in order to analyse dynamics of the agroecosystem throughout the year.

Table A3.5. Seed requirements for vegetables, cereals, potatoes and legumes. Sources: Adapted from Consorci de Gallecs (2010), Sáez-Bastante et al. (2016), Soroa (1953), Tuson (2009)

	Seed (kg/ha)
Vegetables (Y_{11})	154
***Montcada* wheat (Y_{21})**	135
Chickpeas (Y_{22})	40
***Spelt* wheat (Y_{23})**	135
Lentils (Y_{24})	200
Mustard (Y_{25})	20

	Seed (kg/ha)
Triticale (Y_{26})	135
Fenugreek (Y_{27})	70
Barley (Y_{28})	135
Potatoes (Y_{29})	495
***Fava* beans (Y_{20})**	200

3. Constraints

Once we fixed the boundary conditions for setting the limits of the agroecosystem, we continue with the constraints for the non-linear programming. For this, we use the flows defined in Figure A3.7.1 of chapter 7.

3.1 Constraints for society fund

The two flows that are part of the *SFRA* within the optimization for society fund are both food and domestic residues that return for restoring soil fertility. As already mentioned above, we do not consider neither workflow nor fuel wood, which result from the model itself.

3.1.1 Food

Food, together with the maintenance or reduction of the forest area, is the flow that determines different scenarios. As mentioned above, we consider 3 different options of diet optimization:

a. Production that maximizes complete food baskets that satisfy current diet (CD scenario). In this case, what we want is to maximize the amount of population (T) which can be satisfied with this diet.
b. Production of complete food baskets planned according to human physiological needs (HD scenario). In the same way as with the previous, in this case we want to maximize the amount of population that can be held on a healthy diet (T).
c. Production that maximizes the amount of food produced in the territory, regardless of the needs of the local diets (MO scenario). In this case, unlike CD and HD cases, what we maximize is total amount of food produced (U) in terms of metabolizable energy.

We are aware that maximizing the production of metabolizable energy does not entail maximizing the profit from production. Beyond the energy obtained, people have other physiological and social needs. However, we understand that, despite not being able to avoid a certain energy reduction (Georgescu-Roegen, 1971), the value of metabolizable energy for a certain type of food is the best approximation that can be made to its in use value (compared to kg of fresh biomass, total protein content or others). Moreover, we consider this socio-ecological value much more significant than maximizing the income, because due to its volatility and speculation, prices would force a change in the way of optimizing the territory every year. This would result unsustainable for the biological basis of agrarian economies.

Regarding the current diet (CD), we use data from the Food Consumption Panel of Households (MAGRAMA, 2009). There, they present the consumption in kg of fresh matter of around 400 different types of food, at regional level (Catalonia). We group and transform them to obtain data of the necessary agricultural products. As well, since in the model we simplify the range of products, we have to adapt some of them. For example, for beef we consider consumption of sheep meat. At the same time, there are several products that do not have a substitute within the agricultural system e.g., cocoa or rice. Therefore, when calculating the potential supply of complete diets at an agroecosystem level, we will take into account only the possible importation of fish[62]. Then we will proportionally escalate the rest of the products of the agroecosystem to obtain the required energy quantity (2,256 Kcal/day). We show the final diet obtained in Table A3.6.

Table A3.6. Daily consumption (g of f.m.) per person estimated for current diet in 2009. Source: Adapted from MAGRAMA, (2009) and FAO (2004)[63]

	Consumption
Vegetables	302,7
Fresh fruit	359,4
Dry fruits	10,3
Wheat flour	201,4
Legumes	12,2
Potatoes	83,9
Oil	33,6
Wine	43,0

	Consumption
Poultry meat	54,4
Pork meat	86,8
Sheep meat	25,1
Eggs	28,2
Milk	488,0
Fish	90,2

Therefore, we built as many constraints as products produced in the agroecosystem by establishing an equality between production and requirement per person. We have to take into account, for this CD scenario but also for the rest, that food products are not entirely consumable. There are parts of them (skins, bones, etc.) that are outside real consumption. Because of this, we apply some correction factors for the edible part (Farran et al., 2004).

On the other hand, regarding animal production, and also obtained from data in sources in section 2.2, we consider that hens (W_{14} and W_{15}) lay about 14 kg eggs/year. For each chicken place kept throughout the year (W_2) we obtain 5 kg of meat, and for each place for mature laying hens (W_{15}) we obtain 1 kg of meat. In relation to pigs, each place for breeding sows (W_{37}, W_{38} and W_{39}) produces 1.590 kg of pork meat. And finally, for sheep, from each dry adult sheep or milk producer (W_{411} and W_{412}) we obtain 13 kg of lamb meat, while we estimate a total of 320 l/year for each sheep for milk production (W_{412}).

For the second scenario, HD, what we look for is whether a diet adapted to the physiological needs of people, but also to the potential of territory, could generate a greater degree of self-sufficiency than the previous scenario. For this, we do not pay attention to the current

[62] As it is known, current fishing is unsustainable. While some strategies such as aquaculture can mitigate the impact on marine ecosystems (Subasinghe et al., 2009) in this SFRA consider the provision of fish is given, in order to avoid new elements that escape from current goals.
[63] Regarding milk, data includes amount of cheese consumed by transforming it to milk according to milk ratio necessary to make cheese at state level (MAPA, 2009).

consumptions, but to the physiological needs and the ability of the agroecosystem to supply resources. Thus, the main restriction of this diet will be that the obtained ME equals the energy requirements of people. However, this is not enough; we have to set other constraints that guarantee this diet is healthy and palatable.

Through medical studies and their recommendations, we first establish an approach to the Mediterranean diet. Thus, in Estruch et al. (2013), a study on the potential of the Mediterranean diet in the prevention of cardiovascular diseases, they set different criteria, which we take as a basis. We also confirm them with the pyramid defined by the Spanish Society of Community Nutrition (SENC, 2016).

a. Between 300 and 400 grams of vegetables per day.
b. Between 360 and 600 grams of fresh fruits per day.
c. At least 20 grams of olive oil per day.
d. Between 20 and 30 grams of dry fruits per day.
e. At least 180 grams of dry legumes per week (3 servings per week).
f. A glass of wine per day, calculated in 12 cl. per glass.
g. Reduce consumption of red meet to less of a serving per day (100 grams).

Therefore, based on these limitations, we set specific restrictions for each product. However, again, this is not enough for the resulting diet to be healthy. Based on the recommendations for the Spanish State carried out by the Spanish Federation of Nutrition and Dietary Nutrition Societies (SENC, 2016), we also include the following precepts. We define them, as well, as restrictions.

h. The percentage of energy provided by carbohydrates must remain between 50-55% in the diet
i. The energy contribution through fats must be less than 35%. Moreover, less than 25% of these fats can be saturated from an animal origin.
j. At least 15% of the consumed energy must be protein, of which more than 50% of vegetable origin.
k. Fibre consumption must exceede 25 grams per day.

Finally, for the third case, MO scenario, diets are no relevant at all. Their main interest is to maximize the total amount of ME at an agroecosystem scale. Thus, the scenario has a single restriction in which we weigh all the consumable products according to their edible part, and value them in terms of metabolizable energy.

3.1.2 Domestic residues

As mentioned in the previous section, in many foods, there is a proportional non-edible part, which will be domestic waste. The amount of waste will be the result of the food flow allocated to society fund, through the fractions defined by CESNID (Farran et al., 2004). We insist that we will only consider those residues produced within a certain agroecosystem in order not to set the bases for sustainability on importation of nutrients from abroad.

3.2 Constraints for livestock

In order to guarantee the livestock fund reproducibility, we take into account four different flows: the needs for their maintenance, both feeding and stall bedding; and in terms of their outputs, their production of manure and food. Of these, we already explained the restrictions for meat, milk and eggs in section 3.1.1. Therefore, we set two groups of restrictions: the ones related to food and those related to manure. Taking into account that stall bedding becomes finally part of the manure, we consider them as a constrain within excrete.

3.2.1 Livestock feeding

Regarding livestock feeding we define some feed constraints in which the supplied food is equated to the animal needs. Considering the most relevant nutritional elements to satisfy, we decided to limit this analysis to the sufficient supply of metabolizable energy (ME) and crude protein (CP). The specific restrictions of feeding we want to meet take the formulations indicated in Eq.3.

$$\sum_{i=1}^{i=n} A_{abc} \cdot B_f \cdot Z_{abcd} \geq C_{fg} \cdot W_{fg} \quad \text{(Eq. 3)}$$

Where A_{abc} is the yield of a specific crop product *abc*, B_f is the content in ME or CP for a specific species*f*, Z_{abcd} is the variable of the surface associated with the flow, C_{fg} the annual requirement in terms of ME or CP for a specific animal *f* in stage *g* and W_{fg} , the number of animals *f* in stage *g*.

Thus, we first define which are the products that can be consumed by livestock according to species and phase of animal cycle. At the same time, we look for their maximum intake in order to avoid anti nutritive factors or that low palatability products make up important parts of the diet, which will be used later for specific restrictions (FEDNA, 2010). Table A3.7 shows consumable products according to animals and phases, as well as their inclusion thresholds in diets.

Table A3.7. Consumable feed by animals estimated regarding its live cycle stage and incorporation thresholds. Source: Our own based on FEDNA (2010). In grey, consumable products. Numbers represent the incorporation threshold in percentage.

Crop or land use	Product	Product Variable	W_{11}-W_{13}+ W_{21}-W_{23}	W_{14}-W_{17}	W_{31}-W_{36}	W_{37}-W_{39}	W_{41}-W_{411}	W_{412}
Vegetables (Y_{11})	Vegetables	Z_{111}						
	Crop residues	Z_{112}	10	10	10	10		
Fresh fruits (Y_{12})	Fresh fruit	Z_{121}						
	Wood	Z_{122}						
***Montcada* wheat (Y_{21})**	Grain	Z_{211}	30	30	35	40	30	30
	Straw	Z_{212}			1	4	25*	25*
	Stubble	Z_{213}					25*	25*
Chickpeas (Y_{22})	Chickpeas	Z_{221}						
	Straw	Z_{222}					25*	25*
***Spelt* wheat (Y_{23})**	Grain	Z_{231}						
	Straw	Z_{232}			1	4	25*	25*
	Stubble	Z_{233}					25*	25*
Lentils (Y_{24})	Grain	Z_{241}	10	10	20	16	26	26
	Straw	Z_{242}						
Mustard (Y_{25})	Grain	Z_{251}	2,5	2,5	2,5	2,5	20	20
	Straw	Z_{252}						
Triticale (Y_{26})	Grain	Z_{261}						
	Straw	Z_{262}			1	4	25*	25*
	Stubble	Z_{263}					25*	25*
Fenugreek (Y_{27})	Grain	Z_{271}						
	Straw	Z_{272}						
Barley (Y_{28})	Grain	Z_{281}						
	Straw	Z_{282}			1	4	25*	25*
	Stubble	Z_{283}					25*	25*
Potatoes (Y_{29})	Potatoes	Z_{291}					15	15
	Stems & leaves	Z_{292}						
***Fava* beans (Y_{20})**	*Fava* beans	Z_{201}	5	0	10	7	22	22
	Stems & leaves	Z_{202}					25	25
Olive groves (Y_{31})	Olive oil	Z_{311}						
	Olive oil pomace	Z_{312}			12	6	5	5
	Olive tree browsing	Z_{313}			2	5	4	4
	Wood	Z_{314}						
	Pasture	Z_{315}						

Crop or land use	Product	Product Variable	W_{11}-W_{13}+ W_{21}-W_{23}	W_{14}-W_{17}	W_{31}-W_{36}	W_{37}-W_{39}	W_{41}-W_{411}	W_{412}
Almond groves (Y_{32})	Almonds	Z_{321}						
	Husk and shell	Z_{322}						
	Wood	Z_{323}						
	Pasture	Z_{324}						
Vineyards (Y_{41})	Grapevine juice	Z_{411}						
	Grapevine pomace	Z_{412}				2	8	8
	Leaves	Z_{413}						
	Wood	Z_{414}						
	Pasture	Z_{415}						
Pastures (Y_{51})	Pasture	Z_{511}						
***Pine* forest (Y_{61})**	Wood	Z_{611}						
	Pasture	Z_{612}						
***Pine* forest (Y_{62})**	Wood	Z_{621}						
	Pasture	Z_{622}						
***Holm oak* forest (Y_{63})**	Wood	Z_{631}						
	Pasture	Z_{632}						
***Holm oak* forest (Y_{64})**	Wood	Z_{641}						
	Pasture	Z_{642}						
***Pine* forest (Y_{65})**	Wood	Z_{651}						
***Holm oak* forest (Y_{66})**	Wood	Z_{661}						

* Straws have a recommended threshold of 25% as a whole. Therefore, the sum of all cereal straws can not be greater than 25% of diet requirements.

For all these possible feeding products for livestock, we search their contributions in ME (MJ/kg) and CP (%) for each different animal species, basically through data collected by Church (1984). Remember that we define so many Z_{abcd} variables as different directions the Z_{abc} flow can take, according to the amount of W_{fg} animal stages that can be supplied. As this is a surface variable, the dimension of the flow (in terms of ME or CP), will result in multiplying this Z_{abcd} variable by yield of Z_{abc} product and its energy content in MJ/kg or crude protein per feed unit.

Once all food supply sources have been defined, we must formulate generic food restrictions, to do so, it is necessary to know what the energy and crude protein requirements are for each stage of the animal cycle. These come from the same sources defined in section 2.2. and are shown on Table A3.8. For W_{41}, W_{43}, and W_{47} stages, there are no requirements because they are lambs in breastfeeding phase, not supplemented. On the contrary, W_{31} are piglets in breastfeeding phase but with some solid supplementation.

Table A3.8. Requirements on ME and CP for each animal stage considered. Source: Our own adapted from other sources (Church, 1984; Milán Sendra and Caja López, 2014; Pino de Delàs and Vila Camps, 2005; Pont Andrés, 2009; UPAE, 2010; Vila Camps, 2007).

	Energy (MJ ME/year)	CP min (kg/year)	CP max (kg/year)
W_{11}	197	3.2	3.5
W_{12}	218	4.9	5.6
W_{13}	305	5.5	6.4
W_{14}	445	7.5	8.4
W_{15}	514	6.4	7.1
W_{16}	386	3.3	3.9
W_{17}	514	5.5	6.4
W_{21}	86		1.5
W_{22}	261		4.2
W_{23}	336		4.7
W_{31}	1,152	16.4	
W_{32}	4,147	59.1	
W_{33}	7,898	105.1	105.1
W_{34}	13,983	175.2	186.2
W_{35}	7,898	105.1	105.1
W_{36}	13,983	175.2	186.2

	Energy (MJ ME/year)	CP min (kg/year)	CP max (kg/year)
W_{37}	18,644	189.8	204.4
W_{38}	23,882	312.1	312.1
W_{39}	13,983	175.2	186.2
W_{41}	0		
W_{42}	2,428	25.2	25.2
W_{43}	0		
W_{44}	2,428	25.2	25.2
W_{45}	4,307	42.0	42.0
W_{46}	3,283	17.5	17.5
W_{47}	0		
W_{48}	2,428	25.2	25.2
W_{49}	4,307	42.0	42.0
W_{40}	3,299	39.4	39.4
W_{411}	5,024	50.1	50.1
W_{412}	5,788	56.6	56.6

Once these specific dietary restrictions are defined, we have to limit the consumption of certain products that may have anti-nutritive or unpleasant factors, based on the thresholds indicated on Table A3.6. For these, we indicate a general formulation in Eq. 4. There, A_{abc} is the yield of a specific product (Z_{abc}), B_f is the content in ME for a given species *f*, Z_{abcd} is the variable of flow, D_{fg} is the threshold set according to the criteria of FEDNA (2010), C_{fg} is the requirement in ME for a specific animal stage (*fg*) and W_{fg} the number of individuals in this stage.

$$A_{abc} \cdot B_f \cdot Z_{abcd} \leq D_{fg} \cdot C_{fg} \cdot W_{fg} \quad \text{(Eq. 4)}$$

3.2.2 Animal excrete and stall bedding

As we have said, the second fundamental flow for the integration between self-reproducing funds is the return of animal excretion towards soil fund for the restoration of fertility. As detailed below, it is not a direct process but subsequent to a composting phase along with the rest of nutrient sources, with the exception of *in situ* animal consumption. This last aspect affects all the improved pastures, the grazing on forest and the grazing on crops associated to woody crops. In Figure A3.8 we show an estimation of the excreta's retrieve in stable according to types of feeding.

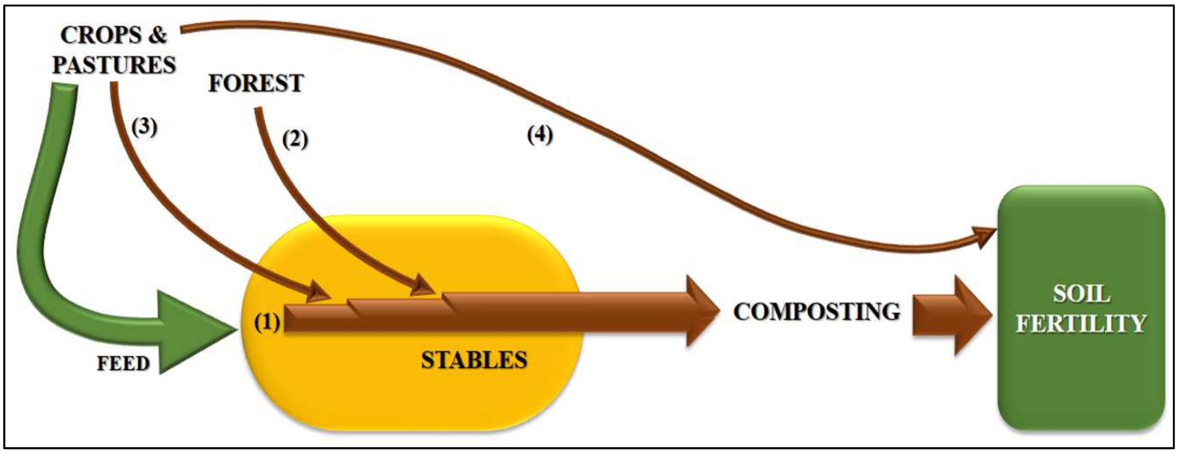

Figura A3.8. Figures of manure considered in the SFRA for 2009. Source: Our own.

Most of the feed, the total in the case of chickens and pigs, is consumed in barns. Therefore, these nutrients come from crops and manure is produced directly in stables, so the retrieve ratio is 100% (flow 1). However, in the case of sheep we also consider the ability of grazing both on woodland and on woody crops.

For the first ones, farmers will only collect manure deposited while sheep are not grazing (flow 2), as well as it will happen for their consumption in crops and pastures (flow 3). We estimate a retrieve percentage of 50%, based on studies that range from 40-60% (Ayantunde et al., 2001; JH Cascón, 1918; Oenema, 2006). All this manure accumulated in stables will then go through a composting process explained in section 3.3 (flows 1, 2 and 3).

However, within nutrient input we also have to consider the excreta retrieved from consumption *in situ* on woody crops. There, some part is directly disposed as animal excreta in cropland (flow 4). Thus, 50% of excreta will remain *in situ*, although logically it will undergo some nutrient loss processes.

In order to calculate these processes, we need to set two new variables -U and V- associated to sheep grazing. We define U as the ratio between consumption outside barn and total consumption, in dry matter. From here, we can calculate the total rate of excreta retrieved within stables, as shown in equation 5.

$$Ratio1 = 0.50 + (1 - U) \cdot 0.50 \quad \text{(Eq. 5)}$$

Indeed, we also need to define a ratio of manure retrieved directly on cropland. Thus, we define V as the proportion between consumption in cropland and improved pastures divided by the total consumption. With this, we can calculate the ratio of excreta deposited *in situ*, as in equation 6.

$$Ratio2 = 0.50 \cdot V \quad \text{(Eq. 6)}$$

Apart from these ratios, a fundamental element will be the amount and the composition of excreta. Using information of ASAE (2000), we consider a first estimation on the productions of excreta and their composition. We modified these values, through an iteration process, to ensure that the excreted amounts of nutrients do not exceed the consumption by discounting the retention ratio by animals (Brito et al., 2006; Hutton et al., 1967; Jørgensen et al., 2013; Kebreab et al., 2008; Rattray and Joyce, 1974; Reffett and Boling, 1985; Shalit et al., 1991; Sutton and Lander, 2003; Wu et al., 2003). We did it in order to ensure that the fertilizing capacity of excretion is not overestimated. Final values on N, P, K, are shown in Table A3.9

A last aspect to consider is stall bedding for livestock. As mentioned before, stall bedding is closely related to excretion, because it goes through the same composting process. Therefore, we start from the recommendations in Soroa (1953), who set a daily requirement of 1.5 kg for pigs and 0.2 kg for sheep. We calculated the requirement for poultry to 1.25 kg/year (UPAE, 2011). Hence, these needs must be satisfied with suitable types of straw, such as wheat (Z_{212}), chickpeas (Z_{222}), spelt (Z_{232}), lentils (Z_{242}), triticale (Z_{262}), fenugreek (Z_{272}) or barley (Z_{282}). These types of straw will go through the composting process together with excretion, so the used flow variables are the same as in the case described in section 3.3.2.

Table A3.9. Estimated manure amount and composition regarding livestock stage in the SFRA for 2009. Source: Our own, adapted from ASAE (2000)

		Nutrients composition (kg/day·1000 kg live weight)		
	Kg/year·unit	**N**	**P**	**K**
W_{11}	12	0,58	0,13	0,20
W_{12}	23	0,58	0,13	0,20
W_{13}	35	0,58	0,13	0,20
W_{14}	47	0,58	0,13	0,20
W_{15}	47	0,58	0,13	0,20
W_{16}	47	0,58	0,13	0,20
W_{17}	47	0,58	0,13	0,20
W_{21}	15	0,76	0,13	0,27
W_{22}	31	0,76	0,13	0,27
W_{23}	62	0,76	0,13	0,27
W_{31}	107	0,52	0,07	0,16
W_{32}	460	0,52	0,07	0,16
W_{33}	1119	0,52	0,07	0,16
W_{34}	2453	0,52	0,07	0,16
W_{35}	1119	0,52	0,07	0,16
W_{36}	2759	0,52	0,07	0,16
W_{37}	4599	0,52	0,07	0,16
W_{38}	3986	0,52	0,07	0,16
W_{39}	3986	0,52	0,07	0,16
W_{41}	77	0,50	0,08	0,49
W_{42}	223	0,50	0,08	0,49
W_{43}	77	0,50	0,08	0,49
W_{44}	223	0,50	0,08	0,49
W_{45}	511	0,50	0,08	0,49
W_{46}	730	0,50	0,08	0,49
W_{47}	77	0,50	0,08	0,49
W_{48}	223	0,50	0,08	0,49
W_{49}	511	0,50	0,08	0,49
W_{40}	730	0,50	0,08	0,49
W_{411}	730	0,50	0,08	0,49
W_{412}	730	0,50	0,08	0,49

3.3 Constraints for soil fund and farm-associated biodiversity

Here we present the main constraints of two funds that we deem linked to each other, but involve very different aspects. As we stated in other chapters, soil is the thin layer between the atmosphere and geological material and which allows growth and sustain of vegetation, as well as being part of several regulatory functions. Indeed, since we consider that soil regards also to the territorial expression of the agroecosystem, we consider that through land use composition the material conditions for farm-associated biodiversity are also affected.

As we stated in section 2.3 of chapter 7, in this *SFRA* we will consider three aspects to which we define some constraints: i) total surface and its capacity of land use transformation; ii) nutrient balance as an approach to biogeochemical cycles; and iii) landscape patterns analysis as an approach to habitat conditions for farm-associated biodiversity. Below we detail the restrictions given in these three groups.

3.3.1 Constraints for land uses

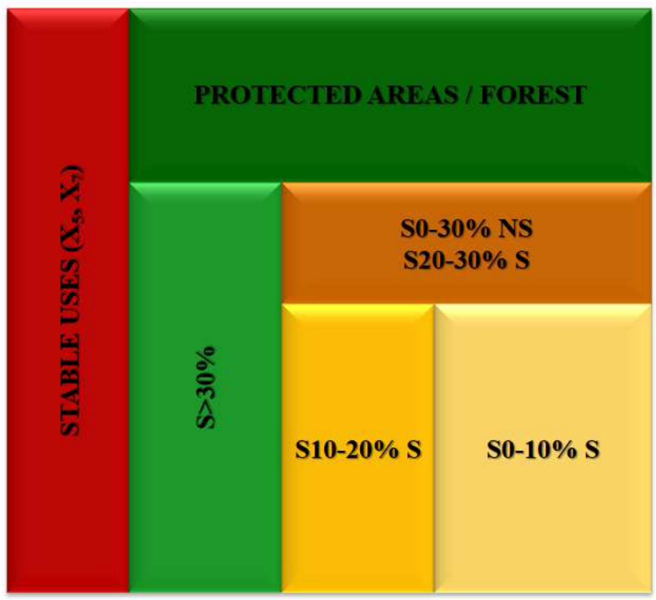

Figure A3.9. Land use categories considered in the SFRA for 2009. Source: Our own.

To define possible evolution of land uses in the territory, we use a hierarchical approach, starting with the most restrictive uses and progressively defining possibilities of change according to preceding uses and suitability of the territory. To do this analysis, we use current land use maps, land suitability for different crops, historical land use maps and the map of protected figures (Catalan Geological Institute, 2010; CREAF, 2009; DGPAM, 2017; Rodríguez Valle, 2003; Tello et al., 2004). With these, we define categories of analysis using ArcMap 10.4.1, taking into account that land suitability is different according to the targeted crops.

Before establishing the possibilities of uses transformation, we distribute the total area of the municipalities in 75 different units by merging the possible categories (shown in Figure A3.9) and the preceding land uses.

As we said, we set these categories in a hierarchical form, so we divide the territory following these criteria:

1. Stable use: It includes all those uses that cannot undergo any transformation. This subgroup includes surface of inert use from an agricultural point of view (X_7), as well as areas declared as pastures (X_5), since we consider them a key element for landscape from a point of view of biodiversity maintenance, because of their value as open spaces and as edge habitats (Marull et al., 2015, 2014).
2. Protected areas or forest: This category is mobile depending on the considered scenario. As it was mentioned, one of the axes for scenarios is the maintenance or not of the forest area. Thus, if we consider the maintenance of the whole forest, this category supposes 7,407 ha. However, if we consider appropriate to restore certain areas for agricultural use,

we set a limit on the maintained forest area. Thus, as we have mentioned, protection figures (DGPAMN, 2017), as well as areas that have been maintained as forest during the last 150 years, are taken into account. In this second case, there would be 3,752 ha that would remain within this category.

3. Areas with slopes greater than 30%: Although steps 1 and 2 are the ones which fix those areas that have to maintain their use, we have to consider some technical-agroeconomic criteria. Thus, we will assume the protection of all those areas where slope is greater than 30%, for a matter of environmental protection. However, we place here an exception. Of the 2,060 ha that belong to this category, there are 284 ha catalogued as herbaceous dryland or woody crops. We understand that, within the margin of error of the study carried out with GIS and the sensitivity of the digital model of the terrain, it is possible that these surfaces are in suitable terrain. This can happen either because of the presence of human conservation artefacts (such as terraces) or because cultivation conservation practices allow for it. Therefore, we would assume they can be maintained if the output of the *SFRA* considers it. For all the rest, the use will be forest.
4. Non-suitable areas with slopes of 0-30% and suitable areas with slopes of 20-30% . Following the technical criteria of the Center of the Forest Property (Baiges and Tusell, 1988), as well as the Law of Forests 43/2003 and the Forest Law of Catalonia 6/1988, we consider that only the use of areas below 30% of slope can be broken and changed. Even so, only if their slope is less than 20% they can be transformed to agricultural uses. Therefore, within this category, forest uses can only be pasture. On the other hand, also within this category we will maintain those surfaces declared as ploughed areas, as in the previous category.
5. Suitable areas with slopes of 10-20%: Here, transformation of uses and possible clear cuts of forests allow transformation to woody uses with herbaceous cover, such as olive trees and almonds trees (X_3) or vineyards (X_4). We assume this restrictive criteria for cereals because of forecast erosion conditions. Surely, we would be able to reconsider it with a more in-depth study of erosion risks (based not only on slope but also on length of the slope at plots level). However, it is proved that this assumption does not limit the model, so the result would be the same if we considered feasible to grow herbaceous areas in crops with 10-20% of slope.
6. Suitable areas with slopes of 0-10%: This last category, which includes 1,176 ha, allows transformation of any land use to any other, as long as they meet the criteria of suitability, considering here also the uses of irrigated land.

Thus, from the various categories and defined units, we set the corresponding constraints that determine the capacity of transformation of the various preceding land uses.

3.3.2 Constraints regarding biogeochemical cycles

In order to define the nutrient recovery thresholds necessary to maintain the metabolic cycles, in the process for the construction of these associated constraints, it is first necessary to know which extractions exists in terms of nitrogen, phosphorus and potassium (N, P and K respectively, and thereafter). Table A3.10 shows the total requirement values based on average productivities. We note that these values would be different in the analysis of sensitivity, depending on extraction, because we apply technical factors to yields considered in each case.

As we can see, in the two main rotations of herbaceous dryland (for *Montcada* wheat and for mustard), there appears green manure. This is any legume crop that once in flower, it is buried in order to take advantage of its contribution in nitrogen. Therefore, this allows reducing the total nitrogen requirements. These total requirements take into account, following the proposal from González de Molina et al. (2010), both direct extraction and edaphic processes that take place over a year (atmospheric deposition, irrigation, symbiotic and non-symbiotic nitrogen fixation, denitrification, volatilization, and seeds). We corroborate the resulting values with general information on crop needs at the state level (López Bellido et al., 2009).

Table A3.10. Estimation on nutrients requirements per crop in the SFRA for 2009. Source: Our own

	Nutrients requirements (Kg/ha)		
	Nitrogen	**Phosphorus**	**Potassium**
Vegetables (Y_{11})	208,4	50,1	141,9
Fresh fruits (Y_{12})	12,9	3,6	23,6
***Montcada* wheat (Y_{21})**	79,0	13,7	31,3
Green manure	-101,2		
Chickpeas (Y_{22})	-4,5	2,9	2,6
***Spelt* wheat (Y_{23})**	78,5	13,6	31,1
Lentils (Y_{24})	-11,7	3,0	6,6
Mustard (Y_{25})	37,3	8,7	16,6
Green manure	-101,2		
Triticale (Y_{26})	28,6	30,8	25,8
Fenugreek (Y_{27})	-9,9	18,8	23,2
Barley (Y_{28})	42,3	6,6	25,1
Potatoes (Y_{29})	43,5	7,4	42,9
***Fava* beans (Y_{20})**	-16,2	5,3	16,6
Olive groves (Y_{31})	43,2	8,9	29,1
Almond groves (Y_{32})	40,9	11,7	33,0
Vineyards (Y_{41})	77,5	15,0	68,7
Pastures (Y_{51})	23,6	8,8	34,5

Once we defined the nutrient requirements defined, the next step is to determine the multiple sources for restoring soil fertility. They are the following:

1. Animal excreta: As explained in section 3.2.2., including its nutrient composition.
2. Crop residues: There is an important part of by-products that are not consumed by livestock and we reuse them to restore soil fertility.
3. Domestic residues: As we said, we consider their return to the agroecosystem.
4. Nutrient import from forest: A last possible source of nutrients is the importation of green materials (biomass from woods).

As indicated in Figure A3.8, in view of its application in cultivation, we consider necessary to establish a composting process with all the products destined to restore the soil fertility. The only one that we considered directly applied it is animal excretion by consumption *in situ*, which reduces its nitrogen composition with a loss of 20% by volatilization (IPCC, 2006b).

One important aspect to keep in mind is that this is a reproductive model and that we do not consider the annual rate of mineralization of organic matter. That is to say, the nutrients of the incorporated biomass are not totally available for the plants of the following year. However if the incorporation is proportional to extractions in a continuous way along the years, and it is done by guaranteeing that this does not suppose an immobilization of certain nutrients, it would end up establishing a dynamic balance between extractions and mineralization. This is an analysis of biogeochemical cycles at a medium term and does not take into account annual processes that are very specific to plot and not to landscape scale.

Regarding composting processes, the way in which farmers carry them out is highly determinant of nutrient losses. By making a review of possible nitrogen losses, they range from 20 to 60% depending on the form of handling (Eghball et al., 1997; IPCC, 2006a; Larney et al., 2006; Michel et al., 2004; Salter and Schollenberger, 1939; Sommer, 2001). We consider that a loss of 30% would be reasonable. Since subsequently, by its application to ground, losses increase by 20% on total, we consider that the total nitrogen loss will approximately be of 50% (IPCC, 2006b).

In the case of phosphorus or potassium, we observe lower losses, and even less in a Mediterranean context if practices for protecting composting piles are correct, since leaching is the most determining process. Therefore, we consider phosphorus losses of approximately 2% and around 20% for potassium (Eghball et al., 1997; Larney et al., 2006; Michel et al., 2004; Salter and Schollenberger, 1939; Sommer, 2001).

Thus, we will define twenty-one restrictions (three nutrients for seven groups of crops to be fertilized) in which the requirements have to be lower than the sources of nutrients once they are composted, except for the excreta laid *in situ*.

Finally, we point out that, as indicated in section 5.2. of chapter 7, in order to meet the nutrient needs, we will also consider the possibility of using soil nutrient stocks of both forest and agricultural land. This requires the use of the variables M, N and O (stock use of agricultural soils, in kg of N, P or K/ha) and P, Q and R (associated to the flows from forests stock to cropped areas in kg of N, P or K/ha).

For these, we will set two groups of restrictions. The first, in relation to forest soils, are that P, Q and R must be equal to all the extractions in these soils by exporting green biomass and pasture extraction, once the non-anthropogenic input fluxes discounted (symbiotic fixation, deposition or weathering).

The second ones correspond to the fact that the use of nutrient stocks of agricultural soils (M, N and O) must be higher than the forest ones (P, Q, R), proportionally to the size of their nutrient stock.

As a last step, we will add extractions corresponding to M, N and O to the 21 restrictions of fertilization, being then a fifth source for obtaining nutrients.

3.3.3 <u>Constraints for farm-associated biodiversity</u>

The last remaining constraint refers to the diversity of land covers. As mentioned in the methodological development of the *SFRA* for 2009, in section 4.1.2 of chapter 7, we will do an estimation of habitats from the equidistribution of land covers by means of the Shannon Index (Shannon and Weaver, 1949). In order to adapt it to the agrarian metabolism, we discount the effect of X_7 cover (agrarian inert uses), as proposed in chapter 3 (Eq. 7). Thus, we consider the following land covers: irrigated land, herbaceous dryland, woody crops with olive or almond, vineyards, pastures and forest. Let us repeat again, that this is not a sign of all the different land uses, but different types of covers. Moreover, we are aware that not considering internal differences among forests also entail some probable biases. Therefore, in subsequent studies we would try to include other indexes that account for this broader diversity.

$$L = \left(-\sum_{i=1}^{6} p_i log_6 p_i\right) \cdot (1 - p_7) \quad \text{(Eq. 7)}$$

As we have to fix a threshold value, what we considered is that the Shannon's value of the optimal use distribution must be greater than the value observed for 2009. Thus, although we cannot guarantee it entails a specific value of biodiversity due to the lack of studies in this regard, we consider this supposes an increase in the habitat differentiation for the edge effect (Tscharntke et al., 2012). Therefore, the value obtained from analysis of L must be greater than the reference value of 0.37 observed for 2009.

4. Objective functions

In order to complete the structure of the *SFRA* model, we need some last fundamental elements. These are the objective functions. They depend on the scenario we want to analyse. As we indicated in section 3.1.1, scenarios are different contexts of diets, as well as considering whether cultivated surface can be increased or not. This second consideration entails a package of restrictions, while diets are also packages of restrictions, but associated to an objective function. Therefore, based on the three different optimization objectives, we detail the objective functions below.

1. Maximization of the capacity of self-sufficiency with current diets: Here what we want to see is the maximum population that could receive a current diet. Therefore, the objective function will simply maximize the value of T (population).

2. Maximization of self-sufficiency with a healthy diet from a nutritional point of view: like in the previous case, here what we want to maximize is the number of individuals that the agroecosystem can hold. In this case with a healthy diet. Therefore, it is still a maximization of the T variable (population).

3. Maximization of the amount of food produced: Detached from diet, in this case what we want is to maximize the amount of metabolizable energy provided by the agroecosystem. Thus, we do not speak of population but of metabolizable energy. Therefore, instead of maximizing T, this scenario maximizes U (amount of food in MJ of ME)

5. Sensitivity analysis of the *SFRA*, defining the conservative criterion

5.1 Identification of possible sources of uncertainty on the model

In order to try to capture the degree of sensitivity of the model, we first proceed to define different types of uncertainty that we can find in models and how we confront them or not within this theoretical approach (Wynne, 1992).

- Risk: The risk study refers to variables for which we know the probability and their variability. We analysed the most sensitive assumptions and we will only consider the possible variations of agricultural productivity, assuming that they are the variables that most variations present from one year to another. For this, we design an analysis that allows us to identify a maximum and minimum range of optimal results, as explained in the following section.
- Uncertainty: Uncertainties refer to parameters that we know that can present variations but for which we do not know what their possible variations are. In this sense, the lack of appropriate current and site-specific data and records increases the degree of uncertainty. However, because this is an initial methodological proposal, we understand that we do

not need to introduce this specific analysis. For the moment, this is not a proposal that could be required for designing public policies at this stage of development, as we are still in a theoretical proposal.

- Ignorance: Until now, this kind of socio-ecological modelling is a perspective that has never been applied in policies for landscape scale, thus, it makes it difficult to infer aspects that may remain within the field of ignorance. Only from empirical work on the analysis in socioecological terms of agroecosystems, could we identify possible ranges of variation based on the remaining uncertainties.
- Indeterminacy: The highest degree of indeterminacy, caused by open causal networks, comes from the fact that this is a socioecological study. Therefore, the behaviour of human beings involved in any agroecosystem obviously affects its results. Precisely for this reason, we consider it essential that agroecological transitions take into account the necessary democratizing elements and deliberations (Tello and González de Molina, 2017). Thus, the role of these studies must not be that of modelling how social behaviour should be, but to identify the potentiality of any territory to achieve, from a technical-agronomic point of view, a high degree of performance of any social objectives set within it.

As we can see, given the limitations of the study, in this case we carry out a study of the variations that the model would suffer based on the variability of certain input data, doing risk analysis

5.2 Defining variables for the sensitivity analysis

In this *SFRA* we will carry out a risk study. This allows us to identify the maximum and minimum range in which results could vary for the different proposed scenarios. We will run this analysis on the agrarian variable that has higher variation over years due to weather reasons: agricultural yields. In addition, we have annual series for this variable at a medium term at regional scale. We will then try to see what impact the annual variability of yields has in order to identify the sensitivity of this model.

Thus, the criterion that we will take is that if variations in input variables (yields) are higher than variations in the output ones (dimensions of funds), then the model is robust and minimizes these differences instead of amplifying them. On the contrary, if variations in input variables result in a greater increase than variations in output, then the model will be sensitive to changes from one year to another and we will not be able to confirm its robustness.

We are aware that considering risk analysis only for yields limits a lot the real variability that occurs in an agroecosystem due to changes in weather conditions. These changes in productivity also have effects in other technical coefficients of the model. Thus, we must identify if these variations could also significantly change other coefficients by generating scenarios of indeterminacy. Figure A3.10 shows this relationship in a simplified way. It is obvious that changes in precipitation and temperatures affect more elements than those considered here, such as animal welfare and, therefore, their growth, pest diseases or even water availability for irrigation. The amount of interactions is huge. Despite this, we believe that these considered factors probably collect most significant variabilities on all aspects, with the exception of water metabolism. We already indicated in chapter 7 that we would also have to analyse it a part in further developments.

What we will initially consider is the impact on yields, using annual series of crop productivities, adapted for organic farming. This is the starting data. However, as we show in Figure A3.10, at the same time, they influence other relevant technical factors such as the harvest index or the nutrient content. Since we do not consider them in the sensitivity analysis, due to difficulties in clearly establishing what variations are, and as well as for the lack of local information, we try to infer what impact they would have if we considered them. That is, if they would further increase variability with respect to yields variation or, on the contrary, they would reduce them.

The harvest index value is related to yield per hectare in a directly proportional relationship. Thus, a greater productivity, means higher harvest index. This means that the proportion of grain over the entire production (grain and straw) will be higher. That happens both in cereals and wheat (Akram, 2011; Fischer and Maurer, 1978), and in legumes (Ramirez-Vallejo and Kelly, 1998).

However, if we analyse the relationship between HI and the grain productivity, what we observe is that the amount of by-products in absolute terms will continue increasing. Despite that, it will happen at a lower proportion than that for grain, with a slope between them of 0.47 with a R^2 of 0.634 (Fischer and Maurer, 1978; data treated by us).

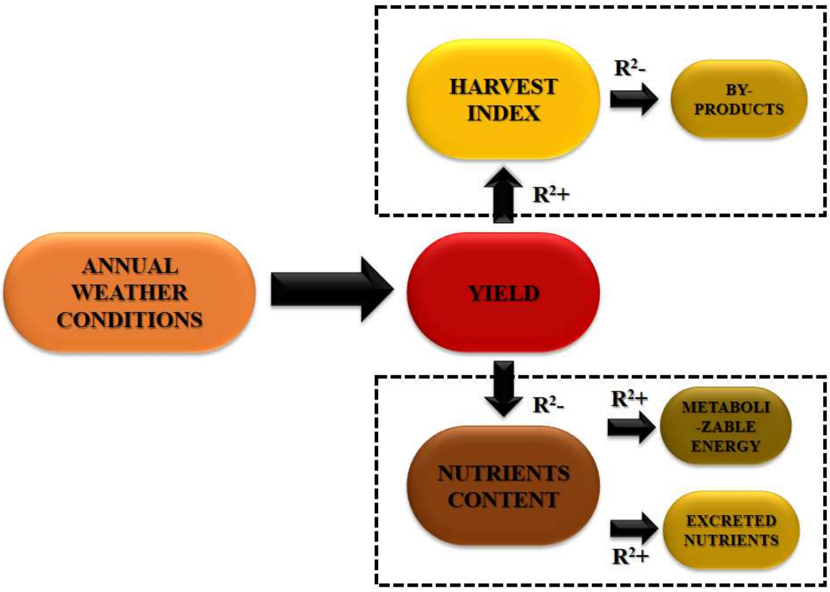

Figure A3.10. Relation among variables considered in the sensitivity analysis in the SFRA for 2009. Source: Our own.

Therefore, with the model, when we do not take into account this effect of increase, since the variable that suffers a modification is the total grain production, the amount of straw produced is overestimated. This, in terms of impact on one of the most limiting processes -the nutrients cycling-, increases the extraction of nutrients in absolute terms. In addition, most of the straw normally returns to the soil, according to the results of the models. Thus, because this high degree of uncertainty it is difficult to be clear about its effect. However, we consider feasible to approximate that the main effect from this process would be a higher degradation on the nutrient cycles. This is given the losses that happen, especially in terms of nitrogen, in the process of production and re-incorporation of biomass into soil. Therefore, probably, considering variations on HI as well as on yields, would lead to a result where we would observe a certain buffer effect with respect to variations between scenarios.

In fact, as an internal verification, we put it into practice and analysed how the scenario of the healthy diet in 2007 compared to 2009 would vary, considering the possible effect on HI. Here, we applied a factor of the fall on HI that would suppose a reduction in 439 kg/ha of wheat yield and we applied it for all the grain crops. Regarding sources, this fall in 15% of production would suppose a fall of 5.5% of straw in absolute terms. When applying the model, the sustainable population increases by 0.2%, reducing the difference over the total population between 2007 and 2009 by 3%. This is due to a significant change in livestock, where sheep increased from a herd of 28,817 to 29,015, thus reducing differences by 9%. In addition, the surfaces also varied, diminishing approximately a 5% difference between 2007 and 2009. Regarding the nutrient balances, the modified 2007 pattern is much more similar to that of 2009, reducing the share of harvest residues and significantly increasing the share of manure imported from pasture to the forest as well as *in situ* consumption.

Therefore, this analysis confirms the assumption of the buffer role that would suppose the fact of considering the effect of the productivity changes on the harvest index and this one on the final results. However, we consider that the data on the direct impact between productivity and HI is not sufficiently robust for applying these factors without the risk of biasing the model. Therefore, being aware that the impact of considering it would reduce differences from one year to another, we take a conservative approach and keep only yield variations. Thus, the results that come out of the analysis of sensitivity will be overestimating the real differences we would observe from one year to another, but at least they fix a maximum threshold for variation.

We move to the second group of coefficients that we suppose would be affected by changes in yields. These are the nutrient content of the agricultural production. There is an inversely proportional relationship between productivity and availability of nutrients. For example, in the case of wheat, a study confirms that nitrogen content ranges from 10.5 to 11.5% depending on yields (Woodard and Bly, 1998). In contrast, for phosphorus, it seems that in legumes it has no significant effects while there is a non-significant trend in wheat (Nuruzzaman et al., 2005). In any case, these variations appear to be smaller than changes in productivity, in such a way that in absolute terms, an increase in yield per hectare would mean an increase in extractions.

Although these changes may be not huge, this would have an impact on the metabolizable energy of these agrarian products, both for humans and animals. Thus, they would need to consume more product to get the same benefit in terms of nutrition. This would result in an absolute reduction in the quantity of livestock and population that could be sustained, minimizing relatively positive impacts of increasing productivities. At the same time, given the lower nutritional quality of the products, animal excretion would be greater but with a similar nutrient content. This is because there is a direct relationship between nutrient content of animal feed and nutrient content in excretion (Canh, 1998). Therefore, again, we would find a buffer effect, just as we observed in the case of the harvest index. Unfortunately, since we do not have not enough information to make here an estimation of the reduction of nutrient content, in this case we cannot quantitatively consider what would happen.

All in all, we can cautiously conclude that the consideration of variations in yields, without considering the effect on the harvest index or on dilution of nutrients, works in conservative scenarios that maximize the differences from one year to the other. Therefore, when these differences are smaller than the variations on input variables, we will conclude that it would probably be true, and validate the hypothesis of equality.

On the other hand, when results show variations higher than the introduced ones on input variables, then the possibility of overestimating this variation would be possible. However, as we have observe in the case of the HI, these variations do not seem very significant in the case of population, surfaces or diversity of covers. In addition, according to the data on nutrient variation in crops, it seems that they are relatively small with respect to changes in yields (Nuruzzaman et al., 2005; Woodard and Bly, 1998). Therefore, if differences are significantly larger, we will also conclude that the model has a high sensitivity.

5.3 Sensitivity analysis

We apply the model on the 10 years of the series to analyse the resulting configurations according to variations in annual conditions. One important aspect to take into account is that for less perishable crops, such as cereal or legumes, we perform a two-year moving average in yields. This is because part of the harvest from years with a production above average can be stored as surplus for the following year. However, this is not possible with most products, including those of animal origin, which are largely damaged from one year to another and require consumption within the same year they have been produced.

Regarding the comparison of the results, the model consists of more than 1400 variables. Thus, it would be very difficult to analyse them all at the same time. Therefore, we choose only key characteristics of the considered funds: population, dimension and composition of agricultural land, composition of livestock and configuration of the landscape patterns.

In order to respond to the robustness of the model when changing productivity situations, taking a conservative position, we apply the model on the different crops productivities during the period 2007-2016. We thus obtain the variation in the resulting scenario depending on whether it was run on one year or another. We represent these results in figures 11 and 12.

Thus, we compare which are the coefficients of variation (CV) of the model's main variables (those that characterize the funds) with respect to the variation introduced in yields. The CV of yields, making a weighted average with crop distributions, ranges from 12.7 to 16.4%, as we show in Table A3.11. Therefore, we expect that the results of CV lower than these threshold values indicate that the model internalizes variability, while surpassing them indicates that the model is more sensitive to these variations.

Table A3.11. Variation coefficients for inputs and main outputs of the model for each scenario of the SFRA for 2009[64]. Source: Our own.

	Equal cropping area			**More cropping area**		
	CD	**HD**	**MO**	**CD**	**HD**	**MO**
Input variation	*12,7*	*15,2*	*15,7*	*14,3*	*15,9*	*16,4*
Population	9,7	9,3	3,5	11,0	9,4	3,8
Surfaces	5,4	7,7	25,2*	13,0	8,1	20,9*
Livestock density	9,7	11,2	4,6	11,0	9,2	8,0
Shannon	1,0	0,5	2,5	6,5	1,5	2,8

Let us start with the analysis of the total population sustained in the territory (see Figure A3.11). All the values are below 11%, with CDII being the one with the greatest variability. Lower CV are those corresponding to MO scenarios, around 4%, although we must take into account that these values are of equivalent population. Since this last estimation simply corresponds to the division of all the MJ of ME obtained by the energy requirement for one person/year, and there are no other restrictions, we consider logical that these scenarios present a lower variability in terms of total population than others do.

Where there is a greater variability, it is on surface. We calculate CV of each land cover, weighted by the covers distribution, from where we obtain the values indicated in Table A3.12. These values are quite different in relation to those corresponding to population. While distribution of surfaces in HD presents CV lower than those of population, in the MO scenarios results are the opposite. Although there were very low variations in population, land use distributions in this case exceeds the threshold value for MO. This is because the variations in surface of irrigated land and herbaceous dryland, that present values between 30 and 60% of CV from one year to another, due to nutrient balances explained in section 5.4 of chapter 7. They are, therefore, scenarios where the risk associated with this fund is high.

[64] Asterisks indicate coefficients of variation that exceed the variation of inputs.

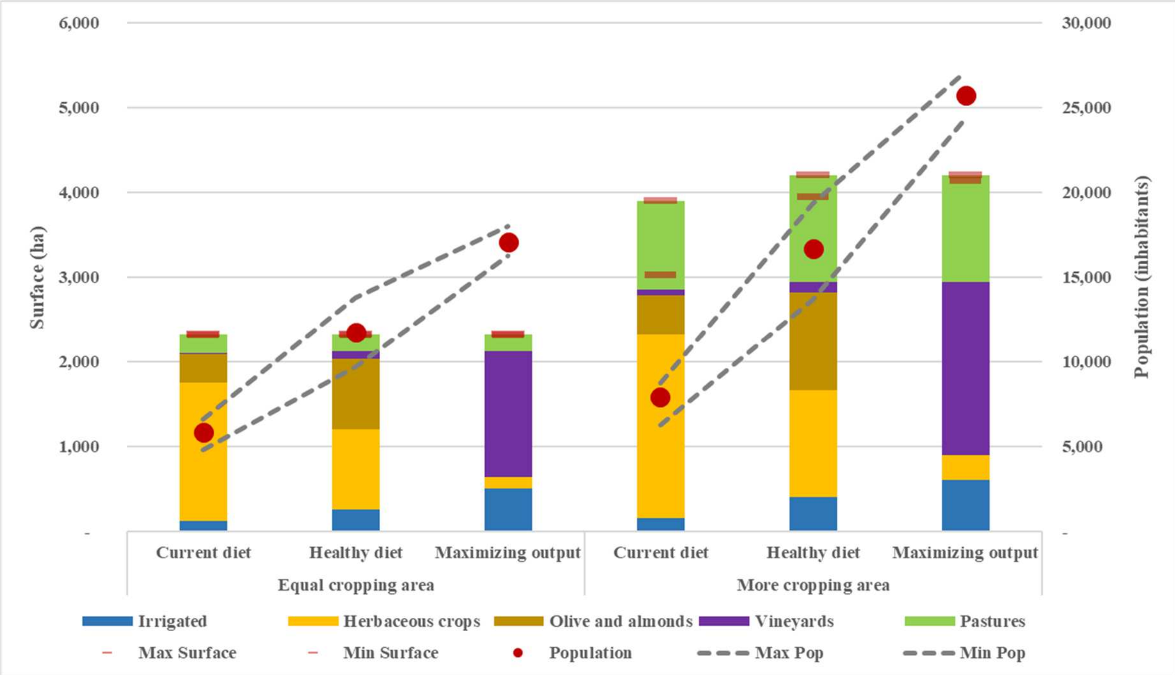

Figure A3.11. Variations in the model's variables of population and land use distribution regarding the scenario run for the period 2007-2016. Source: our own.

Also in the case of CDII, there are variations of 13%, slightly below the 14% threshold. These are due to variations between pasture and forest. Since it is a question of two complementary uses (despite sheep can graze in forest to a lesser extent), we understand that these variations, apart from being within the range, do not imply significant doubts about uses. Therefore, we can conclude that in these terms, MO scenarios amplify variations in input variables and, thus, do not present stability.

Considering the analysis of results for livestock, we present values of livestock density as well as proportional composition according to animal products. As we can see, variations of these variables for all scenarios remain below the threshold of the variation of inputs. Those corresponding to CD fluctuate exactly like the amount of population, while HD and MO vary a bit more with respect to population but always within the allowed range.

In the case of landscape patterns, we take as reference the modified Shannon index. We also show in Figure A3.12 the threshold value that we set as a constraint, over which the equidistribution of land covers is greater than the one observed in 2009. The variations of this indicator are due to the variations in land use composition, and therefore, affected by the variations observed in Figure A3.11. Thus, in the case of scenarios in which the total agricultural area is fixed, CV are always lower to 3%. Regarding scenarios in which agricultural surface can increase, the maximum CV value corresponds to CD, which is 6.5%. Therefore, we can conclude that on this indicator, variations are much lower than changes in the observed productivity.

Finally, we want to point out that if longer series of crop yields were available, these variations would probably continue diminishing, due to the effect that some atypical years, from a climatological point of view, may have on the sample used.

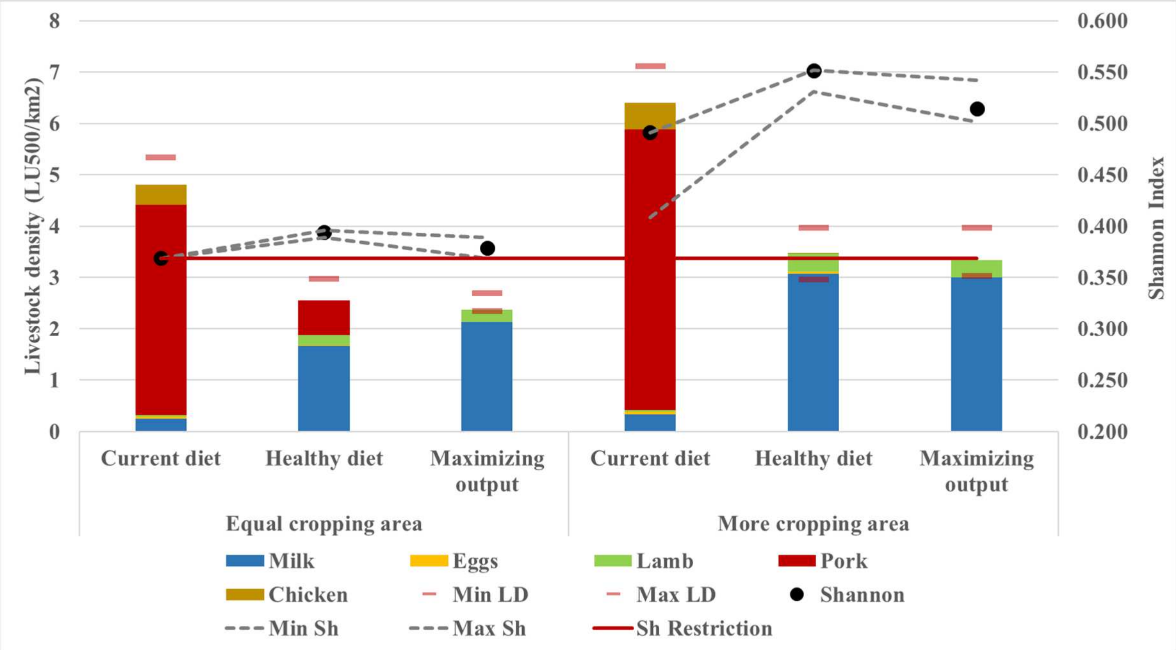

Figure A3.12. Variations in de model's variables of livestock and Shannon index regarding the scenario run for the period 2007-2016. Source: our own.

6. Non-linear programming formulas[65]

Land cover – Land use

-X1 + Y11 + Y12 = 0;
-X2 + Y21 + Y22 + Y23 + Y24 + Y25 + Y26 + Y27 + Y28 + Y29 + Y20 + Y21A + Y21B = 0;
-X3 + Y31 + Y32 = 0;
-X4 + Y41 = 0;
-X5 + Y51 = 0;
-X6 + Y61 + Y62 + Y63 + Y64 + Y65 = 0;
-X7 + Y71 = 0;
-X8 + Y81 = 0;

Land use – Products

Y11 - Z111 = 0;
Y12 - Z121 = 0;
Y21 - Z211 = 0;
Y22 - Z221 = 0;
Y23 - Z231 = 0;
Y24 - Z241 = 0;
Y25 - Z251 = 0;
Y26 - Z261 = 0;
Y27 - Z271 = 0;
Y28 - Z281 = 0;
Y29 - Z291 = 0;
Y20 - Z201 = 0;
Y31 - Z311 = 0;
Y32 - Z321 = 0;
Y41 - Z411 = 0;
Y51 - Z511 = 0;
Y61 - Z611 = 0;
Y62 - Z621 = 0;
Y63 - Z631 = 0;
Y64 - Z641 = 0;
Y11 - Z112 = 0;
Y12 - Z122 = 0;
Y21 - Z212 = 0;
Y22 - Z222 = 0;
Y23 - Z232 = 0;
Y24 - Z242 = 0;
Y25 - Z252 = 0;
Y26 - Z262 = 0;
Y27 - Z272 = 0;
Y28 - Z282 = 0;
Y29 - Z292 = 0;
Y20 - Z202 = 0;
Y31 - Z312 = 0;
Y32 - Z322 = 0;
Y41 - Z412 = 0;
Y61 - Z612 = 0;
Y62 - Z622 = 0;
Y63 - Z632 = 0;
Y64 - Z642 = 0;
Y12 - Z123 = 0;
Y21 - Z213 = 0;
Y23 - Z233 = 0;
Y26 - Z263 = 0;
Y28 - Z283 = 0;
Y31 - Z313 = 0;
Y32 - Z323 = 0;
Y41 - Z413 = 0;
Y31 - Z314 = 0;
Y32 - Z324 = 0;
Y41 - Z414 = 0;
Y31 - Z315 = 0;
Y41 - Z415 = 0;

Rotations

Y21 - Y22 = 0;
Y25 - Y26 = 0;
Y29 - Y20 = 0;
Y21 - Y23 = 0;
Y25 - Y27 = 0;
Y21 - Y24 = 0;
Y25 - Y28 = 0;
Y21 - Y21A = 0;
Y25 - Y21B = 0;

Products – Phytomass flows

Z111 - Z11101 - Z11102 = 0;
Z112 - Z11201 - Z11202 - Z11203 - Z11204 - Z11205 - Z11206 - Z11207 - Z11208 - Z11209 - Z11210 - Z11211 - Z11212 - Z11213 - Z11214 - Z11215 - Z11216 - Z11217 - Z11218 - Z11219 - Z11220 - Z11221 - Z11222 - Z11223 - Z11224 - Z11225 - Z11226 - Z11227 = 0;
Z121 - Z12101 - Z12102 = 0;
Z122 - Z12201 - Z12202 - Z12203 - Z12204 - Z12205 - Z12206 - Z12207 - Z12208 - Z12209 = 0;
Z123 - Z12301 = 0;
Z211 - Z21101 - Z21102 - Z21103 - Z21104 - Z21105 - Z21106 - Z21107 - Z21108 - Z21109 - Z21110 - Z21111 - Z21112 - Z21113 - Z21114 - Z21115 - Z21116 - Z21117 - Z21118 - Z21119 - Z21120 - Z21121 - Z21122 - Z21123 - Z21124 - Z21125 - Z21126 - Z21127 - Z21128 - Z21129 - Z21130 - Z21131 - Z21132 - Z21133 = 0;
Z212 - Z21201 - Z21202 - Z21203 - Z21204 - Z21205 - Z21206 - Z21207 - Z21208 - Z21209 - Z21210 - Z21211 - Z21212 - Z21213 - Z21214 - Z21215 - Z21216 - Z21217 - Z21218 - Z21219 - Z21220 - Z21221 - Z21222 - Z21223 - Z21224 - Z21225 - Z21226 - Z21227 - Z21228 - Z21229 = 0;
Z213 - Z21301 - Z21302 - Z21303 - Z21304 - Z21305 - Z21306 - Z21307 - Z21308 - Z21309 - Z21310 - Z21311 - Z21312 - Z21313 = 0;
Z221 - Z22101 - Z22102 = 0;
Z222 - Z22201 - Z22202 - Z22203 - Z22204 - Z22205 - Z22206 - Z22207 - Z22208 - Z22209 - Z22210 - Z22211 - Z22212 - Z22213 - Z22214 - Z22215 - Z22216 - Z22217 - Z22218 - Z22219 - Z22220 = 0;
Z231 - Z23101 - Z23102 = 0;
Z232 - Z23201 - Z23202 - Z23203 - Z23204 - Z23205 - Z23206 - Z23207 - Z23208 - Z23209 - Z23210 - Z23211 - Z23212 - Z23213 - Z23214 - Z23215 - Z23216 - Z23217 - Z23218 - Z23219 - Z23220 - Z23221 - Z23222 - Z23223 - Z23224 - Z23225 - Z23226 - Z23227 - Z23228 - Z23229 = 0;
Z233 - Z23301 - Z23302 - Z23303 - Z23304 - Z23305 - Z23306 - Z23307 - Z23308 - Z23309 - Z23310 - Z23311 - Z23312 - Z23313 = 0;
Z241 - Z24101 - Z24102 - Z24103 - Z24104 - Z24105 - Z24106 - Z24107 - Z24108 - Z24109 - Z24110 - Z24111 - Z24112 - Z24113 - Z24114 - Z24115 - Z24116 - Z24117 - Z24118 - Z24119 - Z24120 - Z24121 - Z24122 - Z24123 - Z24124 - Z24125 - Z24126 - Z24127 - Z24128 - Z24129 - Z24130 - Z24131 - Z24132 - Z24133 = 0;
Z242 - Z24201 - Z24202 - Z24203 - Z24204 - Z24205 - Z24206 - Z24207 - Z24208 - Z24209 - Z24210 - Z24211 - Z24212 - Z24213 - Z24214 - Z24215 - Z24216 - Z24217 - Z24218 - Z24219 - Z24220 = 0;
Z251 - Z25101 - Z25102 - Z25103 - Z25104 - Z25105 - Z25106 - Z25107 - Z25108 - Z25109 - Z25110 - Z25111 - Z25112 - Z25113 - Z25114 - Z25115 - Z25116 - Z25117 - Z25118 - Z25119 - Z25120 - Z25121 - Z25122 - Z25123 - Z25124 - Z25125 - Z25126 - Z25127 - Z25128 - Z25129 - Z25130 - Z25131 - Z25132 = 0;
Z252 - Z25201 - Z25202 = 0;
Z261 - Z26101 - Z26102 - Z26103 - Z26104 - Z26105 - Z26106 - Z26107 - Z26108 - Z26109 - Z26110 - Z26111 - Z26112 - Z26113 - Z26114 - Z26115 - Z26116 - Z26117 - Z26118 - Z26119 - Z26120 - Z26121 - Z26122 - Z26123 - Z26124 - Z26125 - Z26126 - Z26127 - Z26128 - Z26129 - Z26130 - Z26131 - Z26132 = 0;
Z262 - Z26201 - Z26202 - Z26203 - Z26204 - Z26205 - Z26206 - Z26207 - Z26208 - Z26209 - Z26210 - Z26211 - Z26212 - Z26213 - Z26214 - Z26215 - Z26216 - Z26217 - Z26218 - Z26219 - Z26220 - Z26221 - Z26222 - Z26223 - Z26224 - Z26225 - Z26226 - Z26227 - Z26228 - Z26229 = 0;
Z263 - Z26301 - Z26302 - Z26303 - Z26304 - Z26305 - Z26306 - Z26307 - Z26308 - Z26309 - Z26310 - Z26311 - Z26312 - Z26313 = 0;
Z271 - Z27101 - Z27102 - Z27103 - Z27104 - Z27105 - Z27106 - Z27107 - Z27108 - Z27109 - Z27110 - Z27111 - Z27112 - Z27113 - Z27114 - Z27115 - Z27116 - Z27117 - Z27118 - Z27119 - Z27120 - Z27121 - Z27122 - Z27123 - Z27124 - Z27125 - Z27126 - Z27127 - Z27128 - Z27129 - Z27130 - Z27131 - Z27132 = 0;
Z272 - Z27201 - Z27202 - Z27203 - Z27204 - Z27205 - Z27206 - Z27207 - Z27208 - Z27209 - Z27210 - Z27211 - Z27212 - Z27213 - Z27214 - Z27215 - Z27216 - Z27217 - Z27218 - Z27219 - Z27220 = 0;
Z281 - Z28101 - Z28102 - Z28103 - Z28104 - Z28105 - Z28106 - Z28107 - Z28108 - Z28109 - Z28110 - Z28111 - Z28112 - Z28113 - Z28114 - Z28115 - Z28116 - Z28117 - Z28118 - Z28119 - Z28120 - Z28121 - Z28122 - Z28123 - Z28124 - Z28125 - Z28126 - Z28127 - Z28128 - Z28129 - Z28130 - Z28131 - Z28132 = 0;
Z282 - Z28201 - Z28202 - Z28203 - Z28204 - Z28205 - Z28206 - Z28207 - Z28208 - Z28209 - Z28210 - Z28211 - Z28212 - Z28213 - Z28214 - Z28215 - Z28216 - Z28217 - Z28218 - Z28219 - Z28220 - Z28221 - Z28222 - Z28223 - Z28224 - Z28225 - Z28226 - Z28227 - Z28228 - Z28229 = 0;
Z283 - Z28301 - Z28302 - Z28303 - Z28304 - Z28305 - Z28306 - Z28307 - Z28308 - Z28309 - Z28310 - Z28311 - Z28312 - Z28313 = 0;
Z291 - Z29101 - Z29102 - Z29103 - Z29104 - Z29105 - Z29106 - Z29107 - Z29108 - Z29109 - Z29110 - Z29111 - Z29112 - Z29113 - Z29114 - Z29115 - Z29116 - Z29117 - Z29118 - Z29119 - Z29120 - Z29121 - Z29122 - Z29123 - Z29124 - Z29125 - Z29126 - Z29127 - Z29128 - Z29129 - Z29130 - Z29131 - Z29132 - Z29133 = 0;
Z292 - Z29201 - Z29202 = 0;
Z201 - Z20101 - Z20102 - Z20103 - Z20104 - Z20105 - Z20106 - Z20107 - Z20108 - Z20109 - Z20110 - Z20111 - Z20112 - Z20113 - Z20114 - Z20115 - Z20116 - Z20117 - Z20118 - Z20119 - Z20120 - Z20121 - Z20122 - Z20123 - Z20124 - Z20125 - Z20126 - Z20127 - Z20128 - Z20129 - Z20130 - Z20131 - Z20132 = 0;
Z202 - Z20201 - Z20202 - Z20203 - Z20204 - Z20205 - Z20206 - Z20207 - Z20208 - Z20209 - Z20210 - Z20211 - Z20212 - Z20213 - Z20214 = 0;
Z311 - Z31101 - Z31102 = 0;
Z312 - Z31201 - Z31202 - Z31203 - Z31204 - Z31205 - Z31206 - Z31207 - Z31208 - Z31209 - Z31210 - Z31211 - Z31212 - Z31213 - Z31214 - Z31215 - Z31216 - Z31217 - Z31218 - Z31219 - Z31220 - Z31221 - Z31222 - Z31223 - Z31224 - Z31225 - Z31226 - Z31227 - Z31228 - Z31229 = 0;
Z313 - Z31301 - Z31302 - Z31303 - Z31304 - Z31305 - Z31306 - Z31307 - Z31308 - Z31309 - Z31310 - Z31311 - Z31312 - Z31313 - Z31314 - Z31315 - Z31316 - Z31317 - Z31318 - Z31319 - Z31320 - Z31321 - Z31322 = 0;
Z314 - Z31401 - Z31402 - Z31403 - Z31404 - Z31405 - Z31406 - Z31407 - Z31408 - Z31409 = 0;
Z315 - Z31501 - Z31502 - Z31503 - Z31504 - Z31505 - Z31506 - Z31507 - Z31508 - Z31509 - Z31510 - Z31511 - Z31512 - Z31513 = 0;
Z321 - Z32101 - Z32102 = 0;

[65] Data for 2009. Variables L refer to the ratios explained in section 3.2.2

Z322 - Z32201 - Z32202 - Z32203 - Z32204 - Z32205 - Z32206 - Z32207 - Z32208 - Z32209 = 0;
Z323 - Z32301 - Z32302 - Z32303 - Z32304 - Z32305 - Z32306 - Z32307 - Z32308 - Z32309 = 0;
Z324 - Z32401 - Z32402 - Z32403 - Z32404 - Z32405 - Z32406 - Z32407 - Z32408 - Z32409 - Z32410 - Z32411 - Z32412 - Z32413 = 0;
Z411 - Z41101 - Z41102 = 0;
Z412 - Z41201 - Z41202 - Z41203 - Z41204 - Z41205 - Z41206 - Z41207 - Z41208 - Z41209 - Z41210 - Z41211 - Z41212 - Z41213 - Z41214 - Z41215 - Z41216 - Z41217 - Z41218 - Z41219 - Z41220 - Z41221 - Z41222 - Z41223 - Z41224 - Z41225 - Z41226 - Z41227 - Z41228 - Z41229 - Z41230 - Z41231 - Z41232 - Z41233 - Z41234 - Z41235 - Z41236 - Z41237 - Z41238 - Z41239 = 0;
Z413 - Z41301 - Z41302 - Z41303 - Z41304 - Z41305 - Z41306 - Z41307 - Z41308 - Z41309 - Z41310 - Z41311 - Z41312 - Z41313 - Z41314 - Z41315 - Z41316 - Z41317 - Z41318 - Z41319 - Z41320 = 0;
Z414 - Z41401 - Z41402 - Z41403 - Z41404 - Z41405 - Z41406 - Z41407 - Z41408 - Z41409 = 0;
Z415 - Z41501 - Z41502 - Z41503 - Z41504 - Z41505 - Z41506 - Z41507 - Z41508 - Z41509 - Z41510 - Z41511 - Z41512 - Z41513 = 0;
Z511 - Z51101 - Z51102 - Z51103 - Z51104 - Z51105 - Z51106 - Z51107 - Z51108 - Z51109 - Z51110 - Z51111 - Z51112 - Z51113 = 0;
Z611 - Z61101 - Z61102 - Z61103 - Z61104 - Z61105 - Z61106 - Z61107 - Z61108 - Z61109 = 0;
Z612 - Z61201 - Z61202 - Z61203 - Z61204 - Z61205 - Z61206 - Z61207 - Z61208 - Z61209 - Z61210 - Z61211 - Z61212 = 0;
Z621 - Z62101 - Z62102 - Z62103 - Z62104 - Z62105 - Z62106 - Z62107 - Z62108 - Z62109 = 0;
Z622 - Z62201 - Z62202 - Z62203 - Z62204 - Z62205 - Z62206 - Z62207 - Z62208 - Z62209 - Z62210 - Z62211 - Z62212 = 0;
Z631 - Z63101 - Z63102 - Z63103 - Z63104 - Z63105 - Z63106 - Z63107 - Z63108 - Z63109 = 0;
Z632 - Z63201 - Z63202 - Z63203 - Z63204 - Z63205 - Z63206 - Z63207 - Z63208 - Z63209 - Z63210 - Z63211 - Z63212 = 0;
Z641 - Z64101 - Z64102 - Z64103 - Z64104 - Z64105 - Z64106 - Z64107 - Z64108 - Z64109 = 0;
Z642 - Z64201 - Z64202 - Z64203 - Z64204 - Z64205 - Z64206 - Z64207 - Z64208 - Z64209 - Z64210 - Z64211 - Z64212 = 0;
Z651 - Z65101 - Z65102 - Z65103 - Z65104 - Z65105 - Z65106 - Z65107 - Z65108 - Z65109 = 0;

Animal species – Animal stage

1*W1 + -1*W11 + -1*W12 + -1*W13 + -1*W14 + -1*W15 + -1*W16 + -1*W17 = 0;
0.067*W1 + -1*W11 = 0;
0.05*W1 + -1*W12 = 0;
0.05*W1 + -1*W13 = 0;
0.17*W1 + -1*W14 = 0;
0.64*W1 + -1*W15 = 0;
0.012*W1 + -1*W16 = 0;
0.013*W1 + -1*W17 = 0;
1*W2 + -1*W21 + -1*W22 + -1*W23 = 0;
0.25*W2 + -1*W21 = 0;
0.3125*W2 + -1*W22 = 0;
0.4375*W2 + -1*W23 = 0;
1*W3 + -1*W31 + -1*W32 + -1*W33 + -1*W34 + -1*W35 + -1*W36 + -1*W37 + -1*W38 + -1*W39 = 0;
0.41*W31 + 0.41*W32 + -1*W37 + -1*W38 + -1*W39 = 0;
0.33*W33 + 0.33*W34 + -1*W37 + -1*W38 + -1*W39 = 0;
6.67*W35 + 6.67*W36 + -1*W37 + -1*W38 + -1*W39 = 0;
-1*W31 + 2.5*W32 = 0;
-1*W33 + 1*W34 = 0;
-1*W35 + 0.14*W36 = 0;
-1*W37 + 2.83*W38 = 0;
-1*W37 + 5.67*W39 = 0;
1*W4 + -1*W41 + -1*W42 + -1*W43 + -1*W44 + -1*W45 + -1*W46 + -1*W47 + -1*W48 + -1*W49 + -1*W40 + -1*W411 + -1*W412 = 0;
3.64*W41 + 3.64*W42 + -1*W411 + -1*W412 = 0;
6.67*W43 + 6.67*W44 + 6.67*W45 + 6.67*W46 + -1*W411 + -1*W412 = 0;
50*W47 + 50*W48 + 50*W49 + 50*W40 + -1*W411 + -1*W412 = 0;
-1*W41 + 0.83*W42 = 0;
-1*W43 + 0.83*W44 = 0;
-1*W43 + 0.38*W45 = 0;
-1*W43 + 0.12*W46 = 0;
-1*W47 + 0.83*W48 = 0;
-1*W47 + 0.38*W49 = 0;
-1*W47 + 0.05*W40 = 0;

Animal stage – Animal flow

W1101 + W1102 + W1103 + W1104 + W1105 + W1106 + W1107 - W11 = 0;
W1201 + W1202 + W1203 + W1204 + W1205 + W1206 + W1207 - W12 = 0;
W1301 + W1302 + W1303 + W1304 + W1305 + W1306 + W1307 - W13 = 0;
W1401 + W1402 + W1403 + W1404 + W1405 + W1406 + W1407 - W14 = 0;
W1501 + W1502 + W1503 + W1504 + W1505 + W1506 + W1507 - W15 = 0;
W1601 + W1602 + W1603 + W1604 + W1605 + W1606 + W1607 - W16 = 0;
W1701 + W1702 + W1703 + W1704 + W1705 + W1706 + W1707 - W17 = 0;
W2101 + W2102 + W2103 + W2104 + W2105 + W2106 + W2107 - W21 = 0;
W2201 + W2202 + W2203 + W2204 + W2205 + W2206 + W2207 - W22 = 0;
W2301 + W2302 + W2303 + W2304 + W2305 + W2306 + W2307 - W23 = 0;
W3101 + W3102 + W3103 + W3104 + W3105 + W3106 + W3107 - W31 = 0;
W3201 + W3202 + W3203 + W3204 + W3205 + W3206 + W3207 - W32 = 0;
W3301 + W3302 + W3303 + W3304 + W3305 + W3306 + W3307 - W33 = 0;
W3401 + W3402 + W3403 + W3404 + W3405 + W3406 + W3407 - W34 = 0;
W3501 + W3502 + W3503 + W3504 + W3505 + W3506 + W3507 - W35 = 0;
W3601 + W3602 + W3603 + W3604 + W3605 + W3606 + W3607 - W36 = 0;
W3701 + W3702 + W3703 + W3704 + W3705 + W3706 + W3707 - W37 = 0;
W3801 + W3802 + W3803 + W3804 + W3805 + W3806 + W3807 - W38 = 0;
W3901 + W3902 + W3903 + W3904 + W3905 + W3906 + W3907 - W39 = 0;
W4101 + W4102 + W4103 + W4104 + W4105 + W4106 + W4107 - W41 = 0;
W4201 + W4202 + W4203 + W4204 + W4205 + W4206 + W4207 - W42 = 0;
W4301 + W4302 + W4303 + W4304 + W4305 + W4306 + W4307 - W43 = 0;
W4401 + W4402 + W4403 + W4404 + W4405 + W4406 + W4407 - W44 = 0;
W4501 + W4502 + W4503 + W4504 + W4505 + W4506 + W4507 - W45 = 0;
W4601 + W4602 + W4603 + W4604 + W4605 + W4606 + W4607 - W46 = 0;
W4701 + W4702 + W4703 + W4704 + W4705 + W4706 + W4707 - W47 = 0;
W4801 + W4802 + W4803 + W4804 + W4805 + W4806 + W4807 - W48 = 0;
W4901 + W4902 + W4903 + W4904 + W4905 + W4906 + W4907 - W49 = 0;
W4001 + W4002 + W4003 + W4004 + W4005 + W4006 + W4007 - W40 = 0;
W4111 + W4112 + W4113 + W4114 + W4115 + W4116 + W4117 - W411 = 0;
W4121 + W4122 + W4123 + W4124 + W4125 + W4126 + W4127 - W412 = 0;

Phytomass flow – Domestic residues

Z11101C1 + Z11101C2 + Z11101C3 + Z11101C4 + Z11101C5 + Z11101C6 + Z11101C7 - Z11101 = 0;
Z12101C1 + Z12101C2 + Z12101C3 + Z12101C4 + Z12101C5 + Z12101C6 + Z12101C7 - Z12101 = 0;
Z29101C1 + Z29101C2 + Z29101C3 + Z29101C4 + Z29101C5 + Z29101C6 + Z29101C7 - Z29101 = 0;

Animal flow – Domestic residues

W37C1 + W37C2 + W37C3 + W37C4 + W37C5 + W37C6 + W37C7 - W37 = 0;
W38C1 + W38C2 + W38C3 + W38C4 + W38C5 + W38C6 + W38C7 - W38 = 0;
W39C1 + W39C2 + W39C3 + W39C4 + W39C5 + W39C6 + W39C7 - W39 = 0;
W411C1 + W411C2 + W411C3 + W411C4 + W411C5 + W411C6 + W411C7 - W411 = 0;
W412C1 + W412C2 + W412C3 + W412C4 + W412C5 + W412C6 + W412C7 - W412 = 0;
W2C1 + W2C2 + W2C3 + W2C4 + W2C5 + W2C6 + W2C7 - W2 = 0;
W15C1 + W15C2 + W15C3 + W15C4 + W15C5 + W15C6 + W15C7 - W15 = 0;
W152C1 + W152C2 + W152C3 + W152C4 + W152C5 + W152C6 + W152C7 - W15 = 0;

Constraints for animal feeding

3,890*2.13*Z11201 + 2,343*12.56*Z21102 + 502*10.13*Z24102 + 900*10.14*Z25101 + 1,896*12.35*Z26101 + 685*10.89*Z27101 + 1,428*10.42*Z28101 + 658*9.63*Z20101 - 197.00*W11 = 0;
3,890*2.13*Z11202 + 2,343*12.56*Z21103 + 502*10.13*Z24103 + 900*10.14*Z25102 + 1,896*12.35*Z26102 + 685*10.89*Z27102 + 1,428*10.42*Z28102 + 658*9.63*Z20102 - 218*W12 = 0;
3,890*2.13*Z11203 + 2,343*12.56*Z21104 + 502*10.13*Z24104 + 900*10.14*Z25103 + 1,896*12.35*Z26103 + 685*10.89*Z27103 + 1,428*10.42*Z28103 + 658*9.63*Z20103 - 305*W13 = 0;
3,890*2.13*Z11204 + 2,343*13.64*Z21105 + 502*11.18*Z24105 + 900*11.13*Z25104 + 1,896*12.85*Z26104 + 685*10.89*Z27104 + 1,428*11.64*Z28104 + 658*10.47*Z20104 - 445*W14 = 0;
3,890*2.13*Z11205 + 2,343*13.64*Z21106 + 502*11.18*Z24106 + 900*11.13*Z25105 + 1,896*12.85*Z26105 + 685*10.89*Z27105 + 1,428*11.64*Z28105 + 658*10.47*Z20105 - 514*W15 = 0;
3,890*2.13*Z11206 + 2,343*13.64*Z21107 + 502*11.18*Z24107 + 900*11.13*Z25106 + 1,896*12.85*Z26106 + 685*10.89*Z27106 + 1,428*11.64*Z28106 + 658*10.47*Z20106 - 386*W16 = 0;
3,890*2.13*Z11207 + 2,343*13.64*Z21108 + 502*11.18*Z24108 + 900*11.13*Z25107 + 1,896*12.85*Z26107 + 685*10.89*Z27107 + 1,428*11.64*Z28107 + 658*10.47*Z20107 - 514*W17 = 0;

3,890*2.13*Z11208 + 2,343*12.56*Z21109 +
502*10.13*Z24109 + 900*10.14*Z25108 +
1,896*12.35*Z26108 + 685*10.89*Z27108 +
1,428*10.42*Z28108 + 658*9.63*Z20108 -
86*W21 = 0;
3,890*2.13*Z11209 + 2,343*12.56*Z21110 +
502*10.13*Z24110 + 900*10.14*Z25109 +
1,896*12.35*Z26109 + 685*10.89*Z27109 +
1,428*10.42*Z28109 + 658*9.63*Z20109 -
261*W22 = 0;
3,890*2.13*Z11210 + 2,343*12.56*Z21111 +
502*10.13*Z24111 + 900*10.14*Z25110 +
1,896*12.35*Z26110 + 685*10.89*Z27110 +
1,428*10.42*Z28110 + 658*9.63*Z20110 -
336*W23 = 0;
3,890*4.4*Z11211 + 2,343*14.57*Z21112 +
3,858*2.05*Z21201 + 3,837*2.05*Z23201 +
502*13.31*Z24112 + 900*14.69*Z25111 +
1,896*14.32*Z26111 + 3,156*2.05*Z26201 +
1,428*13.69*Z28111 + 2,423*2.05*Z28201 +
658*13.06*Z20111 + 645*6.34*Z31201 +
513*2.89*Z31301 - 1152*W31 = 0;
3,890*4.4*Z11212 + 2,343*14.57*Z21113 +
3,858*2.05*Z21202 + 3,837*2.05*Z23202 +
502*13.31*Z24113 + 900*14.69*Z25112 +
1,896*14.32*Z26112 + 3,156*2.05*Z26202 +
1,428*13.69*Z28112 + 2,423*2.05*Z28202 +
658*13.06*Z20112 + 645*6.34*Z31202 +
513*2.89*Z31302 - 4147*W32 = 0;
3,890*4.4*Z11213 + 2,343*14.57*Z21114 +
3,858*2.05*Z21203 + 3,837*2.05*Z23203 +
502*13.31*Z24114 + 900*14.69*Z25113 +
1,896*14.32*Z26113 + 3,156*2.05*Z26203 +
1,428*13.69*Z28113 + 2,423*2.05*Z28203 +
658*13.06*Z20113 + 645*6.34*Z31203 +
513*2.89*Z31303 - 7898*W33 = 0;
3,890*4.4*Z11214 + 2,343*14.57*Z21115 +
3,858*2.05*Z21204 + 3,837*2.05*Z23204 +
502*13.31*Z24115 + 900*14.69*Z25114 +
1,896*14.32*Z26114 + 3,156*2.05*Z26204 +
1,428*13.69*Z28114 + 2,423*2.05*Z28204 +
658*13.06*Z20114 + 645*6.34*Z31204 +
513*2.89*Z31304 - 13983*W34 = 0;
3,890*4.4*Z11215 + 2,343*14.57*Z21116 +
3,858*2.05*Z21205 + 3,837*2.05*Z23205 +
502*13.31*Z24116 + 900*14.69*Z25115 +
1,896*14.32*Z26115 + 3,156*2.05*Z26205 +
1,428*13.69*Z28115 + 2,423*2.05*Z28205 +
658*13.06*Z20115 + 645*6.34*Z31205 +
513*2.89*Z31305 - 7898*W35 = 0;
3,890*4.4*Z11216 + 2,343*14.57*Z21117 +
3,858*2.05*Z21206 + 3,837*2.05*Z23206 +
502*13.31*Z24117 + 900*14.69*Z25116 +
1,896*14.32*Z26116 + 3,156*2.05*Z26206 +
1,428*13.69*Z28116 + 2,423*2.05*Z28206 +
658*13.06*Z20116 + 645*6.34*Z31206 +
513*2.89*Z31306 - 13983*W36 = 0;
3,890*4.4*Z11217 + 2,343*14.69*Z21118 +
3,858*2.68*Z21207 + 3,837*2.68*Z23207 +
502*13.61*Z24118 + 900*15.55*Z25117 +
1,896*14.55*Z26117 + 3,156*2.68*Z26207 +
1,428*13.98*Z28117 + 2,423*2.68*Z28207 +
658*13.25*Z20117 + 645*6.5*Z31207 +
513*3*Z31307 + 1,402*4.23*Z41217 -
18644*W37 = 0;
3,890*4.4*Z11218 + 2,343*14.69*Z21119 +
3,858*2.68*Z21208 + 3,837*2.68*Z23208 +
502*13.61*Z24119 + 900*15.55*Z25118 +
1,896*14.55*Z26118 + 3,156*2.68*Z26208 +
1,428*13.98*Z28118 + 2,423*2.68*Z28208 +
658*13.25*Z20118 + 645*6.5*Z31208 +
513*3*Z31308 + 1,402*4.23*Z41218 -
23882*W38 = 0;
3,890*4.4*Z11219 + 2,343*14.69*Z21120 +
3,858*2.68*Z21209 + 3,837*2.68*Z23209 +
502*13.61*Z24120 + 900*15.55*Z25119 +
1,896*14.55*Z26119 + 3,156*2.68*Z26209 +
1,428*13.98*Z28119 + 2,423*2.68*Z28209 +
658*13.25*Z20119 + 645*6.5*Z31209 +
513*3*Z31309 + 1,402*4.23*Z41219 -
13983*W39 = 0;
2,343*11.72*Z21121 + 3,858*5.02*Z21210 +
177*5.02*Z21301 + 534*8.3*Z22201 +
3,837*5.02*Z23210 + 176*5.02*Z23301 +
502*11.81*Z24121 + 732*7.62*Z24201 +
900*13.33*Z25120 + 1,896*11.7*Z26120 +
3,156*5.02*Z26210 + 145*5.02*Z26301 +
685*13.53*Z27120 + 1,016*9.21*Z27201 +
1,428*11.33*Z28120 + 2,423*5.19*Z28210 +
111*5.19*Z28301 + 1,613*10.99*Z29121 +
658*11.76*Z20120 + 1,130*7.62*Z20201 +
645*7.77*Z31210 + 513*4.22*Z31310 +
1,282*9.42*Z31501 + 1,282*9.42*Z32401 +
1,402*4.08*Z41220 + 635*4.02*Z41301 +
1,282*9.42*Z41501 + 2,136*11.5*Z51101 +
1,500*8.87*Z61201 + 1,850*8.87*Z62201 +
1,500*9.42*Z63201 + 1,850*9.42*Z64201 -
0*W41 = 0;
2,343*11.72*Z21122 + 3,858*5.02*Z21211 +
177*5.02*Z21302 + 534*8.3*Z22202 +
3,837*5.02*Z23211 + 176*5.02*Z23302 +
502*11.81*Z24122 + 732*7.62*Z24202 +
900*13.33*Z25121 + 1,896*11.7*Z26121 +
3,156*5.02*Z26211 + 145*5.02*Z26302 +
685*13.53*Z27121 + 1,016*9.21*Z27202 +
1,428*11.33*Z28121 + 2,423*5.19*Z28211 +
111*5.19*Z28302 + 1,613*10.99*Z29122 +
658*11.76*Z20121 + 1,130*7.62*Z20202 +
645*7.77*Z31211 + 513*4.22*Z31311 +
1,282*9.42*Z31502 + 1,282*9.42*Z32402 +
1,402*4.08*Z41221 + 635*4.02*Z41302 +
1,282*9.42*Z41502 + 2,136*11.5*Z51102 +
1,500*8.87*Z61202 + 1,850*8.87*Z62202 +
1,500*9.42*Z63202 + 1,850*9.42*Z64202 -
2428*W42 = 0;
2,343*11.72*Z21123 + 3,858*5.02*Z21212 +
177*5.02*Z21303 + 534*8.3*Z22203 +
3,837*5.02*Z23212 + 176*5.02*Z23303 +
502*11.81*Z24123 + 732*7.62*Z24203 +
900*13.33*Z25122 + 1,896*11.7*Z26122 +
3,156*5.02*Z26212 + 145*5.02*Z26303 +
685*13.53*Z27122 + 1,016*9.21*Z27203 +
1,428*11.33*Z28122 + 2,423*5.19*Z28212 +
111*5.19*Z28303 + 1,613*10.99*Z29123 +
658*11.76*Z20122 + 1,130*7.62*Z20203 +
645*7.77*Z31212 + 513*4.22*Z31312 +
1,282*9.42*Z31503 + 1,282*9.42*Z32403 +
1,402*4.08*Z41222 + 635*4.02*Z41303 +
1,282*9.42*Z41503 + 2,136*11.5*Z51103 +
1,500*8.87*Z61203 + 1,850*8.87*Z62203 +
1,500*9.42*Z63203 + 1,850*9.42*Z64203 -
0*W43 = 0;
2,343*11.72*Z21124 + 3,858*5.02*Z21213 +
177*5.02*Z21304 + 534*8.3*Z22204 +
3,837*5.02*Z23213 + 176*5.02*Z23304 +
502*11.81*Z24124 + 732*7.62*Z24204 +
900*13.33*Z25123 + 1,896*11.7*Z26123 +
3,156*5.02*Z26213 + 145*5.02*Z26304 +
685*13.53*Z27123 + 1,016*9.21*Z27204 +
1,428*11.33*Z28123 + 2,423*5.19*Z28213 +
111*5.19*Z28304 + 1,613*10.99*Z29124 +
658*11.76*Z20123 + 1,130*7.62*Z20204 +
645*7.77*Z31213 + 513*4.22*Z31313 +
1,282*9.42*Z31504 + 1,282*9.42*Z32404 +
1,402*4.08*Z41223 + 635*4.02*Z41304 +
1,282*9.42*Z41504 + 2,136*11.5*Z51104 +
1,500*8.87*Z61204 + 1,850*8.87*Z62204 +
1,500*9.42*Z63204 + 1,850*9.42*Z64204 -
2428*W44 = 0;
2,343*11.72*Z21125 + 3,858*5.02*Z21214 +
177*5.02*Z21305 + 534*8.3*Z22205 +
3,837*5.02*Z23214 + 176*5.02*Z23305 +
502*11.81*Z24125 + 732*7.62*Z24205 +
900*13.33*Z25124 + 1,896*11.7*Z26124 +
3,156*5.02*Z26214 + 145*5.02*Z26305 +
685*13.53*Z27124 + 1,016*9.21*Z27205 +
1,428*11.33*Z28124 + 2,423*5.19*Z28214 +
111*5.19*Z28305 + 1,613*10.99*Z29125 +
658*11.76*Z20124 + 1,130*7.62*Z20205 +
645*7.77*Z31214 + 513*4.22*Z31314 +
1,282*9.42*Z31505 + 1,282*9.42*Z32405 +
1,402*4.08*Z41224 + 635*4.02*Z41305 +
1,282*9.42*Z41505 + 2,136*11.5*Z51105 +
1,500*8.87*Z61205 + 1,850*8.87*Z62205 +
1,500*9.42*Z63205 + 1,850*9.42*Z64205 -
4307*W45 = 0;
2,343*11.72*Z21126 + 3,858*5.02*Z21215 +
177*5.02*Z21306 + 534*8.3*Z22206 +
3,837*5.02*Z23215 + 176*5.02*Z23306 +
502*11.81*Z24126 + 732*7.62*Z24206 +
900*13.33*Z25125 + 1,896*11.7*Z26125 +
3,156*5.02*Z26215 + 145*5.02*Z26306 +
685*13.53*Z27125 + 1,016*9.21*Z27206 +
1,428*11.33*Z28125 + 2,423*5.19*Z28215 +
111*5.19*Z28306 + 1,613*10.99*Z29126 +
658*11.76*Z20125 + 1,130*7.62*Z20206 +
645*7.77*Z31215 + 513*4.22*Z31315 +
1,282*9.42*Z31506 + 1,282*9.42*Z32406 +
1,402*4.08*Z41225 + 635*4.02*Z41306 +
1,282*9.42*Z41506 + 2,136*11.5*Z51106 +
1,500*8.87*Z61206 + 1,850*8.87*Z62206 +
1,500*9.42*Z63206 + 1,850*9.42*Z64206 -
3283*W46 = 0;
2,343*11.72*Z21127 + 3,858*5.02*Z21216 +
177*5.02*Z21307 + 534*8.3*Z22207 +
3,837*5.02*Z23216 + 176*5.02*Z23307 +
502*11.81*Z24127 + 732*7.62*Z24207 +
900*13.33*Z25126 + 1,896*11.7*Z26126 +
3,156*5.02*Z26216 + 145*5.02*Z26307 +
685*13.53*Z27126 + 1,016*9.21*Z27207 +
1,428*11.33*Z28126 + 2,423*5.19*Z28216 +
111*5.19*Z28307 + 1,613*10.99*Z29127 +
658*11.76*Z20126 + 1,130*7.62*Z20207 +
645*7.77*Z31216 + 513*4.22*Z31316 +
1,282*9.42*Z31507 + 1,282*9.42*Z32407 +
1,402*4.08*Z41226 + 635*4.02*Z41307 +
1,282*9.42*Z41507 + 2,136*11.5*Z51107 +
1,500*8.87*Z61207 + 1,850*8.87*Z62207 +
1,500*9.42*Z63207 + 1,850*9.42*Z64207 -
0*W47 = 0;
2,343*11.72*Z21128 + 3,858*5.02*Z21217 +
177*5.02*Z21308 + 534*8.3*Z22208 +
3,837*5.02*Z23217 + 176*5.02*Z23308 +
502*11.81*Z24128 + 732*7.62*Z24208 +
900*13.33*Z25127 + 1,896*11.7*Z26127 +
3,156*5.02*Z26217 + 145*5.02*Z26308 +
685*13.53*Z27127 + 1,016*9.21*Z27208 +
1,428*11.33*Z28127 + 2,423*5.19*Z28217 +
111*5.19*Z28308 + 1,613*10.99*Z29128 +
658*11.76*Z20127 + 1,130*7.62*Z20208 +
645*7.77*Z31217 + 513*4.22*Z31317 +
1,282*9.42*Z31508 + 1,282*9.42*Z32408 +
1,402*4.08*Z41227 + 635*4.02*Z41308 +
1,282*9.42*Z41508 + 2,136*11.5*Z51108 +
1,500*8.87*Z61208 + 1,850*8.87*Z62208 +
1,500*9.42*Z63208 + 1,850*9.42*Z64208 -
2428*W48 = 0;
2,343*11.72*Z21129 + 3,858*5.02*Z21218 +
177*5.02*Z21309 + 534*8.3*Z22209 +
3,837*5.02*Z23218 + 176*5.02*Z23309 +
502*11.81*Z24129 + 732*7.62*Z24209 +
900*13.33*Z25128 + 1,896*11.7*Z26128 +
3,156*5.02*Z26218 + 145*5.02*Z26309 +
685*13.53*Z27128 + 1,016*9.21*Z27209 +
1,428*11.33*Z28128 + 2,423*5.19*Z28218 +
111*5.19*Z28309 + 1,613*10.99*Z29129 +
658*11.76*Z20128 + 1,130*7.62*Z20209 +
645*7.77*Z31218 + 513*4.22*Z31318 +
1,282*9.42*Z31509 + 1,282*9.42*Z32409 +
1,402*4.08*Z41228 + 635*4.02*Z41309 +
1,282*9.42*Z41509 + 2,136*11.5*Z51109 +
1,500*8.87*Z61209 + 1,850*8.87*Z62209 +
1,500*9.42*Z63209 + 1,850*9.42*Z64209 -
4307*W49 = 0;
2,343*11.72*Z21130 + 3,858*5.02*Z21219 +
177*5.02*Z21310 + 534*8.3*Z22210 +
3,837*5.02*Z23219 + 176*5.02*Z23310 +
502*11.81*Z24130 + 732*7.62*Z24210 +
900*13.33*Z25129 + 1,896*11.7*Z26129 +
3,156*5.02*Z26219 + 145*5.02*Z26310 +
685*13.53*Z27129 + 1,016*9.21*Z27210 +
1,428*11.33*Z28129 + 2,423*5.19*Z28219 +
111*5.19*Z28310 + 1,613*10.99*Z29130 +
658*11.76*Z20129 + 1,130*7.62*Z20210 +
645*7.77*Z31219 + 513*4.22*Z31319 +
1,282*9.42*Z31510 + 1,282*9.42*Z32410 +
1,402*4.08*Z41229 + 635*4.02*Z41310 +
1,282*9.42*Z41510 + 2,136*11.5*Z51110 +
1,500*8.87*Z61210 + 1,850*8.87*Z62210 +
1,500*9.42*Z63210 + 1,850*9.42*Z64210 -
3299*W40 = 0;
2,343*11.72*Z21131 + 3,858*5.02*Z21220 +
177*5.02*Z21311 + 534*8.3*Z22211 +
3,837*5.02*Z23220 + 176*5.02*Z23311 +
502*11.81*Z24131 + 732*7.62*Z24211 +
900*13.33*Z25130 + 1,896*11.7*Z26130 +
3,156*5.02*Z26220 + 145*5.02*Z26311 +
685*13.53*Z27130 + 1,016*9.21*Z27211 +

1,428*11.33*Z28130 + 2,423*5.19*Z28220 +
111*5.19*Z28311 + 1,613*10.99*Z29131 +
658*11.76*Z20130 + 1,130*7.62*Z20211 +
645*7.77*Z31220 + 513*4.22*Z31320 +
1,282*9.42*Z31511 + 1,282*9.42*Z32411 +
1,402*4.08*Z41230 + 635*4.02*Z41311 +
1,282*9.42*Z41511 + 2,136*11.5*Z51111 +
1,500*8.87*Z61211 + 1,850*8.87*Z62211 +
1,500*9.42*Z63211 + 1,850*9.42*Z64211 -
5024*W411 = 0;
2,343*11.72*Z21132 + 3,858*5.02*Z21221 +
177*5.02*Z21312 + 534*8.3*Z22212 +
3,837*5.02*Z23221 + 176*5.02*Z23312 +
502*11.81*Z24132 + 732*7.62*Z24212 +
900*13.33*Z25131 + 1,896*11.7*Z26131 +
3,156*5.02*Z26221 + 145*5.02*Z26312 +
685*13.53*Z27131 + 1,016*9.21*Z27212 +
1,428*11.33*Z28131 + 2,423*5.19*Z28221 +
111*5.19*Z28312 + 1,613*10.99*Z29132 +
658*11.76*Z20131 + 1,130*7.62*Z20212 +
645*7.77*Z31221 + 513*4.22*Z31321 +
1,282*9.42*Z31512 + 1,282*9.42*Z32412 +
1,402*4.08*Z41231 + 635*4.02*Z41312 +
1,282*9.42*Z41512 + 2,136*11.5*Z51112 -
5788*W412 = 0;
0.155*3,890*Z11201 + 0.138*2,343*Z21102 +
0.206*502*Z24102 + 0.41*900*Z25101 +
0.107*1,896*Z26101 + 0.265*685*Z27101 +
0.113*1,428*Z28101 + 0.089*1,613*Z29102 +
0.242*658*Z20101 + 0.128*1,402*Z41201 -
3.2*W11 >= 0;
0.155*3,890*Z11202 + 0.138*2,343*Z21103 +
0.206*502*Z24103 + 0.41*900*Z25102 +
0.107*1,896*Z26102 + 0.265*685*Z27102 +
0.113*1,428*Z28102 + 0.089*1,613*Z29103 +
0.242*658*Z20102 + 0.128*1,402*Z41202 -
4.9*W12 >= 0;
0.155*3,890*Z11203 + 0.138*2,343*Z21104 +
0.206*502*Z24104 + 0.41*900*Z25103 +
0.107*1,896*Z26103 + 0.265*685*Z27103 +
0.113*1,428*Z28103 + 0.089*1,613*Z29104 +
0.242*658*Z20103 + 0.128*1,402*Z41203 -
5.5*W13 >= 0;
0.155*3,890*Z11204 + 0.138*2,343*Z21105 +
0.206*502*Z24105 + 0.41*900*Z25104 +
0.107*1,896*Z26104 + 0.265*685*Z27104 +
0.113*1,428*Z28104 + 0.089*1,613*Z29105 +
0.242*658*Z20104 + 0.128*1,402*Z41204 -
7.5*W14 >= 0;
0.155*3,890*Z11205 + 0.138*2,343*Z21106 +
0.206*502*Z24106 + 0.41*900*Z25105 +
0.107*1,896*Z26105 + 0.265*685*Z27105 +
0.113*1,428*Z28105 + 0.089*1,613*Z29106 +
0.242*658*Z20105 + 0.128*1,402*Z41205 -
6.4*W15 >= 0;
0.155*3,890*Z11206 + 0.138*2,343*Z21107 +
0.206*502*Z24107 + 0.41*900*Z25106 +
0.107*1,896*Z26106 + 0.265*685*Z27106 +
0.113*1,428*Z28106 + 0.089*1,613*Z29107 +
0.242*658*Z20106 + 0.128*1,402*Z41206 -
3.3*W16 >= 0;
0.155*3,890*Z11207 + 0.138*2,343*Z21108 +
0.206*502*Z24108 + 0.41*900*Z25107 +
0.107*1,896*Z26107 + 0.265*685*Z27107 +
0.113*1,428*Z28107 + 0.089*1,613*Z29108 +
0.242*658*Z20107 + 0.128*1,402*Z41207 -
5.5*W17 >= 0;
0.155*3,890*Z11211 + 0.138*2,343*Z21112 +
0.037*3,858*Z21201 + 0.037*3,837*Z23201 +
0.206*502*Z24112 + 0.41*900*Z25111 +
0.107*1,896*Z26111 + 0.037*3,156*Z26201 +
0.265*685*Z27111 + 0.113*1,428*Z28111 +
0.04*2,423*Z28201 + 0.089*1,613*Z29112 +
0.242*658*Z20111 + 0.096*645*Z31201 +
0.084*513*Z31301 + 0.128*1,402*Z41211 -
16.4*W31 >= 0;
0.155*3,890*Z11212 + 0.138*2,343*Z21113 +
0.037*3,858*Z21202 + 0.037*3,837*Z23202 +
0.206*502*Z24113 + 0.41*900*Z25112 +
0.107*1,896*Z26112 + 0.037*3,156*Z26202 +
0.265*685*Z27112 + 0.113*1,428*Z28112 +
0.04*2,423*Z28202 + 0.089*1,613*Z29113 +
0.242*658*Z20112 + 0.096*645*Z31202 +
0.084*513*Z31302 + 0.128*1,402*Z41212 -
59.1*W32 >= 0;
0.155*3,890*Z11213 + 0.138*2,343*Z21114 +
0.037*3,858*Z21203 + 0.037*3,837*Z23203 +
0.206*502*Z24114 + 0.41*900*Z25113 +
0.107*1,896*Z26113 + 0.037*3,156*Z26203 +
0.265*685*Z27113 + 0.113*1,428*Z28113 +
0.04*2,423*Z28203 + 0.089*1,613*Z29114 +
0.242*658*Z20113 + 0.096*645*Z31203 +
0.084*513*Z31303 + 0.128*1,402*Z41213 -
105.1*W33 >= 0;
0.155*3,890*Z11214 + 0.138*2,343*Z21115 +
0.037*3,858*Z21204 + 0.037*3,837*Z23204 +
0.206*502*Z24115 + 0.41*900*Z25114 +
0.107*1,896*Z26114 + 0.037*3,156*Z26204 +
0.265*685*Z27114 + 0.113*1,428*Z28114 +
0.04*2,423*Z28204 + 0.089*1,613*Z29115 +
0.242*658*Z20114 + 0.096*645*Z31204 +
0.084*513*Z31304 + 0.128*1,402*Z41214 -
175.2*W34 >= 0;
0.155*3,890*Z11215 + 0.138*2,343*Z21116 +
0.037*3,858*Z21205 + 0.037*3,837*Z23205 +
0.206*502*Z24116 + 0.41*900*Z25115 +
0.107*1,896*Z26115 + 0.037*3,156*Z26205 +
0.265*685*Z27115 + 0.113*1,428*Z28115 +
0.04*2,423*Z28205 + 0.089*1,613*Z29116 +
0.242*658*Z20115 + 0.096*645*Z31205 +
0.084*513*Z31305 + 0.128*1,402*Z41215 -
105.1*W35 >= 0;
0.155*3,890*Z11216 + 0.138*2,343*Z21117 +
0.037*3,858*Z21206 + 0.037*3,837*Z23206 +
0.206*502*Z24117 + 0.41*900*Z25116 +
0.107*1,896*Z26116 + 0.037*3,156*Z26206 +
0.265*685*Z27116 + 0.113*1,428*Z28116 +
0.04*2,423*Z28206 + 0.089*1,613*Z29117 +
0.242*658*Z20116 + 0.096*645*Z31206 +
0.084*513*Z31306 + 0.128*1,402*Z41216 -
175.2*W36 >= 0;
0.155*3,890*Z11217 + 0.138*2,343*Z21118 +
0.037*3,858*Z21207 + 0.037*3,837*Z23207 +
0.206*502*Z24118 + 0.41*900*Z25117 +
0.107*1,896*Z26117 + 0.037*3,156*Z26207 +
0.265*685*Z27117 + 0.113*1,428*Z28117 +
0.04*2,423*Z28207 + 0.089*1,613*Z29118 +
0.242*658*Z20117 + 0.096*645*Z31207 +
0.084*513*Z31307 + 0.128*1,402*Z41217 -
189.8*W37 >= 0;
0.155*3,890*Z11218 + 0.138*2,343*Z21119 +
0.037*3,858*Z21208 + 0.037*3,837*Z23208 +
0.206*502*Z24119 + 0.41*900*Z25118 +
0.107*1,896*Z26118 + 0.037*3,156*Z26208 +
0.265*685*Z27118 + 0.113*1,428*Z28118 +
0.04*2,423*Z28208 + 0.089*1,613*Z29119 +
0.242*658*Z20118 + 0.096*645*Z31208 +
0.084*513*Z31308 + 0.128*1,402*Z41218 -
312.1*W38 >= 0;
0.155*3,890*Z11219 + 0.138*2,343*Z21120 +
0.037*3,858*Z21209 + 0.037*3,837*Z23209 +
0.206*502*Z24120 + 0.41*900*Z25119 +
0.107*1,896*Z26119 + 0.037*3,156*Z26209 +
0.265*685*Z27119 + 0.113*1,428*Z28119 +
0.04*2,423*Z28209 + 0.089*1,613*Z29120 +
0.242*658*Z20119 + 0.096*645*Z31209 +
0.084*513*Z31309 + 0.128*1,402*Z41219 -
175.2*W39 >= 0;
0.138*2,343*Z21122 + 0.037*3,858*Z21211 +
0.037*177*Z21302 + 0.1*534*Z22202 +
0.037*3,837*Z23211 + 0.037*176*Z23302 +
0.206*502*Z24122 + 0.07*732*Z24202 +
0.41*900*Z25121 + 0.107*1,896*Z26121 +
0.037*3,156*Z26211 + 0.037*145*Z26302 +
0.265*685*Z27121 + 0.052*1,016*Z27202 +
0.113*1,428*Z28121 + 0.04*2,423*Z28211 +
0.04*111*Z28302 + 0.089*1,613*Z29122 +
0.242*658*Z20121 + 0.07*1,130*Z20202 +
0.096*645*Z31211 + 0.084*513*Z31311 +
0.15*1,282*Z31502 + 0.15*1,282*Z32402 +
0.128*1,402*Z41221 + 0.068*635*Z41302 +
0.15*1,282*Z41502 + 0.194*2,136*Z51102 +
0.074*1,500*Z61202 + 0.074*1,850*Z62202 +
0.161*1,500*Z63202 + 0.161*1,850*Z64202 -
25.2*W42 >= 0;
0.138*2,343*Z21123 + 0.037*3,858*Z21212 +
0.037*177*Z21303 + 0.1*534*Z22203 +
0.037*3,837*Z23212 + 0.037*176*Z23303 +
0.206*502*Z24123 + 0.07*732*Z24203 +
0.41*900*Z25122 + 0.107*1,896*Z26122 +
0.037*3,156*Z26212 + 0.037*145*Z26303 +
0.265*685*Z27122 + 0.052*1,016*Z27203 +
0.113*1,428*Z28122 + 0.04*2,423*Z28212 +
0.04*111*Z28303 + 0.089*1,613*Z29123 +
0.242*658*Z20122 + 0.07*1,130*Z20203 +
0.096*645*Z31212 + 0.084*513*Z31312 +
0.15*1,282*Z31503 + 0.15*1,282*Z32403 +
0.128*1,402*Z41222 + 0.068*635*Z41303 +
0.15*1,282*Z41503 + 0.194*2,136*Z51103 +
0.074*1,500*Z61203 + 0.074*1,850*Z62203 +
0.161*1,500*Z63203 + 0.161*1,850*Z64203 -
>= 0;
0.138*2,343*Z21124 + 0.037*3,858*Z21213 +
0.037*177*Z21304 + 0.1*534*Z22204 +
0.037*3,837*Z23213 + 0.037*176*Z23304 +
0.206*502*Z24124 + 0.07*732*Z24204 +
0.41*900*Z25123 + 0.107*1,896*Z26123 +
0.037*3,156*Z26213 + 0.037*145*Z26304 +
0.265*685*Z27123 + 0.052*1,016*Z27204 +
0.113*1,428*Z28123 + 0.04*2,423*Z28213 +
0.04*111*Z28304 + 0.089*1,613*Z29124 +
0.242*658*Z20123 + 0.07*1,130*Z20204 +
0.096*645*Z31213 + 0.084*513*Z31313 +
0.15*1,282*Z31504 + 0.15*1,282*Z32404 +
0.128*1,402*Z41223 + 0.068*635*Z41304 +
0.15*1,282*Z41504 + 0.194*2,136*Z51104 +
0.074*1,500*Z61204 + 0.074*1,850*Z62204 +
0.161*1,500*Z63204 + 0.161*1,850*Z64204 -
25.2*W44 >= 0;
0.138*2,343*Z21125 + 0.037*3,858*Z21214 +
0.037*177*Z21305 + 0.1*534*Z22205 +
0.037*3,837*Z23214 + 0.037*176*Z23305 +
0.206*502*Z24125 + 0.07*732*Z24205 +
0.41*900*Z25124 + 0.107*1,896*Z26124 +
0.037*3,156*Z26214 + 0.037*145*Z26305 +
0.265*685*Z27124 + 0.052*1,016*Z27205 +
0.113*1,428*Z28124 + 0.04*2,423*Z28214 +
0.04*111*Z28305 + 0.089*1,613*Z29125 +
0.242*658*Z20124 + 0.07*1,130*Z20205 +
0.096*645*Z31214 + 0.084*513*Z31314 +
0.15*1,282*Z31505 + 0.15*1,282*Z32405 +
0.128*1,402*Z41224 + 0.068*635*Z41305 +
0.15*1,282*Z41505 + 0.194*2,136*Z51105 +
0.074*1,500*Z61205 + 0.074*1,850*Z62205 +
0.161*1,500*Z63205 + 0.161*1,850*Z64205 -
42.0*W45 >= 0;
0.138*2,343*Z21126 + 0.037*3,858*Z21215 +
0.037*177*Z21306 + 0.1*534*Z22206 +
0.037*3,837*Z23215 + 0.037*176*Z23306 +
0.206*502*Z24126 + 0.07*732*Z24206 +
0.41*900*Z25125 + 0.107*1,896*Z26125 +
0.037*3,156*Z26215 + 0.037*145*Z26306 +
0.265*685*Z27125 + 0.052*1,016*Z27206 +
0.113*1,428*Z28125 + 0.04*2,423*Z28215 +
0.04*111*Z28306 + 0.089*1,613*Z29126 +
0.242*658*Z20125 + 0.07*1,130*Z20206 +
0.096*645*Z31215 + 0.084*513*Z31315 +
0.15*1,282*Z31506 + 0.15*1,282*Z32406 +
0.128*1,402*Z41225 + 0.068*635*Z41306 +
0.15*1,282*Z41506 + 0.194*2,136*Z51106 +
0.074*1,500*Z61206 + 0.074*1,850*Z62206 +
0.161*1,500*Z63206 + 0.161*1,850*Z64206 -
17.5*W46 >= 0;
0.138*2,343*Z21127 + 0.037*3,858*Z21216 +
0.037*177*Z21307 + 0.1*534*Z22207 +
0.037*3,837*Z23216 + 0.037*176*Z23307 +
0.206*502*Z24127 + 0.07*732*Z24207 +
0.41*900*Z25126 + 0.107*1,896*Z26126 +
0.037*3,156*Z26216 + 0.037*145*Z26307 +
0.265*685*Z27126 + 0.052*1,016*Z27207 +
0.113*1,428*Z28126 + 0.04*2,423*Z28216 +
0.04*111*Z28307 + 0.089*1,613*Z29127 +
0.242*658*Z20126 + 0.07*1,130*Z20207 +
0.096*645*Z31216 + 0.084*513*Z31316 +
0.15*1,282*Z31507 + 0.15*1,282*Z32407 +
0.128*1,402*Z41226 + 0.068*635*Z41307 +
0.15*1,282*Z41507 + 0.194*2,136*Z51107 +
0.074*1,500*Z61207 + 0.074*1,850*Z62207 +
0.161*1,500*Z63207 + 0.161*1,850*Z64207 -
>= 0;
0.138*2,343*Z21128 + 0.037*3,858*Z21217 +
0.037*177*Z21308 + 0.1*534*Z22208 +
0.037*3,837*Z23217 + 0.037*176*Z23308 +
0.206*502*Z24128 + 0.07*732*Z24208 +
0.41*900*Z25127 + 0.107*1,896*Z26127 +
0.037*3,156*Z26217 + 0.037*145*Z26308 +
0.265*685*Z27127 + 0.052*1,016*Z27208 +

0.113*1,428*Z28127 + 0.04*2,423*Z28217 +
0.04*111*Z28308 + 0.089*1,613*Z29128 +
0.242*658*Z20127 + 0.07*1,130*Z20208 +
0.096*645*Z31217 + 0.084*513*Z31317 +
0.15*1,282*Z31508 + 0.15*1,282*Z32408 +
0.128*1,402*Z41227 + 0.068*635*Z41308 +
0.15*1,282*Z41508 + 0.194*2,136*Z51108 +
0.074*1,500*Z61208 + 0.074*1,850*Z62208 +
0.161*1,500*Z63208 + 0.161*1,850*Z64208 -
25.2*W48 >= 0;
0.138*2,343*Z21129 + 0.037*3,858*Z21218 +
0.037*177*Z21309 + 0.1*534*Z22209 +
0.037*3,837*Z23218 + 0.037*176*Z23309 +
0.206*502*Z24129 + 0.07*732*Z24209 +
0.41*900*Z25128 + 0.107*1,896*Z26128 +
0.037*3,156*Z26218 + 0.037*145*Z26309 +
0.265*685*Z27128 + 0.052*1,016*Z27209 +
0.113*1,428*Z28128 + 0.04*2,423*Z28218 +
0.04*111*Z28309 + 0.089*1,613*Z29129 +
0.242*658*Z20128 + 0.07*1,130*Z20209 +
0.096*645*Z31218 + 0.084*513*Z31318 +
0.15*1,282*Z31509 + 0.15*1,282*Z32409 +
0.128*1,402*Z41228 + 0.068*635*Z41309 +
0.15*1,282*Z41509 + 0.194*2,136*Z51109 +
0.074*1,500*Z61209 + 0.074*1,850*Z62209 +
0.161*1,500*Z63209 + 0.161*1,850*Z64209 -
42.0*W49 >= 0;
0.138*2,343*Z21130 + 0.037*3,858*Z21219 +
0.037*177*Z21310 + 0.1*534*Z22210 +
0.037*3,837*Z23219 + 0.037*176*Z23310 +
0.206*502*Z24130 + 0.07*732*Z24210 +
0.41*900*Z25129 + 0.107*1,896*Z26129 +
0.037*3,156*Z26219 + 0.037*145*Z26310 +
0.265*685*Z27129 + 0.052*1,016*Z27210 +
0.113*1,428*Z28129 + 0.04*2,423*Z28219 +
0.04*111*Z28310 + 0.089*1,613*Z29130 +
0.242*658*Z20129 + 0.07*1,130*Z20210 +
0.096*645*Z31219 + 0.084*513*Z31319 +
0.15*1,282*Z31510 + 0.15*1,282*Z32410 +
0.128*1,402*Z41229 + 0.068*635*Z41310 +
0.15*1,282*Z41510 + 0.194*2,136*Z51110 +
0.074*1,500*Z61210 + 0.074*1,850*Z62210 +
0.161*1,500*Z63210 + 0.161*1,850*Z64210 -
39.4*W40 >= 0;
0.138*2,343*Z21131 + 0.037*3,858*Z21220 +
0.037*177*Z21311 + 0.1*534*Z22211 +
0.037*3,837*Z23220 + 0.037*176*Z23311 +
0.206*502*Z24131 + 0.07*732*Z24211 +
0.41*900*Z25130 + 0.107*1,896*Z26130 +
0.037*3,156*Z26220 + 0.037*145*Z26311 +
0.265*685*Z27130 + 0.052*1,016*Z27211 +
0.113*1,428*Z28130 + 0.04*2,423*Z28220 +
0.04*111*Z28311 + 0.089*1,613*Z29131 +
0.242*658*Z20130 + 0.07*1,130*Z20211 +
0.096*645*Z31220 + 0.084*513*Z31320 +
0.15*1,282*Z31511 + 0.15*1,282*Z32411 +
0.128*1,402*Z41230 + 0.068*635*Z41311 +
0.15*1,282*Z41511 + 0.194*2,136*Z51111 +
0.074*1,500*Z61211 + 0.074*1,850*Z62211 +
0.161*1,500*Z63211 + 0.161*1,850*Z64211 -
50.1*W411 >= 0;
0.138*2,343*Z21132 + 0.037*3,858*Z21221 +
0.037*177*Z21312 + 0.1*534*Z22212 +
0.037*3,837*Z23221 + 0.037*176*Z23312 +
0.206*502*Z24132 + 0.07*732*Z24212 +
0.41*900*Z25131 + 0.107*1,896*Z26131 +
0.037*3,156*Z26221 + 0.037*145*Z26312 +
0.265*685*Z27131 + 0.052*1,016*Z27212 +
0.113*1,428*Z28131 + 0.04*2,423*Z28221 +
0.04*111*Z28312 + 0.089*1,613*Z29132 +
0.242*658*Z20131 + 0.07*1,130*Z20212 +
0.096*645*Z31221 + 0.084*513*Z31321 +
0.15*1,282*Z31512 + 0.15*1,282*Z32412 +
0.128*1,402*Z41231 + 0.068*635*Z41312 +
0.15*1,282*Z41512 + 0.194*2,136*Z51112 -
56.6*W412 >= 0;
3,858*2.05*Z21201 + 3,837*2.05*Z23201 +
3,156*2.05*Z26201 + 2,423*2.05*Z28201 -
0.01*1152*W31 <= 0;
3,858*2.05*Z21202 + 3,837*2.05*Z23202 +
3,156*2.05*Z26202 + 2,423*2.05*Z28202 -
0.01*4147*W32 <= 0;
3,858*2.05*Z21203 + 3,837*2.05*Z23203 +
3,156*2.05*Z26203 + 2,423*2.05*Z28203 -
0.01*7898*W33 <= 0;
3,858*2.05*Z21204 + 3,837*2.05*Z23204 +
3,156*2.05*Z26204 + 2,423*2.05*Z28204 -
0.01*13983*W34 <= 0;
3,858*2.05*Z21205 + 3,837*2.05*Z23205 +
3,156*2.05*Z26205 + 2,423*2.05*Z28205 -
0.01*7898*W35 <= 0;
3,858*2.05*Z21206 + 3,837*2.05*Z23206 +
3,156*2.05*Z26206 + 2,423*2.05*Z28206 -
0.01*13983*W36 <= 0;
3,858*2.68*Z21207 + 3,837*2.68*Z23207 +
3,156*2.68*Z26207 + 2,423*2.68*Z28207 -
0.04*18644*W37 <= 0;
3,858*2.68*Z21208 + 3,837*2.68*Z23208 +
3,156*2.68*Z26208 + 2,423*2.68*Z28208 -
0.04*23882*W38 <= 0;
3,858*2.68*Z21209 + 3,837*2.68*Z23209 +
3,156*2.68*Z26209 + 2,423*2.68*Z28209 -
0.04*13983*W39 <= 0;
3,858*5.02*Z21210 + 177*5.02*Z21301 +
534*8.3*Z22201 + 3,837*5.02*Z23210 +
176*5.02*Z23301 + 3,156*5.02*Z26210 +
145*5.02*Z26301 + 2,423*5.19*Z28210 +
111*5.19*Z28301 + 1,130*7.62*Z20201 -
0.25*0*W41 <= 0;
3,858*5.02*Z21211 + 177*5.02*Z21302 +
534*8.3*Z22202 + 3,837*5.02*Z23211 +
176*5.02*Z23302 + 3,156*5.02*Z26211 +
145*5.02*Z26302 + 2,423*5.19*Z28211 +
111*5.19*Z28302 + 1,130*7.62*Z20202 -
0.25*2428*W42 <= 0;
3,858*5.02*Z21212 + 177*5.02*Z21303 +
534*8.3*Z22203 + 3,837*5.02*Z23212 +
176*5.02*Z23303 + 3,156*5.02*Z26212 +
145*5.02*Z26303 + 2,423*5.19*Z28212 +
111*5.19*Z28303 + 1,130*7.62*Z20203 -
0.25*0*W43 <= 0;
3,858*5.02*Z21213 + 177*5.02*Z21304 +
534*8.3*Z22204 + 3,837*5.02*Z23213 +
176*5.02*Z23304 + 3,156*5.02*Z26213 +
145*5.02*Z26304 + 2,423*5.19*Z28213 +
111*5.19*Z28304 + 1,130*7.62*Z20204 -
0.25*2428*W44 <= 0;
3,858*5.02*Z21214 + 177*5.02*Z21305 +
534*8.3*Z22205 + 3,837*5.02*Z23214 +
176*5.02*Z23305 + 3,156*5.02*Z26214 +
145*5.02*Z26305 + 2,423*5.19*Z28214 +
111*5.19*Z28305 + 1,130*7.62*Z20205 -
0.25*4307*W45 <= 0;
3,858*5.02*Z21215 + 177*5.02*Z21306 +
534*8.3*Z22206 + 3,837*5.02*Z23215 +
176*5.02*Z23306 + 3,156*5.02*Z26215 +
145*5.02*Z26306 + 2,423*5.19*Z28215 +
111*5.19*Z28306 + 1,130*7.62*Z20206 -
0.25*3283*W46 <= 0;
3,858*5.02*Z21216 + 177*5.02*Z21307 +
534*8.3*Z22207 + 3,837*5.02*Z23216 +
176*5.02*Z23307 + 3,156*5.02*Z26216 +
145*5.02*Z26307 + 2,423*5.19*Z28216 +
111*5.19*Z28307 + 1,130*7.62*Z20207 -
0.25*0*W47 <= 0;
3,858*5.02*Z21217 + 177*5.02*Z21308 +
534*8.3*Z22208 + 3,837*5.02*Z23217 +
176*5.02*Z23308 + 3,156*5.02*Z26217 +
145*5.02*Z26308 + 2,423*5.19*Z28217 +
111*5.19*Z28308 + 1,130*7.62*Z20208 -
0.25*2428*W48 <= 0;
3,858*5.02*Z21218 + 177*5.02*Z21309 +
534*8.3*Z22209 + 3,837*5.02*Z23218 +
176*5.02*Z23309 + 3,156*5.02*Z26218 +
145*5.02*Z26309 + 2,423*5.19*Z28218 +
111*5.19*Z28309 + 1,130*7.62*Z20209 -
0.25*4307*W49 <= 0;
3,858*5.02*Z21219 + 177*5.02*Z21310 +
534*8.3*Z22210 + 3,837*5.02*Z23219 +
176*5.02*Z23310 + 3,156*5.02*Z26219 +
145*5.02*Z26310 + 2,423*5.19*Z28219 +
111*5.19*Z28310 + 1,130*7.62*Z20210 -
0.25*3299*W40 <= 0;
3,858*5.02*Z21220 + 177*5.02*Z21311 +
534*8.3*Z22211 + 3,837*5.02*Z23220 +
176*5.02*Z23311 + 3,156*5.02*Z26220 +
145*5.02*Z26311 + 2,423*5.19*Z28220 +
111*5.19*Z28311 + 1,130*7.62*Z20211 -
0.25*5024*W411 <= 0;
3,858*5.02*Z21221 + 177*5.02*Z21312 +
534*8.3*Z22212 + 3,837*5.02*Z23221 +
176*5.02*Z23312 + 3,156*5.02*Z26221 +
145*5.02*Z26312 + 2,423*5.19*Z28221 +
111*5.19*Z28312 + 1,130*7.62*Z20212 -
0.25*5788*W412 <= 0;
2,343*12.56*Z21102 - 0.3*197.00*W11 <= 0;
2,343*12.56*Z21103 - 0.3*218*W12 <= 0;
2,343*12.56*Z21104 - 0.3*305*W13 <= 0;
2,343*13.64*Z21105 - 0.3*445*W14 <= 0;
2,343*13.64*Z21106 - 0.3*514*W15 <= 0;
2,343*13.64*Z21107 - 0.3*386*W16 <= 0;
2,343*13.64*Z21108 - 0.3*514*W17 <= 0;
2,343*12.56*Z21109 - 0.3*86*W21 <= 0;
2,343*12.56*Z21110 - 0.3*261*W22 <= 0;
2,343*12.56*Z21111 - 0.3*336*W23 <= 0;
2,343*14.57*Z21112 - 0.35*1152*W31 <= 0;
2,343*14.57*Z21113 - 0.35*4147*W32 <= 0;
2,343*14.57*Z21114 - 0.35*7898*W33 <= 0;
2,343*14.57*Z21115 - 0.35*13983*W34 <= 0;
2,343*14.57*Z21116 - 0.35*7898*W35 <= 0;
2,343*14.57*Z21117 - 0.35*13983*W36 <= 0;
2,343*14.69*Z21118 - 0.4*18644*W37 <= 0;
2,343*14.69*Z21119 - 0.4*23882*W38 <= 0;
2,343*14.69*Z21120 - 0.4*13983*W39 <= 0;
2,343*11.72*Z21121 - 0.3*0*W41 <= 0;
2,343*11.72*Z21122 - 0.3*2428*W42 <= 0;
2,343*11.72*Z21123 - 0.3*0*W43 <= 0;
2,343*11.72*Z21124 - 0.3*2428*W44 <= 0;
2,343*11.72*Z21125 - 0.3*4307*W45 <= 0;
2,343*11.72*Z21126 - 0.3*3283*W46 <= 0;
2,343*11.72*Z21127 - 0.3*0*W47 <= 0;
2,343*11.72*Z21128 - 0.3*2428*W48 <= 0;
2,343*11.72*Z21129 - 0.3*4307*W49 <= 0;
2,343*11.72*Z21130 - 0.3*3299*W40 <= 0;
2,343*11.72*Z21131 - 0.3*5024*W411 <= 0;
2,343*11.72*Z21132 - 0.3*5788*W412 <= 0;
502*10.13*Z24102 - 0.1*197.00*W11 <= 0;
502*10.13*Z24103 - 0.1*218*W12 <= 0;
502*10.13*Z24104 - 0.1*305*W13 <= 0;
502*11.18*Z24105 - 0.1*445*W14 <= 0;
502*11.18*Z24106 - 0.1*514*W15 <= 0;
502*11.18*Z24107 - 0.1*386*W16 <= 0;
502*11.18*Z24108 - 0.1*514*W17 <= 0;
502*10.13*Z24109 - 0.1*86*W21 <= 0;
502*10.13*Z24110 - 0.1*261*W22 <= 0;
502*10.13*Z24111 - 0.1*336*W23 <= 0;
502*13.31*Z24112 - 0.2*1152*W31 <= 0;
502*13.31*Z24113 - 0.2*4147*W32 <= 0;
502*13.31*Z24114 - 0.2*7898*W33 <= 0;
502*13.31*Z24115 - 0.2*13983*W34 <= 0;
502*13.31*Z24116 - 0.2*7898*W35 <= 0;
502*13.31*Z24117 - 0.2*13983*W36 <= 0;
502*13.61*Z24118 - 0.16*18644*W37 <= 0;
502*13.61*Z24119 - 0.16*23882*W38 <= 0;
502*13.61*Z24120 - 0.16*13983*W39 <= 0;
502*11.81*Z24121 - 0.26*0*W41 <= 0;
502*11.81*Z24122 - 0.26*2428*W42 <= 0;
502*11.81*Z24123 - 0.26*0*W43 <= 0;
502*11.81*Z24124 - 0.26*2428*W44 <= 0;
502*11.81*Z24125 - 0.26*4307*W45 <= 0;
502*11.81*Z24126 - 0.26*3283*W46 <= 0;
502*11.81*Z24127 - 0.26*0*W47 <= 0;
502*11.81*Z24128 - 0.26*2428*W48 <= 0;
502*11.81*Z24129 - 0.26*4307*W49 <= 0;
502*11.81*Z24130 - 0.26*3299*W40 <= 0;
502*11.81*Z24131 - 0.26*5024*W411 <= 0;
502*11.81*Z24132 - 0.26*5788*W412 <= 0;
900*10.14*Z25101 - 0.025*197.00*W11 <= 0;
900*10.14*Z25102 - 0.025*218*W12 <= 0;
900*10.14*Z25103 - 0.025*305*W13 <= 0;
900*11.13*Z25104 - 0.025*445*W14 <= 0;
900*11.13*Z25105 - 0.025*514*W15 <= 0;
900*11.13*Z25106 - 0.025*386*W16 <= 0;
900*11.13*Z25107 - 0.025*514*W17 <= 0;
900*10.14*Z25108 - 0.025*86*W21 <= 0;
900*10.14*Z25109 - 0.025*261*W22 <= 0;
900*10.14*Z25110 - 0.025*336*W23 <= 0;
900*14.69*Z25111 - 0.025*1152*W31 <= 0;
900*14.69*Z25112 - 0.025*4147*W32 <= 0;
900*14.69*Z25113 - 0.025*7898*W33 <= 0;
900*14.69*Z25114 - 0.025*13983*W34 <= 0;
900*14.69*Z25115 - 0.025*7898*W35 <= 0;
900*14.69*Z25116 - 0.025*13983*W36 <= 0;
900*15.55*Z25117 - 0.025*18644*W37 <= 0;
900*15.55*Z25118 - 0.025*23882*W38 <= 0;
900*15.55*Z25119 - 0.025*13983*W39 <= 0;
900*13.33*Z25120 - 0.2*0*W41 <= 0;

900*13.33*Z25121 - 0.2*2428*W42 <= 0;
900*13.33*Z25122 - 0.2*0*W43 <= 0;
900*13.33*Z25123 - 0.2*2428*W44 <= 0;
900*13.33*Z25124 - 0.2*4307*W45 <= 0;
900*13.33*Z25125 - 0.2*3283*W46 <= 0;
900*13.33*Z25126 - 0.2*0*W47 <= 0;
900*13.33*Z25127 - 0.2*2428*W48 <= 0;
900*13.33*Z25128 - 0.2*4307*W49 <= 0;
900*13.33*Z25129 - 0.2*3299*W40 <= 0;
900*13.33*Z25130 - 0.2*5024*W411 <= 0;
900*13.33*Z25131 - 0.2*5788*W412 <= 0;
658*9.63*Z20101 - 0.05*197.00*W11 <= 0;
658*9.63*Z20102 - 0.05*218*W12 <= 0;
658*9.63*Z20103 - 0.05*305*W13 <= 0;
658*10.47*Z20104 - 0*445*W14 <= 0;
658*10.47*Z20105 - 0*514*W15 <= 0;
658*10.47*Z20106 - 0*386*W16 <= 0;
658*10.47*Z20107 - 0*514*W17 <= 0;
658*9.63*Z20108 - 0.05*86*W21 <= 0;
658*9.63*Z20109 - 0.05*261*W22 <= 0;
658*9.63*Z20110 - 0.05*336*W23 <= 0;
658*13.06*Z20111 - 0.1*1152*W31 <= 0;
658*13.06*Z20112 - 0.1*4147*W32 <= 0;
658*13.06*Z20113 - 0.1*7898*W33 <= 0;
658*13.06*Z20114 - 0.1*13983*W34 <= 0;
658*13.06*Z20115 - 0.1*7898*W35 <= 0;
658*13.06*Z20116 - 0.1*13983*W36 <= 0;
658*13.25*Z20117 - 0.07*18644*W37 <= 0;
658*13.25*Z20118 - 0.07*23882*W38 <= 0;
658*13.25*Z20119 - 0.07*13983*W39 <= 0;
658*11.76*Z20120 - 0.22*0*W41 <= 0;
658*11.76*Z20121 - 0.22*2428*W42 <= 0;
658*11.76*Z20122 - 0.22*0*W43 <= 0;
658*11.76*Z20123 - 0.22*2428*W44 <= 0;
658*11.76*Z20124 - 0.22*4307*W45 <= 0;
658*11.76*Z20125 - 0.22*3283*W46 <= 0;
658*11.76*Z20126 - 0.22*0*W47 <= 0;
658*11.76*Z20127 - 0.22*2428*W48 <= 0;
658*11.76*Z20128 - 0.22*4307*W49 <= 0;
658*11.76*Z20129 - 0.22*3299*W40 <= 0;
658*11.76*Z20130 - 0.22*5024*W411 <= 0;
658*11.76*Z20131 - 0.22*5788*W412 <= 0;
645*6.34*Z31201 - 0.12*1152*W31 <= 0;
645*6.34*Z31202 - 0.12*4147*W32 <= 0;
645*6.34*Z31203 - 0.12*7898*W33 <= 0;
645*6.34*Z31204 - 0.12*13983*W34 <= 0;
645*6.34*Z31205 - 0.12*7898*W35 <= 0;
645*6.34*Z31206 - 0.12*13983*W36 <= 0;
645*6.5*Z31207 - 0.06*18644*W37 <= 0;
645*6.5*Z31208 - 0.06*23882*W38 <= 0;
645*6.5*Z31209 - 0.06*13983*W39 <= 0;
513*2.89*Z31301 - 0.02*1152*W31 <= 0;
513*2.89*Z31302 - 0.02*4147*W32 <= 0;
513*2.89*Z31303 - 0.02*7898*W33 <= 0;
513*2.89*Z31304 - 0.02*13983*W34 <= 0;
513*2.89*Z31305 - 0.02*7898*W35 <= 0;
513*2.89*Z31306 - 0.02*13983*W36 <= 0;
513*3*Z31307 - 0.05*18644*W37 <= 0;
513*3*Z31308 - 0.05*23882*W38 <= 0;
513*3*Z31309 - 0.05*13983*W39 <= 0;
1,402*4.23*Z41217 - 0.02*18644*W37 <= 0;
1,402*4.23*Z41218 - 0.02*23882*W38 <= 0;
1,402*4.23*Z41219 - 0.02*13983*W39 <= 0;

Grazing ratios

(1500*Z61201 + 1500*Z61202 + 1500*Z61203
+ 1500*Z61204 + 1500*Z61205 + 1500*Z61206
+ 1500*Z61207 + 1500*Z61208 + 1500*Z61209
+ 1500*Z61210 + 1500*Z61211 + 1850*Z62201
+ 1850*Z62202 + 1850*Z62203 + 1850*Z62204
+ 1850*Z62205 + 1850*Z62206 + 1850*Z62207
+ 1850*Z62208 + 1850*Z62209 + 1850*Z62210
+ 1850*Z62211 + 1500*Z63201 + 1500*Z63202
+ 1500*Z63203 + 1500*Z63204 + 1500*Z63205
+ 1500*Z63206 + 1500*Z63207 + 1500*Z63208
+ 1500*Z63209 + 1500*Z63210 + 1500*Z63211
+ 1850*Z64201 + 1850*Z64202 + 1850*Z64203
+ 1850*Z64204 + 1850*Z64205 + 1850*Z64206
+ 1850*Z64207 + 1850*Z64208 + 1850*Z64209
+ 1850*Z64210 + 1850*Z64211 +
158*Z21301 + 158*Z21302 + 158*Z21303 +
158*Z21304 + 158*Z21305 + 158*Z21306 +
158*Z21307 + 158*Z21308 + 158*Z21309 +
158*Z21310 + 158*Z21311 + 158*Z21312 +
157*Z23301 + 157*Z23302 + 157*Z23303 +
157*Z23304 + 157*Z23305 + 157*Z23306 +
157*Z23307 + 157*Z23308 + 157*Z23309 +
157*Z23310 + 157*Z23311 + 157*Z23312 +
137*Z26301 + 137*Z26302 + 137*Z26303 +
137*Z26304 + 137*Z26305 + 137*Z26306 +
137*Z26307 + 137*Z26308 + 137*Z26309 +
137*Z26310 + 137*Z26311 + 137*Z26312 +
137*Z28301 + 137*Z28302 + 137*Z28303 +
137*Z28304 + 137*Z28305 + 137*Z28306 +
137*Z28307 + 137*Z28308 + 137*Z28309 +
137*Z28310 + 137*Z28311 + 137*Z28312
+ 814*Z31310 + 814*Z31311 + 814*Z31312 +
814*Z31313 + 814*Z31314 + 814*Z31315 +
814*Z31316 + 814*Z31317 + 814*Z31318 +
814*Z31319 + 814*Z31320 + 814*Z31321 +
1000*Z31501 + 1000*Z31502 + 1000*Z31503 +
1000*Z31504 + 1000*Z31505 + 1000*Z31506 +
1000*Z31507 + 1000*Z31508 + 1000*Z31509 +
1000*Z31510 + 1000*Z31511 + 1000*Z31512
+ 1000*Z32401 + 1000*Z32402 +
1000*Z32403 + 1000*Z32404 + 1000*Z32405 +
1000*Z32406 + 1000*Z32407 + 1000*Z32408 +
1000*Z32409 + 1000*Z32410 + 1000*Z32411 +
1000*Z32412
+ 1000*Z41501 + 1000*Z41502 +
1000*Z41503 + 1000*Z41504 + 1000*Z41505 +
1000*Z41506 + 1000*Z41507 + 1000*Z41508 +
1000*Z41509 + 1000*Z41510 + 1000*Z41511 +
1000*Z41512
+ 2136*Z51101 + 2136*Z51102 +
2136*Z51103 + 2136*Z51104 + 2136*Z51105 +
2136*Z51106 + 2136*Z51107 + 2136*Z51108 +
2136*Z51109 + 2136*Z51110 + 2136*Z51111 +
2136*Z51112)/(
1500*Z61201 + 1500*Z61202 + 1500*Z61203 +
1500*Z61204 + 1500*Z61205 + 1500*Z61206 +
1500*Z61207 + 1500*Z61208 + 1500*Z61209 +
1500*Z61210 + 1500*Z61211 + 1850*Z62201 +
1850*Z62202 + 1850*Z62203 + 1850*Z62204 +
1850*Z62205 + 1850*Z62206 + 1850*Z62207 +
1850*Z62208 + 1850*Z62209 + 1850*Z62210 +
1850*Z62211 + 1500*Z63201 + 1500*Z63202 +
1500*Z63203 + 1500*Z63204 + 1500*Z63205 +
1500*Z63206 + 1500*Z63207 + 1500*Z63208 +
1500*Z63209 + 1500*Z63210 + 1500*Z63211 +
1850*Z64201 + 1850*Z64202 + 1850*Z64203 +
1850*Z64204 + 1850*Z64205 + 1850*Z64206 +
1850*Z64207 + 1850*Z64208 + 1850*Z64209 +
1850*Z64210 + 1850*Z64211 +
158*Z21301 + 158*Z21302 + 158*Z21303 +
158*Z21304 + 158*Z21305 + 158*Z21306 +
158*Z21307 + 158*Z21308 + 158*Z21309 +
158*Z21310 + 158*Z21311 + 158*Z21312 +
157*Z23301 + 157*Z23302 + 157*Z23303 +
157*Z23304 + 157*Z23305 + 157*Z23306 +
157*Z23307 + 157*Z23308 + 157*Z23309 +
157*Z23310 + 157*Z23311 + 157*Z23312 +
137*Z26301 + 137*Z26302 + 137*Z26303 +
137*Z26304 + 137*Z26305 + 137*Z26306 +
137*Z26307 + 137*Z26308 + 137*Z26309 +
137*Z26310 + 137*Z26311 + 137*Z26312 +
137*Z28301 + 137*Z28302 + 137*Z28303 +
137*Z28304 + 137*Z28305 + 137*Z28306 +
137*Z28307 + 137*Z28308 + 137*Z28309 +
137*Z28310 + 137*Z28311 + 137*Z28312
+ 814*Z31310 + 814*Z31311 + 814*Z31312 +
814*Z31313 + 814*Z31314 + 814*Z31315 +
814*Z31316 + 814*Z31317 + 814*Z31318 +
814*Z31319 + 814*Z31320 + 814*Z31321 +
1000*Z31501 + 1000*Z31502 + 1000*Z31503 +
1000*Z31504 + 1000*Z31505 + 1000*Z31506 +
1000*Z31507 + 1000*Z31508 + 1000*Z31509 +
1000*Z31510 + 1000*Z31511 + 1000*Z31512
+ 1000*Z32401 + 1000*Z32402 +
1000*Z32403 + 1000*Z32404 + 1000*Z32405 +
1000*Z32406 + 1000*Z32407 + 1000*Z32408 +
1000*Z32409 + 1000*Z32410 + 1000*Z32411 +
1000*Z32412
+ 1000*Z41501 + 1000*Z41502 +
1000*Z41503 + 1000*Z41504 + 1000*Z41505 +
1000*Z41506 + 1000*Z41507 + 1000*Z41508 +
1000*Z41509 + 1000*Z41510 + 1000*Z41511 +
1000*Z41512
+ 2136*Z51101 + 2136*Z51102 +
2136*Z51103 + 2136*Z51104 + 2136*Z51105 +
2136*Z51106 + 2136*Z51107 + 2136*Z51108 +
2136*Z51109 + 2136*Z51110 + 2136*Z51111 +
2136*Z51112
+ 2343*Z21121 + 2343*Z21122 +
2343*Z21123 + 2343*Z21124 + 2343*Z21125 +
2343*Z21126 + 2343*Z21127 + 2343*Z21128 +
2343*Z21129 + 2343*Z21130 + 2343*Z21131 +
2343*Z21132 + 3858*Z21220 + 3858*Z21221 +
3858*Z21222 + 3858*Z21223 + 3858*Z21224 +
3858*Z21225 + 3858*Z21226 + 3858*Z21227 +
3858*Z21228 + 3858*Z21229 + 3858*Z21230 +
3858*Z21231 + 534*Z22201 + 534*Z22202 +
534*Z22203 + 534*Z22204 + 534*Z22205 +
534*Z22206 + 534*Z22207 + 534*Z22208 +
534*Z22209 + 534*Z22210 + 534*Z22211 +
534*Z22212 + 3837*Z23220 + 3837*Z23221 +
3837*Z23222 + 3837*Z23223 + 3837*Z23224 +
3837*Z23225 + 3837*Z23226 + 3837*Z23227 +
3837*Z23228 + 3837*Z23229 + 3837*Z23230 +
3837*Z23231 + 502*Z24121 + 502*Z24122 +
502*Z24123 + 502*Z24124 + 502*Z24125 +
502*Z24126 + 502*Z24127 + 502*Z24128 +
502*Z24129 + 502*Z24130 + 502*Z24131 +
502*Z24132
+ 732*Z24201 + 732*Z24202 + 732*Z24203 +
732*Z24204 + 732*Z24205 + 732*Z24206 +
732*Z24207 + 732*Z24208 + 732*Z24209 +
732*Z24210 + 732*Z24211 + 732*Z24212 +
900*Z25120 + 900*Z25121 + 900*Z25122 +
900*Z25123 + 900*Z25124 + 900*Z25125 +
900*Z25126 + 900*Z25127 + 900*Z25128 +
900*Z25129 + 900*Z25130 + 900*Z25131 +
1896*Z26120 + 1896*Z26121 + 1896*Z26122 +
1896*Z26123 + 1896*Z26124 + 1896*Z26125 +
1896*Z26126 + 1896*Z26127 + 1896*Z26128 +
1896*Z26129 + 1896*Z26130 + 1896*Z26131 +
3156*Z26220 + 3156*Z26221 + 3156*Z26222 +
3156*Z26223 + 3156*Z26224 + 3156*Z26225 +
3156*Z26226 + 3156*Z26227 + 3156*Z26228 +
3156*Z26229 + 3156*Z26230 + 3156*Z26231 +
685*Z27120 + 685*Z27121 + 685*Z27122 +
685*Z27123 + 685*Z27124 + 685*Z27125 +
685*Z27126 + 685*Z27127 + 685*Z27128 +
685*Z27129 + 685*Z27130 + 685*Z27131
+ 1016*Z27201 + 1016*Z27202 +
1016*Z27203 + 1016*Z27204 + 1016*Z27205 +
1016*Z27206 + 1016*Z27207 + 1016*Z27208 +
1016*Z27209 + 1016*Z27210 + 1016*Z27211 +
1016*Z27212 + 1428*Z28120 + 1428*Z28121 +
1428*Z28122 + 1428*Z28123 + 1428*Z28124 +
1428*Z28125 + 1428*Z28126 + 1428*Z28127 +
1428*Z28128 + 1428*Z28129 + 1428*Z28130 +
1428*Z28131 + 2423*Z28220 + 2423*Z28221 +
2423*Z28222 + 2423*Z28223 + 2423*Z28224 +
2423*Z28225 + 2423*Z28226 + 2423*Z28227 +
2423*Z28228 + 2423*Z28229 + 2423*Z28230 +
2423*Z28231 + 1613*Z29121 + 1613*Z29122 +
1613*Z29123 + 1613*Z29124 + 1613*Z29125 +
1613*Z29126 + 1613*Z29127 + 1613*Z29128 +
1613*Z29129 + 1613*Z29130 + 1613*Z29131 +
1613*Z29132 + 658*Z20120 + 658*Z20121 +
658*Z20122 + 658*Z20123 + 658*Z20124 +
658*Z20125 + 658*Z20126 + 658*Z20127 +
658*Z20128 + 658*Z20129 + 658*Z20130 +
658*Z20131
+ 1130*Z20201 + 1130*Z20202 +
1130*Z20203 + 1130*Z20204 + 1130*Z20205 +
1130*Z20206 + 1130*Z20207 + 1130*Z20208 +
1130*Z20209 + 1130*Z20210 + 1130*Z20211 +
1130*Z20212 + 645*Z31210 + 645*Z31211 +
645*Z31212 + 645*Z31213 + 645*Z31214 +
645*Z31215 + 645*Z31216 + 645*Z31217 +
645*Z31218 + 645*Z31219 + 645*Z31220 +
645*Z31221 + 1402*Z41220 + 1402*Z41221 +
1402*Z41222 + 1402*Z41223 + 1402*Z41224 +
1402*Z41225 + 1402*Z41226 + 1402*Z41227 +
1402*Z41228 + 1402*Z41229 + 1402*Z41230 +
1402*Z41231 + 635*Z41301 + 635*Z41302 +
635*Z41303 + 635*Z41304 + 635*Z41305 +
635*Z41306 + 635*Z41307 + 635*Z41308 +
635*Z41309 + 635*Z41310 + 635*Z41311 +
635*Z41312) = U;
(158*Z21301 + 158*Z21302 + 158*Z21303 +
158*Z21304 + 158*Z21305 + 158*Z21306 +

158*Z21307 + 158*Z21308 + 158*Z21309 +
158*Z21310 + 158*Z21311 + 158*Z21312 +
157*Z23301 + 157*Z23302 + 157*Z23303 +
157*Z23304 + 157*Z23305 + 157*Z23306 +
157*Z23307 + 157*Z23308 + 157*Z23309 +
157*Z23310 + 157*Z23311 + 157*Z23312 +
137*Z26301 + 137*Z26302 + 137*Z26303 +
137*Z26304 + 137*Z26305 + 137*Z26306 +
137*Z26307 + 137*Z26308 + 137*Z26309 +
137*Z26310 + 137*Z26311 + 137*Z26312 +
137*Z28301 + 137*Z28302 + 137*Z28303 +
137*Z28304 + 137*Z28305 + 137*Z28306 +
137*Z28307 + 137*Z28308 + 137*Z28309 +
137*Z28310 + 137*Z28311 + 137*Z28312)/(
1500*Z61201 + 1500*Z61202 + 1500*Z61203 +
1500*Z61204 + 1500*Z61205 + 1500*Z61206 +
1500*Z61207 + 1500*Z61208 + 1500*Z61209 +
1500*Z61210 + 1500*Z61211 + 1850*Z62201 +
1850*Z62202 + 1850*Z62203 + 1850*Z62204 +
1850*Z62205 + 1850*Z62206 + 1850*Z62207 +
1850*Z62208 + 1850*Z62209 + 1850*Z62210 +
1850*Z62211 + 1500*Z63201 + 1500*Z63202 +
1500*Z63203 + 1500*Z63204 + 1500*Z63205 +
1500*Z63206 + 1500*Z63207 + 1500*Z63208 +
1500*Z63209 + 1500*Z63210 + 1500*Z63211 +
1850*Z64201 + 1850*Z64202 + 1850*Z64203 +
1850*Z64204 + 1850*Z64205 + 1850*Z64206 +
1850*Z64207 + 1850*Z64208 + 1850*Z64209 +
1850*Z64210 + 1850*Z64211 +
158*Z21301 + 158*Z21302 + 158*Z21303 +
158*Z21304 + 158*Z21305 + 158*Z21306 +
158*Z21307 + 158*Z21308 + 158*Z21309 +
158*Z21310 + 158*Z21311 + 158*Z21312 +
157*Z23301 + 157*Z23302 + 157*Z23303 +
157*Z23304 + 157*Z23305 + 157*Z23306 +
157*Z23307 + 157*Z23308 + 157*Z23309 +
157*Z23310 + 157*Z23311 + 157*Z23312 +
137*Z26301 + 137*Z26302 + 137*Z26303 +
137*Z26304 + 137*Z26305 + 137*Z26306 +
137*Z26307 + 137*Z26308 + 137*Z26309 +
137*Z26310 + 137*Z26311 + 137*Z26312 +
137*Z28301 + 137*Z28302 + 137*Z28303 +
137*Z28304 + 137*Z28305 + 137*Z28306 +
137*Z28307 + 137*Z28308 + 137*Z28309 +
137*Z28310 + 137*Z28311 + 137*Z28312
+ 814*Z31310 + 814*Z31311 + 814*Z31312 +
814*Z31313 + 814*Z31314 + 814*Z31315 +
814*Z31316 + 814*Z31317 + 814*Z31318 +
814*Z31319 + 814*Z31320 + 814*Z31321 +
1000*Z31501 + 1000*Z31502 + 1000*Z31503 +
1000*Z31504 + 1000*Z31505 + 1000*Z31506 +
1000*Z31507 + 1000*Z31508 + 1000*Z31509 +
1000*Z31510 + 1000*Z31511 + 1000*Z31512
+ 1000*Z32401 + 1000*Z32402 +
1000*Z32403 + 1000*Z32404 + 1000*Z32405 +
1000*Z32406 + 1000*Z32407 + 1000*Z32408 +
1000*Z32409 + 1000*Z32410 + 1000*Z32411 +
1000*Z32412
+ 1000*Z41501 + 1000*Z41502 +
1000*Z41503 + 1000*Z41504 + 1000*Z41505 +
1000*Z41506 + 1000*Z41507 + 1000*Z41508 +
1000*Z41509 + 1000*Z41510 + 1000*Z41511 +
1000*Z41512
+ 2136*Z51101 + 2136*Z51102 +
2136*Z51103 + 2136*Z51104 + 2136*Z51105 +
2136*Z51106 + 2136*Z51107 + 2136*Z51108 +
2136*Z51109 + 2136*Z51110 + 2136*Z51111 +
2136*Z51112
+ 2343*Z21121 + 2343*Z21122 +
2343*Z21123 + 2343*Z21124 + 2343*Z21125 +
2343*Z21126 + 2343*Z21127 + 2343*Z21128 +
2343*Z21129 + 2343*Z21130 + 2343*Z21131 +
2343*Z21132 + 3858*Z21220 + 3858*Z21221 +
3858*Z21222 + 3858*Z21223 + 3858*Z21224 +
3858*Z21225 + 3858*Z21226 + 3858*Z21227 +
3858*Z21228 + 3858*Z21229 + 3858*Z21230 +
3858*Z21231 + 534*Z22201 + 534*Z22202 +
534*Z22203 + 534*Z22204 + 534*Z22205 +
534*Z22206 + 534*Z22207 + 534*Z22208 +
534*Z22209 + 534*Z22210 + 534*Z22211 +
534*Z22212 + 3837*Z23220 + 3837*Z23221 +
3837*Z23222 + 3837*Z23223 + 3837*Z23224 +
3837*Z23225 + 3837*Z23226 + 3837*Z23227 +
3837*Z23228 + 3837*Z23229 + 3837*Z23230 +
3837*Z23231 + 502*Z24121 + 502*Z24122 +
502*Z24123 + 502*Z24124 + 502*Z24125 +
502*Z24126 + 502*Z24127 + 502*Z24128 +
502*Z24129 + 502*Z24130 + 502*Z24131 +
502*Z24132
+ 732*Z24201 + 732*Z24202 + 732*Z24203 +
732*Z24204 + 732*Z24205 + 732*Z24206 +
732*Z24207 + 732*Z24208 + 732*Z24209 +
732*Z24210 + 732*Z24211 + 732*Z24212 +
900*Z25120 + 900*Z25121 + 900*Z25122 +
900*Z25123 + 900*Z25124 + 900*Z25125 +
900*Z25126 + 900*Z25127 + 900*Z25128 +
900*Z25129 + 900*Z25130 + 900*Z25131 +
1896*Z26120 + 1896*Z26121 + 1896*Z26122 +
1896*Z26123 + 1896*Z26124 + 1896*Z26125 +
1896*Z26126 + 1896*Z26127 + 1896*Z26128 +
1896*Z26129 + 1896*Z26130 + 1896*Z26131 +
3156*Z26220 + 3156*Z26221 + 3156*Z26222 +
3156*Z26223 + 3156*Z26224 + 3156*Z26225 +
3156*Z26226 + 3156*Z26227 + 3156*Z26228 +
3156*Z26229 + 3156*Z26230 + 3156*Z26231 +
685*Z27120 + 685*Z27121 + 685*Z27122 +
685*Z27123 + 685*Z27124 + 685*Z27125 +
685*Z27126 + 685*Z27127 + 685*Z27128 +
685*Z27129 + 685*Z27130 + 685*Z27131
+ 1016*Z27201 + 1016*Z27202 +
1016*Z27203 + 1016*Z27204 + 1016*Z27205 +
1016*Z27206 + 1016*Z27207 + 1016*Z27208 +
1016*Z27209 + 1016*Z27210 + 1016*Z27211 +
1016*Z27212 + 1428*Z28120 + 1428*Z28121 +
1428*Z28122 + 1428*Z28123 + 1428*Z28124 +
1428*Z28125 + 1428*Z28126 + 1428*Z28127 +
1428*Z28128 + 1428*Z28129 + 1428*Z28130 +
1428*Z28131 + 2423*Z28220 + 2423*Z28221 +
2423*Z28222 + 2423*Z28223 + 2423*Z28224 +
2423*Z28225 + 2423*Z28226 + 2423*Z28227 +
2423*Z28228 + 2423*Z28229 + 2423*Z28230 +
2423*Z28231 + 1613*Z29121 + 1613*Z29122 +
1613*Z29123 + 1613*Z29124 + 1613*Z29125 +
1613*Z29126 + 1613*Z29127 + 1613*Z29128 +
1613*Z29129 + 1613*Z29130 + 1613*Z29131 +
1613*Z29132 + 658*Z20120 + 658*Z20121 +
658*Z20122 + 658*Z20123 + 658*Z20124 +
658*Z20125 + 658*Z20126 + 658*Z20127 +
658*Z20128 + 658*Z20129 + 658*Z20130 +
658*Z20131
+ 1130*Z20201 + 1130*Z20202 +
1130*Z20203 + 1130*Z20204 + 1130*Z20205 +
1130*Z20206 + 1130*Z20207 + 1130*Z20208 +
1130*Z20209 + 1130*Z20210 + 1130*Z20211 +
1130*Z20212 + 645*Z31210 + 645*Z31211 +
645*Z31212 + 645*Z31213 + 645*Z31214 +
645*Z31215 + 645*Z31216 + 645*Z31217 +
645*Z31218 + 645*Z31219 + 645*Z31220 +
645*Z31221 + 1402*Z41220 + 1402*Z41221 +
1402*Z41222 + 1402*Z41223 + 1402*Z41224 +
1402*Z41225 + 1402*Z41226 + 1402*Z41227 +
1402*Z41228 + 1402*Z41229 + 1402*Z41230 +
1402*Z41231 + 635*Z41301 + 635*Z41302 +
635*Z41303 + 635*Z41304 + 635*Z41305 +
635*Z41306 + 635*Z41307 + 635*Z41308 +
635*Z41309 + 635*Z41310 + 635*Z41311 +
635*Z41312) = V1;
(814*Z31310 + 814*Z31311 + 814*Z31312 +
814*Z31313 + 814*Z31314 + 814*Z31315 +
814*Z31316 + 814*Z31317 + 814*Z31318 +
814*Z31319 + 814*Z31320 + 814*Z31321 +
1000*Z31501 + 1000*Z31502 + 1000*Z31503 +
1000*Z31504 + 1000*Z31505 + 1000*Z31506 +
1000*Z31507 + 1000*Z31508 + 1000*Z31509 +
1000*Z31510 + 1000*Z31511 +
1000*Z31512)/(
1500*Z61201 + 1500*Z61202 + 1500*Z61203 +
1500*Z61204 + 1500*Z61205 + 1500*Z61206 +
1500*Z61207 + 1500*Z61208 + 1500*Z61209 +
1500*Z61210 + 1500*Z61211 + 1850*Z62201 +
1850*Z62202 + 1850*Z62203 + 1850*Z62204 +
1850*Z62205 + 1850*Z62206 + 1850*Z62207 +
1850*Z62208 + 1850*Z62209 + 1850*Z62210 +
1850*Z62211 + 1500*Z63201 + 1500*Z63202 +
1500*Z63203 + 1500*Z63204 + 1500*Z63205 +
1500*Z63206 + 1500*Z63207 + 1500*Z63208 +
1500*Z63209 + 1500*Z63210 + 1500*Z63211 +
1850*Z64201 + 1850*Z64202 + 1850*Z64203 +
1850*Z64204 + 1850*Z64205 + 1850*Z64206 +
1850*Z64207 + 1850*Z64208 + 1850*Z64209 +
1850*Z64210 + 1850*Z64211 +
158*Z21301 + 158*Z21302 + 158*Z21303 +
158*Z21304 + 158*Z21305 + 158*Z21306 +
158*Z21307 + 158*Z21308 + 158*Z21309 +
158*Z21310 + 158*Z21311 + 158*Z21312 +
157*Z23301 + 157*Z23302 + 157*Z23303 +
157*Z23304 + 157*Z23305 + 157*Z23306 +
157*Z23307 + 157*Z23308 + 157*Z23309 +
157*Z23310 + 157*Z23311 + 157*Z23312 +
137*Z26301 + 137*Z26302 + 137*Z26303 +
137*Z26304 + 137*Z26305 + 137*Z26306 +
137*Z26307 + 137*Z26308 + 137*Z26309 +
137*Z26310 + 137*Z26311 + 137*Z26312 +
137*Z28301 + 137*Z28302 + 137*Z28303 +
137*Z28304 + 137*Z28305 + 137*Z28306 +
137*Z28307 + 137*Z28308 + 137*Z28309 +
137*Z28310 + 137*Z28311 + 137*Z28312
+ 814*Z31310 + 814*Z31311 + 814*Z31312 +
814*Z31313 + 814*Z31314 + 814*Z31315 +
814*Z31316 + 814*Z31317 + 814*Z31318 +
814*Z31319 + 814*Z31320 + 814*Z31321 +
1000*Z31501 + 1000*Z31502 + 1000*Z31503 +
1000*Z31504 + 1000*Z31505 + 1000*Z31506 +
1000*Z31507 + 1000*Z31508 + 1000*Z31509 +
1000*Z31510 + 1000*Z31511 + 1000*Z31512
+ 1000*Z32401 + 1000*Z32402 +
1000*Z32403 + 1000*Z32404 + 1000*Z32405 +
1000*Z32406 + 1000*Z32407 + 1000*Z32408 +
1000*Z32409 + 1000*Z32410 + 1000*Z32411 +
1000*Z32412
+ 1000*Z41501 + 1000*Z41502 +
1000*Z41503 + 1000*Z41504 + 1000*Z41505 +
1000*Z41506 + 1000*Z41507 + 1000*Z41508 +
1000*Z41509 + 1000*Z41510 + 1000*Z41511 +
1000*Z41512
+ 2136*Z51101 + 2136*Z51102 +
2136*Z51103 + 2136*Z51104 + 2136*Z51105 +
2136*Z51106 + 2136*Z51107 + 2136*Z51108 +
2136*Z51109 + 2136*Z51110 + 2136*Z51111 +
2136*Z51112
+ 2343*Z21121 + 2343*Z21122 +
2343*Z21123 + 2343*Z21124 + 2343*Z21125 +
2343*Z21126 + 2343*Z21127 + 2343*Z21128 +
2343*Z21129 + 2343*Z21130 + 2343*Z21131 +
2343*Z21132 + 3858*Z21220 + 3858*Z21221 +
3858*Z21222 + 3858*Z21223 + 3858*Z21224 +
3858*Z21225 + 3858*Z21226 + 3858*Z21227 +
3858*Z21228 + 3858*Z21229 + 3858*Z21230 +
3858*Z21231 + 534*Z22201 + 534*Z22202 +
534*Z22203 + 534*Z22204 + 534*Z22205 +
534*Z22206 + 534*Z22207 + 534*Z22208 +
534*Z22209 + 534*Z22210 + 534*Z22211 +
534*Z22212 + 3837*Z23220 + 3837*Z23221 +
3837*Z23222 + 3837*Z23223 + 3837*Z23224 +
3837*Z23225 + 3837*Z23226 + 3837*Z23227 +
3837*Z23228 + 3837*Z23229 + 3837*Z23230 +
3837*Z23231 + 502*Z24121 + 502*Z24122 +
502*Z24123 + 502*Z24124 + 502*Z24125 +
502*Z24126 + 502*Z24127 + 502*Z24128 +
502*Z24129 + 502*Z24130 + 502*Z24131 +
502*Z24132
+ 732*Z24201 + 732*Z24202 + 732*Z24203 +
732*Z24204 + 732*Z24205 + 732*Z24206 +
732*Z24207 + 732*Z24208 + 732*Z24209 +
732*Z24210 + 732*Z24211 + 732*Z24212 +
900*Z25120 + 900*Z25121 + 900*Z25122 +
900*Z25123 + 900*Z25124 + 900*Z25125 +
900*Z25126 + 900*Z25127 + 900*Z25128 +
900*Z25129 + 900*Z25130 + 900*Z25131 +
1896*Z26120 + 1896*Z26121 + 1896*Z26122 +
1896*Z26123 + 1896*Z26124 + 1896*Z26125 +
1896*Z26126 + 1896*Z26127 + 1896*Z26128 +
1896*Z26129 + 1896*Z26130 + 1896*Z26131 +
3156*Z26220 + 3156*Z26221 + 3156*Z26222 +
3156*Z26223 + 3156*Z26224 + 3156*Z26225 +
3156*Z26226 + 3156*Z26227 + 3156*Z26228 +
3156*Z26229 + 3156*Z26230 + 3156*Z26231 +
685*Z27120 + 685*Z27121 + 685*Z27122 +
685*Z27123 + 685*Z27124 + 685*Z27125 +
685*Z27126 + 685*Z27127 + 685*Z27128 +
685*Z27129 + 685*Z27130 + 685*Z27131
+ 1016*Z27201 + 1016*Z27202 +
1016*Z27203 + 1016*Z27204 + 1016*Z27205 +
1016*Z27206 + 1016*Z27207 + 1016*Z27208 +
1016*Z27209 + 1016*Z27210 + 1016*Z27211 +
1016*Z27212 + 1428*Z28120 + 1428*Z28121 +
1428*Z28122 + 1428*Z28123 + 1428*Z28124 +

1428*Z28125 + 1428*Z28126 + 1428*Z28127 + 1428*Z28128 + 1428*Z28129 + 1428*Z28130 + 1428*Z28131 + 2423*Z28220 + 2423*Z28221 + 2423*Z28222 + 2423*Z28223 + 2423*Z28224 + 2423*Z28225 + 2423*Z28226 + 2423*Z28227 + 2423*Z28228 + 2423*Z28229 + 2423*Z28230 + 2423*Z28231 + 1613*Z29121 + 1613*Z29122 + 1613*Z29123 + 1613*Z29124 + 1613*Z29125 + 1613*Z29126 + 1613*Z29127 + 1613*Z29128 + 1613*Z29129 + 1613*Z29130 + 1613*Z29131 + 1613*Z29132 + 658*Z20120 + 658*Z20121 + 658*Z20122 + 658*Z20123 + 658*Z20124 + 658*Z20125 + 658*Z20126 + 658*Z20127 + 658*Z20128 + 658*Z20129 + 658*Z20130 + 658*Z20131
+ 1130*Z20201 + 1130*Z20202 + 1130*Z20203 + 1130*Z20204 + 1130*Z20205 + 1130*Z20206 + 1130*Z20207 + 1130*Z20208 + 1130*Z20209 + 1130*Z20210 + 1130*Z20211 + 1130*Z20212 + 645*Z31210 + 645*Z31211 + 645*Z31212 + 645*Z31213 + 645*Z31214 + 645*Z31215 + 645*Z31216 + 645*Z31217 + 645*Z31218 + 645*Z31219 + 645*Z31220 + 645*Z31221 + 1402*Z41220 + 1402*Z41221 + 1402*Z41222 + 1402*Z41223 + 1402*Z41224 + 1402*Z41225 + 1402*Z41226 + 1402*Z41227 + 1402*Z41228 + 1402*Z41229 + 1402*Z41230 + 1402*Z41231 + 635*Z41301 + 635*Z41302 + 635*Z41303 + 635*Z41304 + 635*Z41305 + 635*Z41306 + 635*Z41307 + 635*Z41308 + 635*Z41309 + 635*Z41310 + 635*Z41311 + 635*Z41312) = V2;
(1000*Z32401 + 1000*Z32402 + 1000*Z32403 + 1000*Z32404 + 1000*Z32405 + 1000*Z32406 + 1000*Z32407 + 1000*Z32408 + 1000*Z32409 + 1000*Z32410 + 1000*Z32411 + 1000*Z32412)/(
1500*Z61201 + 1500*Z61202 + 1500*Z61203 + 1500*Z61204 + 1500*Z61205 + 1500*Z61206 + 1500*Z61207 + 1500*Z61208 + 1500*Z61209 + 1500*Z61210 + 1500*Z61211 + 1850*Z62201 + 1850*Z62202 + 1850*Z62203 + 1850*Z62204 + 1850*Z62205 + 1850*Z62206 + 1850*Z62207 + 1850*Z62208 + 1850*Z62209 + 1850*Z62210 + 1850*Z62211 + 1500*Z63201 + 1500*Z63202 + 1500*Z63203 + 1500*Z63204 + 1500*Z63205 + 1500*Z63206 + 1500*Z63207 + 1500*Z63208 + 1500*Z63209 + 1500*Z63210 + 1500*Z63211 + 1850*Z64201 + 1850*Z64202 + 1850*Z64203 + 1850*Z64204 + 1850*Z64205 + 1850*Z64206 + 1850*Z64207 + 1850*Z64208 + 1850*Z64209 + 1850*Z64210 + 1850*Z64211 +
158*Z21301 + 158*Z21302 + 158*Z21303 + 158*Z21304 + 158*Z21305 + 158*Z21306 + 158*Z21307 + 158*Z21308 + 158*Z21309 + 158*Z21310 + 158*Z21311 + 158*Z21312 + 157*Z23301 + 157*Z23302 + 157*Z23303 + 157*Z23304 + 157*Z23305 + 157*Z23306 + 157*Z23307 + 157*Z23308 + 157*Z23309 + 157*Z23310 + 157*Z23311 + 157*Z23312 + 137*Z26301 + 137*Z26302 + 137*Z26303 + 137*Z26304 + 137*Z26305 + 137*Z26306 + 137*Z26307 + 137*Z26308 + 137*Z26309 + 137*Z26310 + 137*Z26311 + 137*Z26312 + 137*Z28301 + 137*Z28302 + 137*Z28303 + 137*Z28304 + 137*Z28305 + 137*Z28306 + 137*Z28307 + 137*Z28308 + 137*Z28309 + 137*Z28310 + 137*Z28311 + 137*Z28312
+ 814*Z31310 + 814*Z31311 + 814*Z31312 + 814*Z31313 + 814*Z31314 + 814*Z31315 + 814*Z31316 + 814*Z31317 + 814*Z31318 + 814*Z31319 + 814*Z31320 + 814*Z31321 + 1000*Z31501 + 1000*Z31502 + 1000*Z31503 + 1000*Z31504 + 1000*Z31505 + 1000*Z31506 + 1000*Z31507 + 1000*Z31508 + 1000*Z31509 + 1000*Z31510 + 1000*Z31511 + 1000*Z31512
+ 1000*Z32401 + 1000*Z32402 + 1000*Z32403 + 1000*Z32404 + 1000*Z32405 + 1000*Z32406 + 1000*Z32407 + 1000*Z32408 + 1000*Z32409 + 1000*Z32410 + 1000*Z32411 + 1000*Z32412
+ 1000*Z41501 + 1000*Z41502 + 1000*Z41503 + 1000*Z41504 + 1000*Z41505 + 1000*Z41506 + 1000*Z41507 + 1000*Z41508 + 1000*Z41509 + 1000*Z41510 + 1000*Z41511 + 1000*Z41512
+ 2136*Z51101 + 2136*Z51102 + 2136*Z51103 + 2136*Z51104 + 2136*Z51105 + 2136*Z51106 + 2136*Z51107 + 2136*Z51108 + 2136*Z51109 + 2136*Z51110 + 2136*Z51111 + 2136*Z51112
+ 2343*Z21121 + 2343*Z21122 + 2343*Z21123 + 2343*Z21124 + 2343*Z21125 + 2343*Z21126 + 2343*Z21127 + 2343*Z21128 + 2343*Z21129 + 2343*Z21130 + 2343*Z21131 + 2343*Z21132 + 3858*Z21220 + 3858*Z21221 + 3858*Z21222 + 3858*Z21223 + 3858*Z21224 + 3858*Z21225 + 3858*Z21226 + 3858*Z21227 + 3858*Z21228 + 3858*Z21229 + 3858*Z21230 + 3858*Z21231 + 534*Z22201 + 534*Z22202 + 534*Z22203 + 534*Z22204 + 534*Z22205 + 534*Z22206 + 534*Z22207 + 534*Z22208 + 534*Z22209 + 534*Z22210 + 534*Z22211 + 534*Z22212 + 3837*Z23220 + 3837*Z23221 + 3837*Z23222 + 3837*Z23223 + 3837*Z23224 + 3837*Z23225 + 3837*Z23226 + 3837*Z23227 + 3837*Z23228 + 3837*Z23229 + 3837*Z23230 + 3837*Z23231 + 502*Z24121 + 502*Z24122 + 502*Z24123 + 502*Z24124 + 502*Z24125 + 502*Z24126 + 502*Z24127 + 502*Z24128 + 502*Z24129 + 502*Z24130 + 502*Z24131 + 502*Z24132
+ 732*Z24201 + 732*Z24202 + 732*Z24203 + 732*Z24204 + 732*Z24205 + 732*Z24206 + 732*Z24207 + 732*Z24208 + 732*Z24209 + 732*Z24210 + 732*Z24211 + 732*Z24212 + 900*Z25120 + 900*Z25121 + 900*Z25122 + 900*Z25123 + 900*Z25124 + 900*Z25125 + 900*Z25126 + 900*Z25127 + 900*Z25128 + 900*Z25129 + 900*Z25130 + 900*Z25131 + 1896*Z26120 + 1896*Z26121 + 1896*Z26122 + 1896*Z26123 + 1896*Z26124 + 1896*Z26125 + 1896*Z26126 + 1896*Z26127 + 1896*Z26128 + 1896*Z26129 + 1896*Z26130 + 1896*Z26131 + 3156*Z26220 + 3156*Z26221 + 3156*Z26222 + 3156*Z26223 + 3156*Z26224 + 3156*Z26225 + 3156*Z26226 + 3156*Z26227 + 3156*Z26228 + 3156*Z26229 + 3156*Z26230 + 3156*Z26231 + 685*Z27120 + 685*Z27121 + 685*Z27122 + 685*Z27123 + 685*Z27124 + 685*Z27125 + 685*Z27126 + 685*Z27127 + 685*Z27128 + 685*Z27129 + 685*Z27130 + 685*Z27131
+ 1016*Z27201 + 1016*Z27202 + 1016*Z27203 + 1016*Z27204 + 1016*Z27205 + 1016*Z27206 + 1016*Z27207 + 1016*Z27208 + 1016*Z27209 + 1016*Z27210 + 1016*Z27211 + 1016*Z27212 + 1428*Z28120 + 1428*Z28121 + 1428*Z28122 + 1428*Z28123 + 1428*Z28124 + 1428*Z28125 + 1428*Z28126 + 1428*Z28127 + 1428*Z28128 + 1428*Z28129 + 1428*Z28130 + 1428*Z28131 + 2423*Z28220 + 2423*Z28221 + 2423*Z28222 + 2423*Z28223 + 2423*Z28224 + 2423*Z28225 + 2423*Z28226 + 2423*Z28227 + 2423*Z28228 + 2423*Z28229 + 2423*Z28230 + 2423*Z28231 + 1613*Z29121 + 1613*Z29122 + 1613*Z29123 + 1613*Z29124 + 1613*Z29125 + 1613*Z29126 + 1613*Z29127 + 1613*Z29128 + 1613*Z29129 + 1613*Z29130 + 1613*Z29131 + 1613*Z29132 + 658*Z20120 + 658*Z20121 + 658*Z20122 + 658*Z20123 + 658*Z20124 + 658*Z20125 + 658*Z20126 + 658*Z20127 + 658*Z20128 + 658*Z20129 + 658*Z20130 + 658*Z20131
+ 1130*Z20201 + 1130*Z20202 + 1130*Z20203 + 1130*Z20204 + 1130*Z20205 + 1130*Z20206 + 1130*Z20207 + 1130*Z20208 + 1130*Z20209 + 1130*Z20210 + 1130*Z20211 + 1130*Z20212 + 645*Z31210 + 645*Z31211 + 645*Z31212 + 645*Z31213 + 645*Z31214 + 645*Z31215 + 645*Z31216 + 645*Z31217 + 645*Z31218 + 645*Z31219 + 645*Z31220 + 645*Z31221 + 1402*Z41220 + 1402*Z41221 + 1402*Z41222 + 1402*Z41223 + 1402*Z41224 + 1402*Z41225 + 1402*Z41226 + 1402*Z41227 + 1402*Z41228 + 1402*Z41229 + 1402*Z41230 + 1402*Z41231 + 635*Z41301 + 635*Z41302 + 635*Z41303 + 635*Z41304 + 635*Z41305 + 635*Z41306 + 635*Z41307 + 635*Z41308 + 635*Z41309 + 635*Z41310 + 635*Z41311 + 635*Z41312) = V3;
(1000*Z41501 + 1000*Z41502 + 1000*Z41503 + 1000*Z41504 + 1000*Z41505 + 1000*Z41506 + 1000*Z41507 + 1000*Z41508 + 1000*Z41509 + 1000*Z41510 + 1000*Z41511 + 1000*Z41512)/(
1500*Z61201 + 1500*Z61202 + 1500*Z61203 + 1500*Z61204 + 1500*Z61205 + 1500*Z61206 + 1500*Z61207 + 1500*Z61208 + 1500*Z61209 + 1500*Z61210 + 1500*Z61211 + 1850*Z62201 + 1850*Z62202 + 1850*Z62203 + 1850*Z62204 + 1850*Z62205 + 1850*Z62206 + 1850*Z62207 + 1850*Z62208 + 1850*Z62209 + 1850*Z62210 + 1850*Z62211 + 1500*Z63201 + 1500*Z63202 + 1500*Z63203 + 1500*Z63204 + 1500*Z63205 + 1500*Z63206 + 1500*Z63207 + 1500*Z63208 + 1500*Z63209 + 1500*Z63210 + 1500*Z63211 + 1850*Z64201 + 1850*Z64202 + 1850*Z64203 + 1850*Z64204 + 1850*Z64205 + 1850*Z64206 + 1850*Z64207 + 1850*Z64208 + 1850*Z64209 + 1850*Z64210 + 1850*Z64211 +
158*Z21301 + 158*Z21302 + 158*Z21303 + 158*Z21304 + 158*Z21305 + 158*Z21306 + 158*Z21307 + 158*Z21308 + 158*Z21309 + 158*Z21310 + 158*Z21311 + 158*Z21312 + 157*Z23301 + 157*Z23302 + 157*Z23303 + 157*Z23304 + 157*Z23305 + 157*Z23306 + 157*Z23307 + 157*Z23308 + 157*Z23309 + 157*Z23310 + 157*Z23311 + 157*Z23312 + 137*Z26301 + 137*Z26302 + 137*Z26303 + 137*Z26304 + 137*Z26305 + 137*Z26306 + 137*Z26307 + 137*Z26308 + 137*Z26309 + 137*Z26310 + 137*Z26311 + 137*Z26312 + 137*Z28301 + 137*Z28302 + 137*Z28303 + 137*Z28304 + 137*Z28305 + 137*Z28306 + 137*Z28307 + 137*Z28308 + 137*Z28309 + 137*Z28310 + 137*Z28311 + 137*Z28312
+ 814*Z31310 + 814*Z31311 + 814*Z31312 + 814*Z31313 + 814*Z31314 + 814*Z31315 + 814*Z31316 + 814*Z31317 + 814*Z31318 + 814*Z31319 + 814*Z31320 + 814*Z31321 + 1000*Z31501 + 1000*Z31502 + 1000*Z31503 + 1000*Z31504 + 1000*Z31505 + 1000*Z31506 + 1000*Z31507 + 1000*Z31508 + 1000*Z31509 + 1000*Z31510 + 1000*Z31511 + 1000*Z31512
+ 1000*Z32401 + 1000*Z32402 + 1000*Z32403 + 1000*Z32404 + 1000*Z32405 + 1000*Z32406 + 1000*Z32407 + 1000*Z32408 + 1000*Z32409 + 1000*Z32410 + 1000*Z32411 + 1000*Z32412
+ 1000*Z41501 + 1000*Z41502 + 1000*Z41503 + 1000*Z41504 + 1000*Z41505 + 1000*Z41506 + 1000*Z41507 + 1000*Z41508 + 1000*Z41509 + 1000*Z41510 + 1000*Z41511 + 1000*Z41512
+ 2136*Z51101 + 2136*Z51102 + 2136*Z51103 + 2136*Z51104 + 2136*Z51105 + 2136*Z51106 + 2136*Z51107 + 2136*Z51108 + 2136*Z51109 + 2136*Z51110 + 2136*Z51111 + 2136*Z51112
+ 2343*Z21121 + 2343*Z21122 + 2343*Z21123 + 2343*Z21124 + 2343*Z21125 + 2343*Z21126 + 2343*Z21127 + 2343*Z21128 + 2343*Z21129 + 2343*Z21130 + 2343*Z21131 + 2343*Z21132 + 3858*Z21220 + 3858*Z21221 + 3858*Z21222 + 3858*Z21223 + 3858*Z21224 + 3858*Z21225 + 3858*Z21226 + 3858*Z21227 + 3858*Z21228 + 3858*Z21229 + 3858*Z21230 + 3858*Z21231 + 534*Z22201 + 534*Z22202 + 534*Z22203 + 534*Z22204 + 534*Z22205 + 534*Z22206 + 534*Z22207 + 534*Z22208 + 534*Z22209 + 534*Z22210 + 534*Z22211 + 534*Z22212 + 3837*Z23220 + 3837*Z23221 + 3837*Z23222 + 3837*Z23223 + 3837*Z23224 + 3837*Z23225 + 3837*Z23226 + 3837*Z23227 + 3837*Z23228 + 3837*Z23229 + 3837*Z23230 + 3837*Z23231 + 502*Z24121 + 502*Z24122 + 502*Z24123 + 502*Z24124 + 502*Z24125 + 502*Z24126 + 502*Z24127 + 502*Z24128 + 502*Z24129 + 502*Z24130 + 502*Z24131 + 502*Z24132
+ 732*Z24201 + 732*Z24202 + 732*Z24203 + 732*Z24204 + 732*Z24205 + 732*Z24206 + 732*Z24207 + 732*Z24208 + 732*Z24209 + 732*Z24210 + 732*Z24211 + 732*Z24212 + 900*Z25120 + 900*Z25121 + 900*Z25122 + 900*Z25123 + 900*Z25124 + 900*Z25125 + 900*Z25126 + 900*Z25127 + 900*Z25128 + 900*Z25129 + 900*Z25130 + 900*Z25131 +

1896*Z26120 + 1896*Z26121 + 1896*Z26122 + 1896*Z26123 + 1896*Z26124 + 1896*Z26125 + 1896*Z26126 + 1896*Z26127 + 1896*Z26128 + 1896*Z26129 + 1896*Z26130 + 1896*Z26131 + 3156*Z26220 + 3156*Z26221 + 3156*Z26222 + 3156*Z26223 + 3156*Z26224 + 3156*Z26225 + 3156*Z26226 + 3156*Z26227 + 3156*Z26228 + 3156*Z26229 + 3156*Z26230 + 3156*Z26231 + 685*Z27120 + 685*Z27121 + 685*Z27122 + 685*Z27123 + 685*Z27124 + 685*Z27125 + 685*Z27126 + 685*Z27127 + 685*Z27128 + 685*Z27129 + 685*Z27130 + 685*Z27131
+ 1016*Z27201 + 1016*Z27202 + 1016*Z27203 + 1016*Z27204 + 1016*Z27205 + 1016*Z27206 + 1016*Z27207 + 1016*Z27208 + 1016*Z27209 + 1016*Z27210 + 1016*Z27211 + 1016*Z27212 + 1428*Z28120 + 1428*Z28121 + 1428*Z28122 + 1428*Z28123 + 1428*Z28124 + 1428*Z28125 + 1428*Z28126 + 1428*Z28127 + 1428*Z28128 + 1428*Z28129 + 1428*Z28130 + 1428*Z28131 + 2423*Z28220 + 2423*Z28221 + 2423*Z28222 + 2423*Z28223 + 2423*Z28224 + 2423*Z28225 + 2423*Z28226 + 2423*Z28227 + 2423*Z28228 + 2423*Z28229 + 2423*Z28230 + 2423*Z28231 + 1613*Z29121 + 1613*Z29122 + 1613*Z29123 + 1613*Z29124 + 1613*Z29125 + 1613*Z29126 + 1613*Z29127 + 1613*Z29128 + 1613*Z29129 + 1613*Z29130 + 1613*Z29131 + 1613*Z29132 + 658*Z20120 + 658*Z20121 + 658*Z20122 + 658*Z20123 + 658*Z20124 + 658*Z20125 + 658*Z20126 + 658*Z20127 + 658*Z20128 + 658*Z20129 + 658*Z20130 + 658*Z20131
+ 1130*Z20201 + 1130*Z20202 + 1130*Z20203 + 1130*Z20204 + 1130*Z20205 + 1130*Z20206 + 1130*Z20207 + 1130*Z20208 + 1130*Z20209 + 1130*Z20210 + 1130*Z20211 + 1130*Z20212 + 645*Z31210 + 645*Z31211 + 645*Z31212 + 645*Z31213 + 645*Z31214 + 645*Z31215 + 645*Z31216 + 645*Z31217 + 645*Z31218 + 645*Z31219 + 645*Z31220 + 645*Z31221 + 1402*Z41220 + 1402*Z41221 + 1402*Z41222 + 1402*Z41223 + 1402*Z41224 + 1402*Z41225 + 1402*Z41226 + 1402*Z41227 + 1402*Z41228 + 1402*Z41229 + 1402*Z41230 + 1402*Z41231 + 635*Z41301 + 635*Z41302 + 635*Z41303 + 635*Z41304 + 635*Z41305 + 635*Z41306 + 635*Z41307 + 635*Z41308 + 635*Z41309 + 635*Z41310 + 635*Z41311 + 635*Z41312) = V4;
(2136*Z51101 + 2136*Z51102 + 2136*Z51103 + 2136*Z51104 + 2136*Z51105 + 2136*Z51106 + 2136*Z51107 + 2136*Z51108 + 2136*Z51109 + 2136*Z51110 + 2136*Z51111 + 2136*Z51112)/(
1500*Z61201 + 1500*Z61202 + 1500*Z61203 + 1500*Z61204 + 1500*Z61205 + 1500*Z61206 + 1500*Z61207 + 1500*Z61208 + 1500*Z61209 + 1500*Z61210 + 1500*Z61211 + 1850*Z62201 + 1850*Z62202 + 1850*Z62203 + 1850*Z62204 + 1850*Z62205 + 1850*Z62206 + 1850*Z62207 + 1850*Z62208 + 1850*Z62209 + 1850*Z62210 + 1850*Z62211 + 1500*Z63201 + 1500*Z63202 + 1500*Z63203 + 1500*Z63204 + 1500*Z63205 + 1500*Z63206 + 1500*Z63207 + 1500*Z63208 + 1500*Z63209 + 1500*Z63210 + 1500*Z63211 + 1850*Z64201 + 1850*Z64202 + 1850*Z64203 + 1850*Z64204 + 1850*Z64205 + 1850*Z64206 + 1850*Z64207 + 1850*Z64208 + 1850*Z64209 + 1850*Z64210 + 1850*Z64211 +
158*Z21301 + 158*Z21302 + 158*Z21303 + 158*Z21304 + 158*Z21305 + 158*Z21306 + 158*Z21307 + 158*Z21308 + 158*Z21309 + 158*Z21310 + 158*Z21311 + 158*Z21312 + 157*Z23301 + 157*Z23302 + 157*Z23303 + 157*Z23304 + 157*Z23305 + 157*Z23306 + 157*Z23307 + 157*Z23308 + 157*Z23309 + 157*Z23310 + 157*Z23311 + 157*Z23312 + 137*Z26301 + 137*Z26302 + 137*Z26303 + 137*Z26304 + 137*Z26305 + 137*Z26306 + 137*Z26307 + 137*Z26308 + 137*Z26309 + 137*Z26310 + 137*Z26311 + 137*Z26312 + 137*Z28301 + 137*Z28302 + 137*Z28303 + 137*Z28304 + 137*Z28305 + 137*Z28306 + 137*Z28307 + 137*Z28308 + 137*Z28309 + 137*Z28310 + 137*Z28311 + 137*Z28312
+ 814*Z31310 + 814*Z31311 + 814*Z31312 + 814*Z31313 + 814*Z31314 + 814*Z31315 + 814*Z31316 + 814*Z31317 + 814*Z31318 + 814*Z31319 + 814*Z31320 + 814*Z31321 + 1000*Z31501 + 1000*Z31502 + 1000*Z31503 + 1000*Z31504 + 1000*Z31505 + 1000*Z31506 + 1000*Z31507 + 1000*Z31508 + 1000*Z31509 + 1000*Z31510 + 1000*Z31511 + 1000*Z31512
+ 1000*Z32401 + 1000*Z32402 + 1000*Z32403 + 1000*Z32404 + 1000*Z32405 + 1000*Z32406 + 1000*Z32407 + 1000*Z32408 + 1000*Z32409 + 1000*Z32410 + 1000*Z32411 + 1000*Z32412
+ 1000*Z41501 + 1000*Z41502 + 1000*Z41503 + 1000*Z41504 + 1000*Z41505 + 1000*Z41506 + 1000*Z41507 + 1000*Z41508 + 1000*Z41509 + 1000*Z41510 + 1000*Z41511 + 1000*Z41512
+ 2136*Z51101 + 2136*Z51102 + 2136*Z51103 + 2136*Z51104 + 2136*Z51105 + 2136*Z51106 + 2136*Z51107 + 2136*Z51108 + 2136*Z51109 + 2136*Z51110 + 2136*Z51111 + 2136*Z51112
+ 2343*Z21121 + 2343*Z21122 + 2343*Z21123 + 2343*Z21124 + 2343*Z21125 + 2343*Z21126 + 2343*Z21127 + 2343*Z21128 + 2343*Z21129 + 2343*Z21130 + 2343*Z21131 + 2343*Z21132 + 3858*Z21220 + 3858*Z21221 + 3858*Z21222 + 3858*Z21223 + 3858*Z21224 + 3858*Z21225 + 3858*Z21226 + 3858*Z21227 + 3858*Z21228 + 3858*Z21229 + 3858*Z21230 + 3858*Z21231 + 534*Z22201 + 534*Z22202 + 534*Z22203 + 534*Z22204 + 534*Z22205 + 534*Z22206 + 534*Z22207 + 534*Z22208 + 534*Z22209 + 534*Z22210 + 534*Z22211 + 534*Z22212 + 3837*Z23220 + 3837*Z23221 + 3837*Z23222 + 3837*Z23223 + 3837*Z23224 + 3837*Z23225 + 3837*Z23226 + 3837*Z23227 + 3837*Z23228 + 3837*Z23229 + 3837*Z23230 + 3837*Z23231 + 502*Z24121 + 502*Z24122 + 502*Z24123 + 502*Z24124 + 502*Z24125 + 502*Z24126 + 502*Z24127 + 502*Z24128 + 502*Z24129 + 502*Z24130 + 502*Z24131 + 502*Z24132
+ 732*Z24201 + 732*Z24202 + 732*Z24203 + 732*Z24204 + 732*Z24205 + 732*Z24206 + 732*Z24207 + 732*Z24208 + 732*Z24209 + 732*Z24210 + 732*Z24211 + 732*Z24212 + 900*Z25120 + 900*Z25121 + 900*Z25122 + 900*Z25123 + 900*Z25124 + 900*Z25125 + 900*Z25126 + 900*Z25127 + 900*Z25128 + 900*Z25129 + 900*Z25130 + 900*Z25131 + 1896*Z26120 + 1896*Z26121 + 1896*Z26122 + 1896*Z26123 + 1896*Z26124 + 1896*Z26125 + 1896*Z26126 + 1896*Z26127 + 1896*Z26128 + 1896*Z26129 + 1896*Z26130 + 1896*Z26131 + 3156*Z26220 + 3156*Z26221 + 3156*Z26222 + 3156*Z26223 + 3156*Z26224 + 3156*Z26225 + 3156*Z26226 + 3156*Z26227 + 3156*Z26228 + 3156*Z26229 + 3156*Z26230 + 3156*Z26231 + 685*Z27120 + 685*Z27121 + 685*Z27122 + 685*Z27123 + 685*Z27124 + 685*Z27125 + 685*Z27126 + 685*Z27127 + 685*Z27128 + 685*Z27129 + 685*Z27130 + 685*Z27131
+ 1016*Z27201 + 1016*Z27202 + 1016*Z27203 + 1016*Z27204 + 1016*Z27205 + 1016*Z27206 + 1016*Z27207 + 1016*Z27208 + 1016*Z27209 + 1016*Z27210 + 1016*Z27211 + 1016*Z27212 + 1428*Z28120 + 1428*Z28121 + 1428*Z28122 + 1428*Z28123 + 1428*Z28124 + 1428*Z28125 + 1428*Z28126 + 1428*Z28127 + 1428*Z28128 + 1428*Z28129 + 1428*Z28130 + 1428*Z28131 + 2423*Z28220 + 2423*Z28221 + 2423*Z28222 + 2423*Z28223 + 2423*Z28224 + 2423*Z28225 + 2423*Z28226 + 2423*Z28227 + 2423*Z28228 + 2423*Z28229 + 2423*Z28230 + 2423*Z28231 + 1613*Z29121 + 1613*Z29122 + 1613*Z29123 + 1613*Z29124 + 1613*Z29125 + 1613*Z29126 + 1613*Z29127 + 1613*Z29128 + 1613*Z29129 + 1613*Z29130 + 1613*Z29131 + 1613*Z29132 + 658*Z20120 + 658*Z20121 + 658*Z20122 + 658*Z20123 + 658*Z20124 + 658*Z20125 + 658*Z20126 + 658*Z20127 + 658*Z20128 + 658*Z20129 + 658*Z20130 + 658*Z20131
+ 1130*Z20201 + 1130*Z20202 + 1130*Z20203 + 1130*Z20204 + 1130*Z20205 + 1130*Z20206 + 1130*Z20207 + 1130*Z20208 + 1130*Z20209 + 1130*Z20210 + 1130*Z20211 + 1130*Z20212 + 645*Z31210 + 645*Z31211 + 645*Z31212 + 645*Z31213 + 645*Z31214 + 645*Z31215 + 645*Z31216 + 645*Z31217 + 645*Z31218 + 645*Z31219 + 645*Z31220 + 645*Z31221 + 1402*Z41220 + 1402*Z41221 + 1402*Z41222 + 1402*Z41223 + 1402*Z41224 + 1402*Z41225 + 1402*Z41226 + 1402*Z41227 + 1402*Z41228 + 1402*Z41229 + 1402*Z41230 + 1402*Z41231 + 635*Z41301 + 635*Z41302 + 635*Z41303 + 635*Z41304 + 635*Z41305 + 635*Z41306 + 635*Z41307 + 635*Z41308 + 635*Z41309 + 635*Z41310 + 635*Z41311 + 635*Z41312) = V5; 0.5 + (1-U)*0.5 – L0 = 0;
V1*0.5 – L1 = 0;
V2*0.5 - L2 = 0;
V3*0.5 - L3 = 0;
V4*0.5 - L4 = 0;
V5*0.5 - L5 = 0;
L6 - (U - V1 - V2 - V3 - V4 - V5)*0.5 = 0;

Constraints for stall bedding

Z21222*4487 + Z22213*668 + Z23222*4462 + Z24213*914 + Z26222*3670 + Z27213*1270 + Z28222*2817 - W1*1.25-W2*1.25-W3*547.6-W4*73 >= 0;

Constraints relating nutrient flows from forest and cropland

W41*0.9497*L6 + W42*2.7586*L6 + W43*0.9497*L6 + W44*2.7586*L6 + W45*6.3313*L6 + W46*9.0447*L6 + W47*0.9497*L6 + W48*2.7586*L6 + W49*6.3313*L6 + W40*9.0447*L6 + W411*9.0447*L6 + W412*9.0447*L6 + (Z61102 + Z61103 + Z61104 + Z61105 + Z61106 + Z61107 + Z61108)*20.6 + (Z62102 + Z62103 + Z62104 + Z62105 + Z62106 + Z62107 + Z62108)*20.6 + (Z63102 + Z63103 + Z63104 + Z63105 + Z63106 + Z63107 + Z63108)*24.7 + (Z64102 + Z64103 + Z64104 + Z64105 + Z64106 + Z64107 + Z64108)*24.7- P = 0;
W41*0.1600*L6 + W42*0.4649*L6 + W43*0.1600*L6 + W44*0.4649*L6 + W45*1.0670*L6 + W46*1.5242*L6 + W47*0.1600*L6 + W48*0.4649*L6 + W49*1.0670*L6 + W40*1.5242*L6 + W411*1.5242*L6 + W412*1.5242*L6 + (Z61102 + Z61103 + Z61104 + Z61105 + Z61106 + Z61107 + Z61108)*2.4 + (Z62102 + Z62103 + Z62104 + Z62105 + Z62106 + Z62107 + Z62108)*2.4 + (Z63102 + Z63103 + Z63104 + Z63105 + Z63106 + Z63107 + Z63108)*3.5 + (Z64102 + Z64103 + Z64104 + Z64105 + Z64106 + Z64107 + Z64108)*3.5- Q = 0;
W41*0.9382*L6 + W42*2.7252*L6 + W43*0.9382*L6 + W44*2.7252*L6 + W45*6.2546*L6 + W46*8.9352*L6 + W47*0.9382*L6 + W48*2.7252*L6 + W49*6.2546*L6 + W40*8.9352*L6 + W411*8.9352*L6 + W412*8.9352*L6 + (Z61102 + Z61103 + Z61104 + Z61105 + Z61106 + Z61107 + Z61108)*7.3 + (Z62102 + Z62103 + Z62104 + Z62105 + Z62106 + Z62107 + Z62108)*7.3 + (Z63102 + Z63103 + Z63104 + Z63105 + Z63106 + Z63107 + Z63108)*8.7 + (Z64102 + Z64103 + Z64104 + Z64105 + Z64106 + Z64107 + Z64108)*8.7- R <= 0;
(W41*0.9497*L6 + W42*2.7586*L6 + W43*0.9497*L6 + W44*2.7586*L6 + W45*6.3313*L6 + W46*9.0447*L6 +

W47*0.9497*L6 + W48*2.7586*L6 +
W49*6.3313*L6 + W40*9.0447*L6 +
W411*9.0447*L6 + W412*9.0447*L6 +
(Z61102 + Z61103 + Z61104 + Z61105 +
Z61106 + Z61107 + Z61108)*20.6 + (Z62102 +
Z62103 + Z62104 + Z62105 + Z62106 +
Z62107 + Z62108)*20.6 + (Z63102 + Z63103 +
Z63104 + Z63105 + Z63106 + Z63107 +
Z63108)*24.7 + (Z64102 + Z64103 + Z64104 +
Z64105 + Z64106 + Z64107 + Z64108)*24.7-
5.8*Y61 - 6.8*Y62 - 9.9*Y63 -
11.8*Y64)*7250/5440
 - M*(X1 + X2 + X3 + X4 + X5) <= 0;
(W41*0.1600*L6 + W42*0.4649*L6 +
W43*0.1600*L6 + W44*0.4649*L6 +
W45*1.0670*L6 + W46*1.5242*L6 +
W47*0.1600*L6 + W48*0.4649*L6 +
W49*1.0670*L6 + W40*1.5242*L6 +
W411*1.5242*L6 + W412*1.5242*L6 +
(Z61102 + Z61103 + Z61104 + Z61105 +
Z61106 + Z61107 + Z61108)*2.4 + (Z62102 +
Z62103 + Z62104 + Z62105 + Z62106 +
Z62107 + Z62108)*2.4 + (Z63102 + Z63103 +
Z63104 + Z63105 + Z63106 + Z63107 +
Z63108)*3.5 + (Z64102 + Z64103 + Z64104 +
Z64105 + Z64106 + Z64107 + Z64108)*3.5 -
0.35*(Y61 + Y62 + Y63 + Y64))*1600/2603
 - N*(X1 + X2 + X3 + X4 + X5) <= 0;

Constraints for nutrient flows

W1101*0.05 + W1201*0.10 + W1301*0.16 +
W1401*0.21 + W1501*0.21 + W1601*0.21 +
W1701*0.21 + W2101*0.07 + W2201*0.14 +
W2301*0.27 + W3101*0.33 + W3201*1.4 +
W3301*3.4 + W3401*7.4 + W3501*3.4 +
W3601*8.4 + W3701*14.0 + W3801*12.1 +
W3901*12.1 + W4101*C*0.5 + W4201*C*1.4
+ W4301*C*0.5 + W4401*C*1.4 +
W4501*C*3.1 + W4601*C*4.4 + W4701*C*0.5
+ W4801*C*1.4 + W4901*C*3.1 +
W4001*C*4.4 + W4111*C*4.4 + W4121*C*4.4
+ Z11220*35.4 + Z12202*4.6 + Z21222*10.6 +
Z22213*3.3 + Z23222*10.5 + Z24213*4.7 +
Z26222*8.6 + Z27213*5.2 + Z28222*7.9 +
Z31222*2.4 + Z31402*9.0 + Z32202*2.1 +
Z32302*0.5 + Z41232*16.9 + Z41313*7.5 +
Z41402*2.4 + Z61102*20.6 + Z62102*20.6 +
Z63102*24.7 + Z64102*24.7 + Z65102*0.0 +
Z11101C1*15.4 + Z12101C1*1.1 +
Z29101C1*2.2 + W37C1*17.8 + W38C1*17.8 +
W39C1*17.8 + W411C1*0.5 + W412C1*0.5 +
W2C1*0.1 + W15C1*0.015 + W152C1*0.07 +
Y11*M - 208.4*Y11 >= 0;
W1101*0.02 + W1201*0.05 + W1301*0.07 +
W1401*0.09 + W1501*0.09 + W1601*0.09 +
W1701*0.09 + W2101*0.02 + W2201*0.05 +
W2301*0.09 + W3101*0.09 + W3201*0.4 +
W3301*0.9 + W3401*2.0 + W3501*0.9 +
W3601*2.3 + W3701*3.8 + W3801*3.3 +
W3901*3.3 + W4101*C*0.2 + W4201*C*0.5 +
W4301*C*0.2 + W4401*C*0.5 + W4501*C*1.0
+ W4601*C*1.5 + W4701*C*0.2 +
W4801*C*0.5 + W4901*C*1.0 + W4001*C*1.5
+ W4111*C*1.5 + W4121*C*1.5 +
Z11220*20.6 + Z12202*1.1 + Z21222*4.2 +
Z22213*1.4 + Z23222*4.2 + Z24213*1.5 +
Z26222*3.5 + Z27213*12.5 + Z28222*2.4 +
Z31222*0.5 + Z31402*3.0 + Z32202*0.3 +
Z32302*1.1 + Z41232*4.4 + Z41313*1.3 +
Z41402*0.4 + Z61102*2.4 + Z62102*2.4 +
Z63102*3.5 + Z64102*3.5 + Z65102*0.0 +
Z11101C1*6.5 + Z12101C1*0.4 +
Z29101C1*0.9 + W37C1*2.6 + W38C1*2.6 +
W39C1*2.6 + W411C1*0.07 + W412C1*0.07 +
W2C1*0.01 + W15C1*0.002 + W152C1*0.012
+ Y11*N - 50.1*Y11 >= 0;
W1101*0.03 + W1201*0.06 + W1301*0.09 +
W1401*0.12 + W1501*0.12 + W1601*0.12 +
W1701*0.12 + W2101*0.04 + W2201*0.08 +
W2301*0.16 + W3101*0.16 + W3201*0.7 +
W3301*1.7 + W3401*3.7 + W3501*1.7 +
W3601*4.1 + W3701*6.9 + W3801*5.9 +
W3901*5.9 + W4101*C*0.8 + W4201*C*2.2 +
W4301*C*0.8 + W4401*C*2.2 + W4501*C*5.0
+ W4601*C*7.1 + W4701*C*0.8 +
W4801*C*2.2 + W4901*C*5.0 + W4001*C*7.1
+ W4111*C*7.1 + W4121*C*7.1 +
Z11220*49.6 + Z12202*3.7 + Z21222*18.8 +
Z22213*2.3 + Z23222*18.7 + Z24213*6.5 +
Z26222*15.4 + Z27213*12.2 + Z28222*19.6 +
Z31222*0.4 + Z31402*6.3 + Z32202*5.8 +
Z32302*1.1 + Z41232*11.5 + Z41313*3.6 +
Z41402*4.9 + Z61102*7.3 + Z62102*7.3 +
Z63102*8.7 + Z64102*8.7 + Z65102*0.0 +
Z11101C1*15.8 + Z12101C1*2.7 +
Z29101C1*5.1 + W37C1*0.9 + W38C1*0.9 +
W39C1*0.9 + W411C1*0.02 + W412C1*0.02 +
W2C1*0.005 + W15C1*0.001 + W152C1*0.006
+ Y11*O - 141.9*Y11 >= 0;
W1102*0.05 + W1202*0.10 + W1302*0.16 +
W1402*0.21 + W1502*0.21 + W1602*0.21 +
W1702*0.21 + W2102*0.07 + W2202*0.14 +
W2302*0.27 + W3102*0.33 + W3202*1.4 +
W3302*3.4 + W3402*7.4 + W3502*3.4 +
W3602*8.4 + W3702*14.0 + W3802*12.1 +
W3902*12.1 + W4102*C*0.5 + W4202*C*1.4
+ W4302*C*0.5 + W4402*C*1.4 +
W4502*C*3.1 + W4602*C*4.4 + W4702*C*0.5
+ W4802*C*1.4 + W4902*C*3.1 +
W4002*C*4.4 + W4112*C*4.4 + W4122*C*4.4
+ Z11221*35.4 + Z12203*4.6 + Z21223*10.6 +
Z22214*3.3 + Z23223*10.5 + Z24214*4.7 +
Z26223*8.6 + Z27214*5.2 + Z28223*7.9 +
Z31223*2.4 + Z31403*9.0 + Z32203*2.1 +
Z32303*0.5 + Z41233*16.9 + Z41314*7.5 +
Z41403*2.4 + Z61103*20.6 + Z62103*20.6 +
Z63103*24.7 + Z64103*24.7 + Z65103*0.0 +
Z11101C2*15.4 + Z12101C2*1.1 +
Z29101C2*2.2 + W37C2*17.8 + W38C2*17.8 +
W39C2*17.8 + W411C2*0.5 + W412C2*0.5 +
W2C2*0.1 + W15C2*0.015 + W152C2*0.07 +
Y12*M - 12.9*Y12 >= 0;
W1102*0.02 + W1202*0.05 + W1302*0.07 +
W1402*0.09 + W1502*0.09 + W1602*0.09 +
W1702*0.09 + W2102*0.02 + W2202*0.05 +
W2302*0.09 + W3102*0.09 + W3202*0.4 +
W3302*0.9 + W3402*2.0 + W3502*0.9 +
W3602*2.3 + W3702*3.8 + W3802*3.3 +
W3902*3.3 + W4102*C*0.2 + W4202*C*0.5 +
W4302*C*0.2 + W4402*C*0.5 + W4502*C*1.0
+ W4602*C*1.5 + W4702*C*0.2 +
W4802*C*0.5 + W4902*C*1.0 + W4002*C*1.5
+ W4112*C*1.5 + W4122*C*1.5 +
Z11221*20.6 + Z12203*1.1 + Z21223*4.2 +
Z22214*1.4 + Z23223*4.2 + Z24214*1.5 +
Z26223*3.5 + Z27214*12.5 + Z28223*2.4 +
Z31223*0.5 + Z31403*3.0 + Z32203*0.3 +
Z32303*1.1 + Z41233*4.4 + Z41314*1.3 +
Z41403*0.4 + Z61103*2.4 + Z62103*2.4 +
Z63103*3.5 + Z64103*3.5 + Z65103*0.0 +
Z11101C2*6.5 + Z12101C2*0.4 +
Z29101C2*0.9 + W37C2*2.6 + W38C2*2.6 +
W39C2*2.6 + W411C2*0.07 + W412C2*0.07 +
W2C2*0.01 + W15C2*0.002 + W152C2*0.012
+ Y12*N - 3.6*Y12 >= 0;
W1102*0.03 + W1202*0.06 + W1302*0.09 +
W1402*0.12 + W1502*0.12 + W1602*0.12 +
W1702*0.12 + W2102*0.04 + W2202*0.08 +
W2302*0.16 + W3102*0.16 + W3202*0.7 +
W3302*1.7 + W3402*3.7 + W3502*1.7 +
W3602*4.1 + W3702*6.9 + W3802*5.9 +
W3902*5.9 + W4102*C*0.8 + W4202*C*2.2 +
W4302*C*0.8 + W4402*C*2.2 + W4502*C*5.0
+ W4602*C*7.1 + W4702*C*0.8 +
W4802*C*2.2 + W4902*C*5.0 + W4002*C*7.1
+ W4112*C*7.1 + W4122*C*7.1 +
Z11221*49.6 + Z12203*3.7 + Z21223*18.8 +
Z22214*2.3 + Z23223*18.7 + Z24214*6.5 +
Z26223*15.4 + Z27214*12.2 + Z28223*19.6 +
Z31223*0.4 + Z31403*6.3 + Z32203*5.8 +
Z32303*1.1 + Z41233*11.5 + Z41314*3.6 +
Z41403*4.9 + Z61103*7.3 + Z62103*7.3 +
Z63103*8.7 + Z64103*8.7 + Z65103*0.0 +
Z11101C2*15.8 + Z12101C2*2.7 +
Z29101C2*5.1 + W37C2*0.9 + W38C2*0.9 +
W39C2*0.9 + W411C2*0.02 + W412C2*0.02 +
W2C2*0.005 + W15C2*0.001 + W152C2*0.006
+ Y12*O - 23.6*Y12 >= 0;
W1103*0.05 + W1203*0.10 + W1303*0.16 +
W1403*0.21 + W1503*0.21 + W1603*0.21 +
W1703*0.21 + W2103*0.07 + W2203*0.14 +
W2303*0.27 + W3103*0.33 + W3203*1.4 +
W3303*3.4 + W3403*7.4 + W3503*3.4 +
W3603*8.4 + W3703*14.0 + W3803*12.1 +
W3903*12.1 + W4103*C*0.5 + W4203*C*1.4
+ W4303*C*0.5 + W4403*C*1.4 +
W4503*C*3.1 + W4603*C*4.4 + W4703*C*0.5
+ W4803*C*1.4 + W4903*C*3.1 +
W4003*C*4.4 + W4113*C*4.4 + W4123*C*4.4
+ W41*0.74*F1 + W42*2.15*F1 +
W43*0.74*F1 + W44*2.15*F1 + W45*4.94*F1
+ W46*7.05*F1 + W47*0.74*F1 +
W48*2.15*F1 + W49*4.94*F1 + W40*7.05*F1
+ W411*7.05*F1 + W412*7.05*F1 +
Z11222*35.4 + Z12204*4.6 + Z21224*10.6 +
Z22215*3.3 + Z23224*10.5 + Z24215*4.7 +
Z25201*5.0 + Z26224*8.6 + Z27215*5.2 +
Z28224*7.9 + Z29201*8.5 + Z20213*7.2 +
Z31224*2.4 + Z31404*9.0 + Z32204*2.1 +
Z32304*0.5 + Z41234*16.9 + Z41315*7.5 +
Z41404*2.4 + Z61104*20.6 + Z62104*20.6 +
Z63104*24.7 + Z64104*24.7 + Z65104*0.0 +
Z11101C3*15.4 + Z12101C3*1.1 +
Z29101C3*2.2 + W37C3*17.8 + W38C3*17.8 +
W39C3*17.8 + W411C3*0.5 + W412C3*0.5 +
W2C3*0.1 + W15C3*0.015 + W152C3*0.07 +
X2*M - 79.0*Y21 - 101.2*Y21A - 4.4*Y22 -
78.5*Y23 - 11.7*Y24 - 37.3*Y25 - 101.2*Y21B
- 28.6*Y26 - 9.8*Y27 - 42.3*Y28 - 43.5*Y29 -
16.2*Y20 >= 0;
W1103*0.02 + W1203*0.05 + W1303*0.07 +
W1403*0.09 + W1503*0.09 + W1603*0.09 +
W1703*0.09 + W2103*0.02 + W2203*0.05 +
W2303*0.09 + W3103*0.09 + W3203*0.4 +
W3303*0.9 + W3403*2.0 + W3503*0.9 +
W3603*2.3 + W3703*3.8 + W3803*3.3 +
W3903*3.3 + W4103*C*0.2 + W4203*C*0.5 +
W4303*C*0.2 + W4403*C*0.5 + W4503*C*1.0
+ W4603*C*1.5 + W4703*C*0.2 +
W4803*C*0.5 + W4903*C*1.0 + W4003*C*1.5
+ W4113*C*1.5 + W4123*C*1.5 +
W41*0.16*F1 + W42*0.46*F1 + W43*0.16*F1
+ W44*0.46*F1 + W45*1.07*F1 +
W46*1.52*F1 + W47*0.16*F1 + W48*0.46*F1
+ W49*1.07*F1 + W40*1.52*F1 +
W411*1.52*F1 + W412*1.52*F1 +
Z11222*20.6 + Z12204*1.1 + Z21224*4.2 +
Z22215*1.4 + Z23224*4.2 + Z24215*1.5 +
Z25201*2.4 + Z26224*3.5 + Z27215*12.5 +
Z28224*2.4 + Z29201*2.4 + Z20213*2.3 +
Z31224*0.5 + Z31404*3.0 + Z32204*0.3 +
Z32304*1.1 + Z41234*4.4 + Z41315*1.3 +
Z41404*0.4 + Z61104*2.4 + Z62104*2.4 +
Z63104*3.5 + Z64104*3.5 + Z65104*0.0 +
Z11101C3*6.5 + Z12101C3*0.4 +
Z29101C3*0.9 + W37C3*2.6 + W38C3*2.6 +
W39C3*2.6 + W411C3*0.07 + W412C3*0.07 +
W2C3*0.01 + W15C3*0.002 + W152C3*0.012
+ X2*N - 13.7*Y21 - 2.9*Y22 - 13.6*Y23 -
3.0*Y24 - 8.7*Y25 - 30.8*Y26 - 18.8*Y27 -
6.6*Y28 - 7.4*Y29 - 5.3*Y20 >= 0;
W1103*0.03 + W1203*0.06 + W1303*0.09 +
W1403*0.12 + W1503*0.12 + W1603*0.12 +
W1703*0.12 + W2103*0.04 + W2203*0.08 +
W2303*0.16 + W3103*0.16 + W3203*0.7 +
W3303*1.7 + W3403*3.7 + W3503*1.7 +
W3603*4.1 + W3703*6.9 + W3803*5.9 +
W3903*5.9 + W4103*C*0.8 + W4203*C*2.2 +
W4303*C*0.8 + W4403*C*2.2 + W4503*C*5.0
+ W4603*C*7.1 + W4703*C*0.8 +
W4803*C*2.2 + W4903*C*5.0 + W4003*C*7.1
+ W4113*C*7.1 + W4123*C*7.1 +
W41*0.94*F1 + W42*2.73*F1 + W43*0.94*F1
+ W44*2.73*F1 + W45*6.25*F1 +
W46*8.94*F1 + W47*0.94*F1 + W48*2.73*F1
+ W49*6.25*F1 + W40*8.94*F1 +
W411*8.94*F1 + W412*8.94*F1 +
Z11222*49.6 + Z12204*3.7 + Z21224*18.8 +
Z22215*2.3 + Z23224*18.7 + Z24215*6.5 +
Z25201*13.1 + Z26224*15.4 + Z27215*12.2 +
Z28224*19.6 + Z29201*10.1 + Z20213*10.0 +
Z31224*0.4 + Z31404*6.3 + Z32204*5.8 +
Z32304*1.1 + Z41234*11.5 + Z41315*3.6 +
Z41404*4.9 + Z61104*7.3 + Z62104*7.3 +

Z63104*8.7 + Z64104*8.7 + Z65104*0.0 +
Z11101C3*15.8 + Z12101C3*2.7 +
Z29101C3*5.1 + W37C3*0.9 + W38C3*0.9 +
W39C3*0.9 + W411C3*0.02 + W412C3*0.02 +
W2C3*0.005 + W15C3*0.001 + W152C3*0.006
+ X2*O - 31.3*Y21 - 2.6*Y22 - 31.1*Y23 -
6.6*Y24 - 16.6*Y25 - 25.8*Y26 - 23.2*Y27 -
25.1*Y28 - 42.9*Y29 - 16.6*Y20 >= 0;
W1104*0.05 + W1204*0.10 + W1304*0.16 +
W1404*0.21 + W1504*0.21 + W1604*0.21 +
W1704*0.21 + W2104*0.07 + W2204*0.14 +
W2304*0.27 + W3104*0.33 + W3204*1.4 +
W3304*3.4 + W3404*7.4 + W3504*3.4 +
W3604*8.4 + W3704*14.0 + W3804*12.1 +
W3904*12.1 + W4104*C*0.5 + W4204*C*1.4
+ W4304*C*0.5 + W4404*C*1.4 +
W4504*C*3.1 + W4604*C*4.4 + W4704*C*0.5
+ W4804*C*1.4 + W4904*C*3.1 +
W4004*C*4.4 + W4114*C*4.4 + W4124*C*4.4
+ W41*0.74*F2 + W42*2.15*F2 +
W43*0.74*F2 + W44*2.15*F2 + W45*4.94*F2
+ W46*7.05*F2 + W47*0.74*F2 +
W48*2.15*F2 + W49*4.94*F2 + W40*7.05*F2
+ W411*7.05*F2 + W412*7.05*F2 +
Z11223*35.4 + Z12205*4.6 + Z21225*10.6 +
Z22216*3.3 + Z23225*10.5 + Z24216*4.7 +
Z26225*8.6 + Z27216*5.2 + Z28225*7.9 +
Z31225*2.4 + Z31405*9.0 + Z32205*2.1 +
Z32305*0.5 + Z41235*16.9 + Z41316*7.5 +
Z41405*2.4 + Z61105*20.6 + Z62105*20.6 +
Z63105*24.7 + Z64105*24.7 + Z65105*0.0 +
Z11101C4*15.4 + Z12101C4*1.1 +
Z29101C4*2.2 + W37C4*17.8 + W38C4*17.8 +
W39C4*17.8 + W411C4*0.5 + W412C4*0.5 +
W2C4*0.1 + W15C4*0.015 + W152C4*0.07 +
Y31*M - 43.2*Y31 >= 0;
W1104*0.02 + W1204*0.05 + W1304*0.07 +
W1404*0.09 + W1504*0.09 + W1604*0.09 +
W1704*0.09 + W2104*0.02 + W2204*0.05 +
W2304*0.09 + W3104*0.09 + W3204*0.4 +
W3304*0.9 + W3404*2.0 + W3504*0.9 +
W3604*2.3 + W3704*3.8 + W3804*3.3 +
W3904*3.3 + W4104*C*0.2 + W4204*C*0.5 +
W4304*C*0.2 + W4404*C*0.5 + W4504*C*1.0
+ W4604*C*1.5 + W4704*C*0.2 +
W4804*C*0.5 + W4904*C*1.0 + W4004*C*1.5
+ W4114*C*1.5 + W4124*C*1.5 +
W41*0.16*F2 + W42*0.46*F2 + W43*0.16*F2
+ W44*0.46*F2 + W45*1.07*F2 +
W46*1.52*F2 + W47*0.16*F2 + W48*0.46*F2
+ W49*1.07*F2 + W40*1.52*F2 +
W411*1.52*F2 + W412*1.52*F2 +
Z11223*20.6 + Z12205*1.1 + Z21225*4.2 +
Z22216*1.4 + Z23225*4.2 + Z24216*1.5 +
Z26225*3.5 + Z27216*12.5 + Z28225*2.4 +
Z31225*0.5 + Z31405*3.0 + Z32205*0.3 +
Z32305*1.1 + Z41235*4.4 + Z41316*1.3 +
Z41405*0.4 + Z61105*2.4 + Z62105*2.4 +
Z63105*3.5 + Z64105*3.5 + Z65105*0.0 +
Z11101C4*6.5 + Z12101C4*0.4 +
Z29101C4*0.9 + W37C4*2.6 + W38C4*2.6 +
W39C4*2.6 + W411C4*0.07 + W412C4*0.07 +
W2C4*0.01 + W15C4*0.002 + W152C4*0.012
+ Y31*N - 8.9*Y31 >= 0;
W1104*0.03 + W1204*0.06 + W1304*0.09 +
W1404*0.12 + W1504*0.12 + W1604*0.12 +
W1704*0.12 + W2104*0.04 + W2204*0.08 +
W2304*0.16 + W3104*0.16 + W3204*0.7 +
W3304*1.7 + W3404*3.7 + W3504*1.7 +
W3604*4.1 + W3704*6.9 + W3804*5.9 +
W3904*5.9 + W4104*C*0.8 + W4204*C*2.2 +
W4304*C*0.8 + W4404*C*2.2 + W4504*C*5.0
+ W4604*C*7.1 + W4704*C*0.8 +
W4804*C*2.2 + W4904*C*5.0 + W4004*C*7.1
+ W4114*C*7.1 + W4124*C*7.1 +
W41*0.94*F2 + W42*2.73*F2 + W43*0.94*F2
+ W44*2.73*F2 + W45*6.25*F2 +
W46*8.94*F2 + W47*0.94*F2 + W48*2.73*F2
+ W49*6.25*F2 + W40*8.94*F2 +
W411*8.94*F2 + W412*8.94*F2 +
Z11223*49.6 + Z12205*3.7 + Z21225*18.8 +
Z22216*2.3 + Z23225*18.7 + Z24216*6.5 +
Z26225*15.4 + Z27216*12.2 + Z28225*19.6 +
Z31225*0.4 + Z31405*6.3 + Z32205*5.8 +
Z32305*1.1 + Z41235*11.5 + Z41316*3.6 +
Z41405*4.9 + Z61105*7.3 + Z62105*7.3 +
Z63105*8.7 + Z64105*8.7 + Z65105*0.0 +
Z11101C4*15.8 + Z12101C4*2.7 +
Z29101C4*5.1 + W37C4*0.9 + W38C4*0.9 +
W39C4*0.9 + W411C4*0.02 + W412C4*0.02 +
W2C4*0.005 + W15C4*0.001 + W152C4*0.006
+ Y31*O - 29.1*Y31 >= 0;
W1105*0.05 + W1205*0.10 + W1305*0.16 +
W1405*0.21 + W1505*0.21 + W1605*0.21 +
W1705*0.21 + W2105*0.07 + W2205*0.14 +
W2305*0.27 + W3105*0.33 + W3205*1.4 +
W3305*3.4 + W3405*7.4 + W3505*3.4 +
W3605*8.4 + W3705*14.0 + W3805*12.1 +
W3905*12.1 + W4105*C*0.5 + W4205*C*1.4
+ W4305*C*0.5 + W4405*C*1.4 +
W4505*C*3.1 + W4605*C*4.4 + W4705*C*0.5
+ W4805*C*1.4 + W4905*C*3.1 +
W4005*C*4.4 + W4115*C*4.4 + W4125*C*4.4
+ W41*0.74*F3 + W42*2.15*F3 +
W43*0.74*F3 + W44*2.15*F3 + W45*4.94*F3
+ W46*7.05*F3 + W47*0.74*F3 +
W48*2.15*F3 + W49*4.94*F3 + W40*7.05*F3
+ W411*7.05*F3 + W412*7.05*F3 +
Z11224*35.4 + Z12206*4.6 + Z21226*10.6 +
Z22217*3.3 + Z23226*10.5 + Z24217*4.7 +
Z26226*8.6 + Z27217*5.2 + Z28226*7.9 +
Z31226*2.4 + Z31406*9.0 + Z32206*2.1 +
Z32306*0.5 + Z41236*16.9 + Z41317*7.5 +
Z41406*2.4 + Z61106*20.6 + Z62106*20.6 +
Z63106*24.7 + Z64106*24.7 + Z65106*0.0 +
Z11101C5*15.4 + Z12101C5*1.1 +
Z29101C5*2.2 + W37C5*17.8 + W38C5*17.8 +
W39C5*17.8 + W411C5*0.5 + W412C5*0.5 +
W2C5*0.1 + W15C5*0.015 + W152C5*0.07 +
Y32*M - 40.9*Y32 >= 0;
W1105*0.02 + W1205*0.05 + W1305*0.07 +
W1405*0.09 + W1505*0.09 + W1605*0.09 +
W1705*0.09 + W2105*0.02 + W2205*0.05 +
W2305*0.09 + W3105*0.09 + W3205*0.4 +
W3305*0.9 + W3405*2.0 + W3505*0.9 +
W3605*2.3 + W3705*3.8 + W3805*3.3 +
W3905*3.3 + W4105*C*0.2 + W4205*C*0.5 +
W4305*C*0.2 + W4405*C*0.5 + W4505*C*1.0
+ W4605*C*1.5 + W4705*C*0.2 +
W4805*C*0.5 + W4905*C*1.0 + W4005*C*1.5
+ W4115*C*1.5 + W4125*C*1.5 +
W41*0.16*F3 + W42*0.46*F3 + W43*0.16*F3
+ W44*0.46*F3 + W45*1.07*F3 +
W46*1.52*F3 + W47*0.16*F3 + W48*0.46*F3
+ W49*1.07*F3 + W40*1.52*F3 +
W411*1.52*F3 + W412*1.52*F3 +
Z11224*20.6 + Z12206*1.1 + Z21226*4.2 +
Z22217*1.4 + Z23226*4.2 + Z24217*1.5 +
Z26226*3.5 + Z27217*12.5 + Z28226*2.4 +
Z31226*0.5 + Z31406*3.0 + Z32206*0.3 +
Z32306*1.1 + Z41236*4.4 + Z41317*1.3 +
Z41406*0.4 + Z61106*2.4 + Z62106*2.4 +
Z63106*3.5 + Z64106*3.5 + Z65106*0.0 +
Z11101C5*6.5 + Z12101C5*0.4 +
Z29101C5*0.9 + W37C5*2.6 + W38C5*2.6 +
W39C5*2.6 + W411C5*0.07 + W412C5*0.07 +
W2C5*0.01 + W15C5*0.002 + W152C5*0.012
+ Y32*N - 11.7*Y32 >= 0;
W1105*0.03 + W1205*0.06 + W1305*0.09 +
W1405*0.12 + W1505*0.12 + W1605*0.12 +
W1705*0.12 + W2105*0.04 + W2205*0.08 +
W2305*0.16 + W3105*0.16 + W3205*0.7 +
W3305*1.7 + W3405*3.7 + W3505*1.7 +
W3605*4.1 + W3705*6.9 + W3805*5.9 +
W3905*5.9 + W4105*C*0.8 + W4205*C*2.2 +
W4305*C*0.8 + W4405*C*2.2 + W4505*C*5.0
+ W4605*C*7.1 + W4705*C*0.8 +
W4805*C*2.2 + W4905*C*5.0 + W4005*C*7.1
+ W4115*C*7.1 + W4125*C*7.1 +
W41*0.94*F3 + W42*2.73*F3 + W43*0.94*F3
+ W44*2.73*F3 + W45*6.25*F3 +
W46*8.94*F3 + W47*0.94*F3 + W48*2.73*F3
+ W49*6.25*F3 + W40*8.94*F3 +
W411*8.94*F3 + W412*8.94*F3 +
Z11224*49.6 + Z12206*3.7 + Z21226*18.8 +
Z22217*2.3 + Z23226*18.7 + Z24217*6.5 +
Z26226*15.4 + Z27217*12.2 + Z28226*19.6 +
Z31226*0.4 + Z31406*6.3 + Z32206*5.8 +
Z32306*1.1 + Z41236*11.5 + Z41317*3.6 +
Z41406*4.9 + Z61106*7.3 + Z62106*7.3 +
Z63106*8.7 + Z64106*8.7 + Z65106*0.0 +
Z11101C5*15.8 + Z12101C5*2.7 +
Z29101C5*5.1 + W37C5*0.9 + W38C5*0.9 +
W39C5*0.9 + W411C5*0.02 + W412C5*0.02 +
W2C5*0.005 + W15C5*0.001 + W152C5*0.006
+ Y32*O - 33.0*Y32 >= 0;
W1106*0.05 + W1206*0.10 + W1306*0.16 +
W1406*0.21 + W1506*0.21 + W1606*0.21 +
W1706*0.21 + W2106*0.07 + W2206*0.14 +
W2306*0.27 + W3106*0.33 + W3206*1.4 +
W3306*3.4 + W3406*7.4 + W3506*3.4 +
W3606*8.4 + W3706*14.0 + W3806*12.1 +
W3906*12.1 + W4106*C*0.5 + W4206*C*1.4
+ W4306*C*0.5 + W4406*C*1.4 +
W4506*C*3.1 + W4606*C*4.4 + W4706*C*0.5
+ W4806*C*1.4 + W4906*C*3.1 +
W4006*C*4.4 + W4116*C*4.4 + W4126*C*4.4
+ W41*0.74*F4 + W42*2.15*F4 +
W43*0.74*F4 + W44*2.15*F4 + W45*4.94*F4
+ W46*7.05*F4 + W47*0.74*F4 +
W48*2.15*F4 + W49*4.94*F4 + W40*7.05*F4
+ W411*7.05*F4 + W412*7.05*F4 +
Z11225*35.4 + Z12207*4.6 + Z21227*10.6 +
Z22218*3.3 + Z23227*10.5 + Z24218*4.7 +
Z26227*8.6 + Z27218*5.2 + Z28227*7.9 +
Z31227*2.4 + Z31407*9.0 + Z32207*2.1 +
Z32307*0.5 + Z41237*16.9 + Z41318*7.5 +
Z41407*2.4 + Z61107*20.6 + Z62107*20.6 +
Z63107*24.7 + Z64107*24.7 + Z65107*0.0 +
Z11101C6*15.4 + Z12101C6*1.1 +
Z29101C6*2.2 + W37C6*17.8 + W38C6*17.8 +
W39C6*17.8 + W411C6*0.5 + W412C6*0.5 +
W2C6*0.1 + W15C6*0.015 + W152C6*0.07 +
Y41*M - 77.5*Y41 >= 0;
W1106*0.02 + W1206*0.05 + W1306*0.07 +
W1406*0.09 + W1506*0.09 + W1606*0.09 +
W1706*0.09 + W2106*0.02 + W2206*0.05 +
W2306*0.09 + W3106*0.09 + W3206*0.4 +
W3306*0.9 + W3406*2.0 + W3506*0.9 +
W3606*2.3 + W3706*3.8 + W3806*3.3 +
W3906*3.3 + W4106*C*0.2 + W4206*C*0.5 +
W4306*C*0.2 + W4406*C*0.5 + W4506*C*1.0
+ W4606*C*1.5 + W4706*C*0.2 +
W4806*C*0.5 + W4906*C*1.0 + W4006*C*1.5
+ W4116*C*1.5 + W4126*C*1.5 +
W41*0.16*F4 + W42*0.46*F4 + W43*0.16*F4
+ W44*0.46*F4 + W45*1.07*F4 +
W46*1.52*F4 + W47*0.16*F4 + W48*0.46*F4
+ W49*1.07*F4 + W40*1.52*F4 +
W411*1.52*F4 + W412*1.52*F4 +
Z11225*20.6 + Z12207*1.1 + Z21227*4.2 +
Z22218*1.4 + Z23227*4.2 + Z24218*1.5 +
Z26227*3.5 + Z27218*12.5 + Z28227*2.4 +
Z31227*0.5 + Z31407*3.0 + Z32207*0.3 +
Z32307*1.1 + Z41237*4.4 + Z41318*1.3 +
Z41407*0.4 + Z61107*2.4 + Z62107*2.4 +
Z63107*3.5 + Z64107*3.5 + Z65107*0.0 +
Z11101C6*6.5 + Z12101C6*0.4 +
Z29101C6*0.9 + W37C6*2.6 + W38C6*2.6 +
W39C6*2.6 + W411C6*0.07 + W412C6*0.07 +
W2C6*0.01 + W15C6*0.002 + W152C6*0.012
+ Y41*N - 15.0*Y41 >= 0;
W1106*0.03 + W1206*0.06 + W1306*0.09 +
W1406*0.12 + W1506*0.12 + W1606*0.12 +
W1706*0.12 + W2106*0.04 + W2206*0.08 +
W2306*0.16 + W3106*0.16 + W3206*0.7 +
W3306*1.7 + W3406*3.7 + W3506*1.7 +
W3606*4.1 + W3706*6.9 + W3806*5.9 +
W3906*5.9 + W4106*C*0.8 + W4206*C*2.2 +
W4306*C*0.8 + W4406*C*2.2 + W4506*C*5.0
+ W4606*C*7.1 + W4706*C*0.8 +
W4806*C*2.2 + W4906*C*5.0 + W4006*C*7.1
+ W4116*C*7.1 + W4126*C*7.1 +
W41*0.94*F4 + W42*2.73*F4 + W43*0.94*F4
+ W44*2.73*F4 + W45*6.25*F4 +
W46*8.94*F4 + W47*0.94*F4 + W48*2.73*F4
+ W49*6.25*F4 + W40*8.94*F4 +
W411*8.94*F4 + W412*8.94*F4 +
Z11225*49.6 + Z12207*3.7 + Z21227*18.8 +
Z22218*2.3 + Z23227*18.7 + Z24218*6.5 +
Z26227*15.4 + Z27218*12.2 + Z28227*19.6 +
Z31227*0.4 + Z31407*6.3 + Z32207*5.8 +
Z32307*1.1 + Z41237*11.5 + Z41318*3.6 +
Z41407*4.9 + Z61107*7.3 + Z62107*7.3 +
Z63107*8.7 + Z64107*8.7 + Z65107*0.0 +
Z11101C6*15.8 + Z12101C6*2.7 +
Z29101C6*5.1 + W37C6*0.9 + W38C6*0.9 +
W39C6*0.9 + W411C6*0.02 + W412C6*0.02 +

W2C6*0.005 + W15C6*0.001 + W152C6*0.006 + Y41*O - 68.7*Y41 >= 0;
W1107*0.05 + W1207*0.10 + W1307*0.16 + W1407*0.21 + W1507*0.21 + W1607*0.21 + W1707*0.21 + W2107*0.07 + W2207*0.14 + W2307*0.27 + W3107*0.33 + W3207*1.4 + W3307*3.4 + W3407*7.4 + W3507*3.4 + W3607*8.4 + W3707*14.0 + W3807*12.1 + W3907*12.1 + W4107*C*0.5 + W4207*C*1.4 + W4307*C*0.5 + W4407*C*1.4 + W4507*C*3.1 + W4607*C*4.4 + W4707*C*0.5 + W4807*C*1.4 + W4907*C*3.1 + W4007*C*4.4 + W4117*C*4.4 + W4127*C*4.4 + W41*0.74*F5 + W42*2.15*F5 + W43*0.74*F5 + W44*2.15*F5 + W45*4.94*F5 + W46*7.05*F5 + W47*0.74*F5 + W48*2.15*F5 + W49*4.94*F5 + W40*7.05*F5 + W411*7.05*F5 + W412*7.05*F5 + Z11226*35.4 + Z12208*4.6 + Z21228*10.6 + Z22219*3.3 + Z23228*10.5 + Z24219*4.7 + Z26228*8.6 + Z27219*5.2 + Z28228*7.9 + Z31228*2.4 + Z31408*9.0 + Z32208*2.1 + Z32308*0.5 + Z41238*16.9 + Z41319*7.5 + Z41408*2.4 + Z61108*20.6 + Z62108*20.6 + Z63108*24.7 + Z64108*24.7 + Z65108*0.0 + Z11101C7*15.4 + Z12101C7*1.1 + Z29101C7*2.2 + W37C7*17.8 + W38C7*17.8 + W39C7*17.8 + W411C7*0.5 + W412C7*0.5 + W2C7*0.1 + W15C7*0.015 + W152C7*0.07 + Y51*M - 23.6*Y51 >= 0;
W1107*0.02 + W1207*0.05 + W1307*0.07 + W1407*0.09 + W1507*0.09 + W1607*0.09 + W1707*0.09 + W2107*0.02 + W2207*0.05 + W2307*0.09 + W3107*0.09 + W3207*0.4 + W3307*0.9 + W3407*2.0 + W3507*0.9 + W3607*2.3 + W3707*3.8 + W3807*3.3 + W3907*3.3 + W4107*C*0.2 + W4207*C*0.5 + W4307*C*0.2 + W4407*C*0.5 + W4507*C*1.0 + W4607*C*1.5 + W4707*C*0.2 + W4807*C*0.5 + W4907*C*1.0 + W4007*C*1.5 + W4117*C*1.5 + W4127*C*1.5 + W41*0.16*F5 + W42*0.46*F5 + W43*0.16*F5 + W44*0.46*F5 + W45*1.07*F5 + W46*1.52*F5 + W47*0.16*F5 + W48*0.46*F5 + W49*1.07*F5 + W40*1.52*F5 + W411*1.52*F5 + W412*1.52*F5 + Z11226*20.6 + Z12208*1.1 + Z21228*4.2 + Z22219*1.4 + Z23228*4.2 + Z24219*1.5 + Z26228*3.5 + Z27219*12.5 + Z28228*2.4 + Z31228*0.5 + Z31408*3.0 + Z32208*0.3 + Z32308*1.1 + Z41238*4.4 + Z41319*1.3 + Z41408*0.4 + Z61108*2.4 + Z62108*2.4 + Z63108*3.5 + Z64108*3.5 + Z65108*0.0 + Z11101C7*6.5 + Z12101C7*0.4 + Z29101C7*0.9 + W37C7*2.6 + W38C7*2.6 + W39C7*2.6 + W411C7*0.07 + W412C7*0.07 + W2C7*0.01 + W15C7*0.002 + W152C7*0.012 + Y51*N - 8.8*Y51 >= 0;
W1107*0.03 + W1207*0.06 + W1307*0.09 + W1407*0.12 + W1507*0.12 + W1607*0.12 + W1707*0.12 + W2107*0.04 + W2207*0.08 + W2307*0.16 + W3107*0.16 + W3207*0.7 + W3307*1.7 + W3407*3.7 + W3507*1.7 + W3607*4.1 + W3707*6.9 + W3807*5.9 + W3907*5.9 + W4107*C*0.8 + W4207*C*2.2 + W4307*C*0.8 + W4407*C*2.2 + W4507*C*5.0 + W4607*C*7.1 + W4707*C*0.8 + W4807*C*2.2 + W4907*C*5.0 + W4007*C*7.1 + W4117*C*7.1 + W4127*C*7.1 + W41*0.94*F5 + W42*2.73*F5 + W43*0.94*F5 + W44*2.73*F5 + W45*6.25*F5 + W46*8.94*F5 + W47*0.94*F5 + W48*2.73*F5 + W49*6.25*F5 + W40*8.94*F5 + W411*8.94*F5 + W412*8.94*F5 + Z11226*49.6 + Z12208*3.7 + Z21228*18.8 + Z22219*2.3 + Z23228*18.7 + Z24219*6.5 + Z26228*15.4 + Z27219*12.2 + Z28228*19.6 + Z31228*0.4 + Z31408*6.3 + Z32208*5.8 + Z32308*1.1 + Z41238*11.5 + Z41319*3.6 + Z41408*4.9 + Z61108*7.3 + Z62108*7.3 + Z63108*8.7 + Z64108*8.7 + Z65108*0.0 + Z11101C7*15.8 + Z12101C7*2.7 + Z29101C7*5.1 + W37C7*0.9 + W38C7*0.9 + W39C7*0.9 + W411C7*0.02 + W412C7*0.02 + W2C7*0.005 + W15C7*0.001 + W152C7*0.006 + Y51*O - 34.5*Y51 >= 0

Constraints for surface, mantaining cropping area

- X1 + X101 + X102 = 0;
X101 + X201 + X301 + X401 - 279.5 = 0;
X101 + X102 - 607.61 = 0;
- X2 + X201 + X202 + X203 + X204 + X205 + X206 + X207 + X208 = 0;
- X3 + X301 + X302 + X303 + X304 + X305 + X306 + X307 + X308 + X309 + X310 + X311 + X312 + X313 + X314 + X315 = 0;
- X4 + X401 + X402 + X403 + X404 + X405 + X406 + X407 + X408 + X409 + X410 + X411 + X412 + X413 + X414 + X415 = 0;
- X5 + X501 + X502 + X503 + X504 + X505 + X506 + X507 + X508 + X509 + X510 + X511 + X512 + X513 + X514 + X515 + X516 = 0;
- X6 + X601 + X602 + X603 + X604 + X605 + X606 + X607 + X608 + X609 + X610 + X611 + X612 + X613 + X614 + X615 + X616 + X617 = 0;
X7 - 30 = 0;
X8 - 2234.7 = 0;
X501 - 206.4 = 0;
X601 - 7406.9 = 0;
X202 + X302 + X402 + X502 + X602 - 211.3 = 0;
X303 + X403 + X503 + X603 - 71.2 = 0;
X304 + X404 + X504 + X604 - 1.1 = 0;
X203 + X305 + X405 + X505 + X605 - 235.2 = 0;
X306 + X406 + X506 + X606 - 56.1 = 0;
X307 + X407 + X507 + X607 - 1.8 = 0;
X204 + X308 + X408 + X508 + X608 - 424.3 = 0;
X309 + X409 + X509 + X609 - 60.9 = 0;
X310 + X410 + X510 + X610 - 4 = 0;
X102 + X205 + X311 + X411 + X511 + X611 - 675.5 = 0;
X206 + X312 + X412 + X512 + X612 - 89.1 = 0;
X207 + X313 + X413 + X513 + X613 - 8.5 = 0;
X208 = 0;
X314 = 0;
X315 = 0;
X414 = 0;
X415 = 0;
X514 = 0;
X515 = 0;
X516 = 0;
X614 = 0;
X615 = 0;
X616 = 0;
X617 = 0;
- X601+ Y6101+ Y6201+ Y6301+ Y6401+ Y6501 = 0;
- X602+ Y6402+ Y6502 = 0;
- X603+ Y6403+ Y6503 = 0;
- X604+ Y6404+ Y6504 = 0;
- X605+ Y6405 = 0;
- X606+ Y6406 = 0;
- X607+ Y6407 = 0;
- X608+ Y6408 = 0;
- X609+ Y6409 = 0;
- X610+ Y6410 = 0;
- X611+ Y6411 = 0;
- X612+ Y6412 = 0;
- X613+ Y6413 = 0;
- Y61+ Y6101 = 0;
- Y62+ Y6201 = 0;
- Y63+ Y6301 = 0;
- Y64+ Y6401+ Y6402+ Y6403+ Y6404+ Y6405+ Y6406+ Y6407+ Y6408+ Y6409+ Y6410+ Y6411+ Y6412+ Y6413 = 0;
- Y65+ Y6501+ Y6502+ Y6503+ Y6504 = 0;
+ Y6101 - 33.22 = 0;
+ Y6201 - 4809.76 = 0;
Y6301 - 9.83 = 0;
Y6401 - 965.96 = 0;
Y6501 - 1588.13 = 0;

Constraints for surface, increasing cropping area

- X1 + X101 + X102 = 0;
+ X101 + X102 - 607.61 = 0;
X101 + X201 + X301 + X401 - 279.5 = 0;
- X2 + X201 + X202 + X203 + X204 + X205 + X206 + X207 + X208 = 0;
- X3 + X301 + X302 + X303 + X304 + X305 + X306 + X307 + X308 + X309 + X310 + X311 + X312 + X313 + X314 + X315 = 0;
- X4 + X401 + X402 + X403 + X404 + X405 + X406 + X407 + X408 + X409 + X410 + X411 + X412 + X413 + X414 + X415 = 0;
- X5 + X501 + X502 + X503 + X504 + X505 + X506 + X507 + X508 + X509 + X510 + X511 + X512 + X513 + X514 + X515 + X516 = 0;
- X6 + X601 + X602 + X603 + X604 + X605 + X606 + X607 + X608 + X609 + X610 + X611 + X612 + X613 + X614 + X615 + X616 + X617 = 0;
X7 - 30 = 0;
X8 - 2234.7 = 0;
X501 - 206.4 = 0;
X601 - 3752 = 0;
X202 + X302 + X402 + X502 + X602 - 211.3 = 0;
X303 + X403 + X503 + X603 - 71.2 = 0;
X304 + X404 + X504 + X604 - 1.1 = 0;
X605 - 1776.2 = 0;
X203 + X305 + X405 + X505 + X606 - 235.2 = 0;
X306 + X406 + X506 + X607 - 56.1 = 0;
X307 + X407 + X507 + X608 - 1.8 = 0;
X508 + X609 - 1057.6 = 0;
X204 + X308 + X408 + X509 + X610 - 424.3 = 0;
X309 + X409 + X510 + X611 - 60.9 = 0;
X310 + X410 + X511 + X612 - 4 = 0;
X311 + X411 + X512 + X613 - 418 = 0;
X102 + X205 + X312 + X412 + X513 + X614 - 675.5 = 0;
X206 + X313 + X413 + X514 + X615 - 89.1 = 0;
X207 + X314 + X414 + X515 + X616 - 8.5 = 0;
X208 + X315 + X415 + X516 + X617 - 403.1 = 0;
- X601+ Y6101+ Y6201+ Y6301+ Y6401+ Y6501 = 0;
- X602+ Y6406+ Y6506 = 0;
- X603+ Y6407+ Y6507 = 0;
- X604+ Y6408+ Y6508 = 0;
- X605+ Y6102+ Y6202+ Y6302+ Y6402+ Y6502 = 0;
- X606+ Y6409 = 0;
- X607+ Y6410 = 0;
- X608+ Y6411 = 0;
- X609+ Y6103+ Y6203+ Y6303+ Y6403+ Y6503 = 0;
- X610+ Y6412 = 0;
- X611+ Y6413 = 0;
- X612+ Y6414 = 0;
- X613+ Y6104+ Y6204+ Y6304+ Y6404+ Y6504 = 0;
- X614+ Y6415 = 0;
- X615+ Y6416 = 0;
- X616+ Y6417 = 0;
- X617+ Y6105+ Y6205+ Y6305+ Y6405+ Y6505 = 0;
- Y61+ Y6101+ Y6102+ Y6103+ Y6104+ Y6105 = 0;
- Y62+ Y6201+ Y6202+ Y6203+ Y6204+ Y6205 = 0;
- Y63+ Y6301+ Y6302+ Y6303+ Y6304+ Y6305 = 0;
- Y64+ Y6401+ Y6402+ Y6403+ Y6404+ Y6405+ Y6406+ Y6407+ Y6408+ Y6409+ Y6410+ Y6411+ Y6412+ Y6413+ Y6414+ Y6415+ Y6416+ Y6417 = 0;
- Y65+ Y6501+ Y6502+ Y6503+ Y6504+ Y6505+ Y6506+ Y6507+ Y6508 = 0;
Y6101 - 128.62 = 0;
Y6201 - 2657.76 = 0;
Y6301 - 1.59 = 0;
Y6401 - 491.26 = 0;
Y6501 - 472.77 = 0;

Y6102 - 92.75 = 0;
Y6202 - 1064.05 = 0;
Y6302 - 36.51 = 0;
Y6402 - 191.56 = 0;
Y6502 - 391.33 = 0;
Y6103 - 5.76 <= 0;
Y6203 - 711.38 <= 0;
Y6303 - 2.44 <= 0;
Y6403 - 158.70 <= 0;
Y6503 - 179.32 <= 0;
Y6104 - 2.47 <= 0;
Y6204 - 211.20 <= 0;
Y6304 - 1.26 <= 0;
Y6404 - 63.10 <= 0;
Y6504 - 139.97 <= 0;
Y6105 - 2.85 <= 0;
Y6205 - 165.31 <= 0;
Y6305 - 0.89 <= 0;
Y6405 - 61.16 <= 0;
Y6505 - 172.89 <= 0;
Y6406 - 182.7 <= 0;
Y6506 - 28.6 <= 0;
Y6407 - 62.8 <= 0;
Y6507 - 8.4 <= 0;
Y6408 - 1.0 <= 0;
Y6508 - 0.1 <= 0;

Constraints for food, scenario current diet

20201*Z11101 - 110*S = 0;
9181*Z12101 - 131*S = 0;
2725*Z21101 + 2709*Z23101 - 74*S = 0;
421*Z22101 + 591*Z24101 - 4.5*S = 0;
244*Z31101 - 12*S = 0;
624*Z32101 - 3.8*S = 0;
6011*Z29101 - 31*S = 0;
6395*Z41101 - 16*S = 0;
1586*W37 + 1586*W38 + 1586*W39 - 32*S = 0;
13*W411 + 13*W412 - 9.1*S = 0;
5.0*W2 + 0.67*W15 - 20*S = 0;
13*(W14+W15) - 10*S = 0;
327*W412 - 178*S = 0;

Constraints for food, scenario healthy diet

20201*Z11101 - 110*S >= 0;
20201*Z11101 - 146*S <= 0;
9181*Z12101 - 132*S >= 0;
9181*Z12101 - 219*S <= 0;
421*Z22101 + 591*Z24101 - 9.6*S >= 0;
244*Z31101 - 7.3*S >= 0;
624*Z32101 - 7.3*S >= 0;
624*Z32101 - 11*S <= 0;
6395*Z41101 - 44*S = 0;
22115*Z11101 + 21017*Z12101 +
37871*Z21101 + 37653*Z23101 +
6424*Z22101 + 9020*Z24101 + 8900*Z31101 +
15675*Z32101 + 14608*Z29101 +
22255*Z41101 + 17465*W37 + 17465*W38 +
17465*W39 + 149*W411 + 149*W412 +
26*W2 + 3.5*W15 + 75*(W14+W15) +
1472*W412 - 3349*S = 0;
20201*55*0.02*Z11101 +
9181*194*0.02*Z12101 +
2724*745*0.02*Z21101 +
2709*745*0.02*Z23101 +
421*630*0.02*Z22101 + 591*634*0.02*Z24101
+ 244*0*0.02*Z31101 + 624*233*0.02*Z32101
+ 6011*124*0.02*Z29101 +
6395*27*0.02*Z41101 + 1586*0*0.02*W37 +
1586*0*0.02*W38 + 1586*0*0.02*W39 +
13*0*0.02*W411 + 13*0*0.02*W412 +
5.0*18*0.02*W2 + 0.67*18*0.02*W15 +
13*7.2*0.02*(W14+W15) +
327*54*0.02*W412 + 33*0*0.02*S -
0.5*S*3349 >= 0;
20201*55*0.02*Z11101 +
9181*194*0.02*Z12101 +
2725*745*0.02*Z21101 +
2709*745*0.02*Z23101 +
421*630*0.02*Z22101 + 591*634*0.02*Z24101
+ 244*0*0.02*Z31101 + 624*233*0.02*Z32101
+ 6011*124*0.02*Z29101 +
6395*27*0.02*Z41101 + 1586*0*0.02*W37 +
1586*0*0.02*W38 + 1586*0*0.02*W39 +
13*0*0.02*W411 + 13*0*0.02*W412 +
5.0*18*0.02*W2 + 0.67*18*0.02*W15 +
13*7.2*0.02*(W14+W15) +
327*54*0.02*W412 + 33*0*0.02*S -
0.55*S*3349 <= 0;
20201*2.1*0.04*Z11101 +
9181*4.3*0.04*Z12101 +
2725*20*0.04*Z21101 + 2709*20*0.04*Z23101
+ 421*60*0.04*Z22101 + 591*11*0.04*Z24101
+ 244*933*0.04*Z31101 +
624*500*0.04*Z32101 + 6011*1*0.04*Z29101
+ 6395*0*0.04*Z41101 + 1586*212*0.04*W37
+ 1586*212*0.04*W38 + 1586*212*0.04*W39
+ 13*234*0.04*W411 + 13*234*0.04*W412 +
5.0*48*0.04*W2 + 0.67*48*0.04*W15 +
13*95*0.04*(W14+W15) + 327*70*0.04*W412
+ 33*2*0.04*S - 0.35*S*3349 <= 0;
1586*212*0.04*W37 + 1586*79*0.04*W38 +
1586*79*0.04*W39 + 13*102*0.04*W411 +
13*102*0.04*W412 + 5.0*43*0.04*W2 +
0.67*43*0.04*W15 + 13*31*0.04*(W14+W15)
+ 327*46*0.04*W412 + 33*4*0.04*S -
0.25*(20201*2.1*0.04*Z11101 +
9181*4.3*0.04*Z12101 +
2725*20*0.04*Z21101 + 2709*20*0.04*Z23101
+ 421*60*0.04*Z22101 + 591*11*0.04*Z24101
+ 244*933*0.04*Z31101 +
624*500*0.04*Z32101 + 6011*1*0.04*Z29101
+ 6395*0*0.04*Z41101 + 1586*212*0.04*W37
+ 1586*212*0.04*W38 + 1586*212*0.04*W39
+ 13*234*0.04*W411 + 13*234*0.04*W412 +
5.0*48*0.04*W2 + 0.67*48*0.04*W15 +
13*95*0.04*(W14+W15) + 327*70*0.04*W412
+ 33*2*0.04*S) <= 0;
20201*13*0.02*Z11101 +
9181*21*0.02*Z12101 + 2725*96*0.02*Z21101
+ 2709*96*0.02*Z23101 +
421*205*0.02*Z22101 + 591*246*0.02*Z24101
+ 244*0*0.02*Z31101 + 624*200*0.02*Z32101
+ 6011*26*0.02*Z29101 +
6395*0.7*0.02*Z41101 + 1586*169*0.02*W37
+ 1586*169*0.02*W38 + 1586*169*0.02*W39
+ 13*166*0.02*W411 + 13*166*0.02*W412 +
5.0*179*0.02*W2 + 0.67*179*0.02*W15 +
13*109*0.02*(W14+W15) +
327*60*0.02*W412 + 33*175*0.02*S -
0.15*S*3349 >= 0;
1586*169*0.02*W37 + 1586*169*0.02*W38 +
1586*169*0.02*W39 + 13*166*0.02*W411 +
13*166*0.02*W412 + 5.0*179*0.02*W2 +
0.67*179*0.02*W15 +
13*109*0.02*(W14+W15) +
327*60*0.02*W412 + 33*175*0.02*S -
0.5*(20201*13*0.02*Z11101 +
9181*21*0.02*Z12101 + 2725*96*0.02*Z21101
+ 2709*96*0.02*Z23101 +
421*205*0.02*Z22101 + 591*246*0.02*Z24101
+ 244*0*0.02*Z31101 + 624*200*0.02*Z32101
+ 6011*26*0.02*Z29101 +
6395*0.7*0.02*Z41101 + 1586*169*0.02*W37
+ 1586*169*0.02*W38 + 1586*169*0.02*W39
+ 13*166*0.02*W411 + 13*166*0.02*W412 +
5.0*179*0.02*W2 + 0.67*179*0.02*W15 +
13*109*0.02*(W14+W15) +
327*60*0.02*W412 + 33*175*0.02*S) <= 0;

Constraints for food, scenario maximizing output

22115*Z11101 + 21017*Z12101 +
37871*Z21101 + 37653*Z23101 +
6424*Z22101 + 9020*Z24101 + 8900*Z31101 +
15675*Z32101 + 14608*Z29101 +
22255*Z41101 + 17465*W37 + 17465*W38 +
17465*W39 + 149*W411 + 149*W412 +
26*W2 + 3.5*W15 + 75*(W14+W15) +
1472*W412 - T = 0;

Other constraints

For all variables: they must be all over 0;

Objective functions

Scenario CD: *max*S

Scenario HD: *max*S

Scenario MO: *max*T

7. References

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