A social-ecological approach to assess the effects of global change on mountain ecosystems: gamification as a strategy to transfer knowledge to society

Anna Zango Palau

A social-ecological approach to assess the effects of global change on mountain ecosystems: gamification as a strategy to transfer knowledge to society

Tesi doctoral

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Agraïments

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Resum

Els sistemes muntanyosos proveeixen recursos essencials que van més enllà dels seus llindars geogràfics, tals com aigua dolça i productes alimentaris. A més, les muntanyes tenen una alta biodiversitat, actuen com a embornals de carboni, i proveeixen serveis intangibles lligats a valors estètics, culturals, i recreacionals. No obstant això, aquestes regions són unes de les més amenaçades pel canvi climàtic, i també es troben exposades a pressions socioeconòmiques. La seva capacitat d'adaptar-se determinarà la preservació dels seus serveis ecosistèmics, així com el benestar dels seus habitants. Així doncs, és essencial que es planifiquin estratègies d'adaptació que assegurin un desenvolupament sostenible d'aquestes regions. Per fer-ho adequadament, cal estudiar les muntanyes emprant aproximacions socioecològiques (SES), que busquen entendre les relacions entre aspectes socioeconòmics i ecològics per fer front a problemes ambientals. Tanmateix, tot i que planificar estratègies per adaptar-se és clau, la conscienciació i la motivació de la població per fer front al canvi climàtic també són aspectes fonamentals del procés d'adaptació. La conscienciació ciutadana envers el canvi climàtic fa que augmenti el suport a polítiques ambientals, facilitant la implementació d'estratègies d'adaptació. Així doncs, experts afegeixen que és clau trobar noves maneres de comunicar ciència i conscienciar sobre el canvi climàtic.

Per tant, aquesta tesi té dos objectius principals. El primer objectiu és estudiar les muntanyes, i especialment els Pirineus, des d'un punt de vista socioecològic. El segon objectiu és desenvolupar una innovadora eina, un *Serious Game* (joc seriós), per transmetre els descobriments de la tesi i conscienciar sobre el canvi climàtic. Per aconseguir el primer objectiu, el Capítol 1 d'aquesta tesi revisa la literatura sobre sistemes socioecològics de muntanya i l'emmarca sota un mateix marc conceptual, a fi d'identificar patrons i buits de coneixements. Els resultats d'aquest capítol mostren que molts dels estudis no combinen informació socioeconòmica i ecològica per analitzar els seus sistemes. La majoria dels treballs inclouen pocs elements socioecològics, i rarament empren dades ambientals quantitatives. A més, sovint ometen els *drivers* socioeconòmics.

Basant-se en els resultats del Capítol 1, els Capítols 2 i 3 miren d'adreçar alguns dels buits de coneixement identificats. Així doncs, el Capítol 2 té l'objectiu de facilitar la inclusió dels *drivers* socioeconòmics en el procés de presa de decisions. En aquest capítol, s'introdueixen unes pautes dissenyades a prevenir la maladaptació, que combinen drivers socioeconòmics i ambientals globals amb

les diverses postures dels locals. Aquestes guies poden ajudar a detectar conflictes entre el que els locals desitgen pel desenvolupament de la regió, i el que s'imposa externament a través de tendències socioeconòmiques. La implementació d'aquestes guies a la regió dels Pirineus mostra que una estratègia *Degrowth* és la que més encaixa amb la població local, mentre que seguir una tendència *Business-As-Usual* aixecaria molt conflicte. El Capítol 3 analitza la mateixa regió dels Pirineus des d'un punt de vista socioecològic utilitzant un ampli rang de variables quantitatives, incloent-hi hidrològiques, d'usos del sòl, climàtiques, ambientals, de biodiversitat i socioeconòmiques. Gràcies a analitzar quantitativament les relacions entre aquests elements, podem descriure i entendre com funciona el sistema. Això permet determinar punts forts i febles del sistema a pressions externes, com el canvi climàtic. Els resultats d'aquest capítol revelen que el sistema depèn molt de fonts externes, majoritàriament turisme, per mantenir un creixement econòmic. Aquest enfocament en turisme, però, afecta negativament els recursos hídrics i a la biodiversitat, situació que es pot veure agreujada pel canvi climàtic. A més, fa que la regió sigui vulnerable a canvis en les tendències macroeconòmiques externes. Una diversificació de l'economia, i particularment potenciar l'agricultura sostenible, ajudaria a prevenir una futura recessió econòmica i la degradació dels ecosistemes de la regió. Finalment, el Capítol 4 descriu el desenvolupament d'un videojoc educatiu fet per comunicar d'una manera amena els descobriments dels Capítols 2 i 3 a un públic no expert. Així doncs, el prototip, anomenat *BALANCE*, mostra com es relacionen les diverses variables socioecològiques dels Pirineus (basat en el Capítol 3), així com possibles escenaris socioeconòmics de desenvolupament i com els interessos dels locals es poden veure afectats per les decisions preses en el joc (basat en el Capítol 2).

En conclusió, els descobriments d'aquesta tesi emfatitzen els avantatges d'utilitzar una aproximació socioecològica per estudiar els sistemes muntanyosos. A més, les eines desenvolupades o emprades en els capítols de la tesi són expressament flexibles i fàcils d'usar, a fi de facilitar la seva aplicació per estudiar altres sistemes socioecològics. Així doncs, les pautes proposades en el Capítol 2 poden servir per detectar i prevenir maladaptació en altres sistemes. D'una manera similar, la metodologia aplicada al Capítol 3 es pot fer servir per analitzar de manera quantitativa altres sistemes socioecològics. Això permetria comparar-los més enllà de descripcions qualitatives. Finalment, el prototip del *Serious Game* descrit en el Capítol 4 ha estat desenvolupat per adaptar-lo fàcilment a representar altres sistemes socioecològics, amb l'objectiu de facilitar la creació de jocs representatius per a diferents grups d'usuaris.

Abstract

Mountain systems provide resources that extend beyond their geographic boundaries, such as freshwater or food products. They are also highly rich in biodiversity, act as carbon sinks, and provide intangible services linked to aesthetics, cultural heritage, and recreational values. These regions are one of the most threatened by climate change, and are also exposed to socioeconomic pressures. Their adaptive capacity will determine the preservation of the ecosystem services they provide, as well as the wellbeing of their inhabitants. It is thus essential to develop sound adaptation strategies to ensure a sustainable development of such systems. To do so, mountains can be studied using social-ecological system (SES) approaches, which aim to understand the interactions between socioeconomic and ecological aspects of environmental challenges. While developing adaptation strategies is key, citizen awareness and engagement are also critical aspects of adaptation. Climate change concern increases citizens' support for environmental policies, contributing to the effective implementation of adaptation strategies. Thus, researchers argue that it is essential to find new ways to communicate science topics and raise awareness about climate change.

In light of this, this thesis has two main objectives. The first objective is to study mountains, and particularly the Pyrenees, from a social-ecological system's perspective. The second objective is to explore the development of an innovative tool, namely a Serious Game, to communicate the findings of this thesis to raise awareness about climate change. To achieve the first objective, Chapter 1 reviews the current mountain SES literature by framing it under the same scope, in order to identify trends and knowledge gaps. Chapter 1 reveals that the majority of the mountain SES literature does not combine socioeconomic and ecological information to study their systems. It shows that most studies include few social-ecological elements, and that quantitative environmental data is seldom used. Additionally, it reveals that socioeconomic drivers are usually overseen.

Based on the findings from Chapter 1, Chapters 2 and 3 attempt to address some of the identified gaps. Chapter 2 aims to facilitate the inclusion of socioeconomic drivers into decision making. It presents a set of guidelines designed to prevent maladaptation by combining socio-economic and environmental drivers with local mindsets. These guidelines can help detect potential sources of conflict between what the locals envision for the regions' development, and what global socioeconomic trends enforce externally. The application of these guidelines to the Pyrenees reveals that *Degrowth* is the socioeconomic trend that better aligns with the locals' interests, while a *Business-As-Usual* path rises great conflict. Chapter 3 analyses the same Pyrenean region from a social-ecological system perspective using a comprehensive set of quantitative variables, including hydrological, land-use, climatic, environmental, biodiversity, and socio-economic elements. By quantitatively analyzing the relationship between these elements, we are able to describe and understand how the system functions. This allows to detect weaknesses and strengths to face external drivers, such as climate change. The results from Chapter 3 reveal that the system heavily relies on external sources, mainly tourism, to maintain economic growth. The focus on tourism has impacts on water resources and biodiversity, which can be aggravated by climate change. Moreover, it makes the region vulnerable to changes in macroeconomic trends. A diversification of the economy, and particularly promoting sustainable agriculture, could help prevent economic recession and environmental degradation in the region. Finally, Chapter 4 explores the development of a Serious Game to communicate the findings of Chapters 2 and 3 in an enjoyable manner to non-expert audiences. Thus, BALANCE, the developed prototype, features how the diverse social-ecological variables of the Pyrenean system are connected (based on Chapter 3), as well as potential socioeconomic pathways for development and how the interests of the inhabitants can be compromised depending on the choices made (based on Chapter 2).

Overall, the findings of this thesis emphasize the advantages of using a social-ecological systems approach to study mountain systems. Moreover, the tools developed or used in the chapters of this thesis are purposely flexible and easy to use, with the aim to facilitate their future application to explore other social-ecological systems. Thus, the guidelines from Chapter 2 can serve to detect and prevent sources of maladaptation elsewhere. Similarly, the methodology applied in Chapter 3 can be employed to quantitatively analyze different social-ecological systems. This enables novel comparisons between SESs beyond qualitative descriptions. Finally, the prototype of the Serious Game described in Chapter 4 has been developed to easily enable the featurization of other social-ecological systems, with the aim to facilitate the development of meaningful games to different audiences.

General introduction

Mountain regions provide multiple tangible and intangible goods to people living both within and outside them (Martín-López *et al.*, 2019). They are often referred to as "water towers" due to their significant contribution to freshwater resources, particularly in arid regions (Viviroli *et al.*, 2007). This water is used for irrigation, industrial and domestic supply, hydropower, ecosystem functioning, and recreational activities, among others (EEA, 2016). The accumulation of snow in winter contributes to the seasonal distribution of water in the form of spring and early summer runoff, reducing flow variability (Viviroli and Weingartner, 2004). Moreover, mountain forests and pastures also contribute to carbon sequestration (Pais *et al.*, 2020; Sil *et al.*, 2017). Mountain regions are also known for their high biodiversity, resulting from unique geological and climatic conditions (Rahbeck *et al.*, 2019b; Antonelli *et al.*, 2018). In Europe, most biodiversity hot-spots are located in mountains (Rahbek *et al.*, 2019a). Additionally, traditional land uses have shaped mountain landscapes, and agricultural and pastoral areas are nowadays highly valued as attractive leisure and tourism destinations (EEA, 2016). Due to the progressive abandonment of agricultural practices in recent decades, tourism has emerged as a significant employment opportunity for locals and has become the main economic sector in many mountain regions (Salukvadze and Backhaus, 2020; Mármol and Vaccaro, 2015; EEA, 2016).

Climate change has impacts on various mountain services and resources. For instance, increasing temperatures pose a threat to many rare endemic species in mountain regions, and shifts in species' elevational ranges have been widely documented across multiple groups (Vitasse *et al.*, 2021; McCain *et al.*, 2021; Rödder *et al.*, 2021). In terms of water, studies show how changes in precipitation patterns due to climate change can affect water resources (Beniston and Stoffel, 2014; Rangecroft *et al.*, 2013; Carvalho-Santos *et al.*, 2017). A study by Viviroli (2020) shows that the dependency on water resources coming from mountain regions is expected to increase in the upcoming decades. It is estimated that approximately 23% of the world's population will depend on runoff from mountains for water consumption. Furthermore, lowland agricultural production will increasingly rely on water from mountain regions. Therefore, a reduction in water resources supplied by mountains will have a massive impact on water availability for human consumption, ecosystem functioning, and agriculture and energy production, both within and outside of mountainous areas. Regions that already struggle to meet their current water demand are predicted to become drier (Camarasa-Belmonte *et al.*, 2020; Zittis *et al.*, 2019). This may be the case of the Mediterranean region, where human populations heavily rely on water resources, particularly during summer months (Grima and Campos, 2020). Coupled with an expected decrease in summer precipitation (Lionello and Scarascia, 2018), Mediterranean regions will become particularly vulnerable to water scarcity during the hot and dry summer months.

Although climate change is a significant driver of current and expected changes in mountain regions, socioeconomic factors are also exerting severe impacts on mountain communities (Adler *et al.*, 2022). Until the twentieth century, most European mountains remained semi-isolated, locally governed regions. However, important changes have occurred since then, as mountain economies have integrated into a globalized market, leading to significant demographic, cultural, and governance changes (Adler *et al.*, 2022; Mitchley *et al.*, 2006; MacDonald *et al.*, 2000). In the Pyrenees, for example, there has been a gradual reduction in the significance of the agricultural sector since the 1950s, with an increased reliance on external sources such as tourists and visitors from lowland areas to sustain the local economy (Jiménez-Olivencia *et al.*, 2021; Offenhenden and Soronellas-Masdeu, 2021). Consequently, while rural areas are being abandoned, there is also a rise in the construction of second homes and tourism-related facilities, a process known as naturbanization (Pallarès-Blanch *et al.*, 2014). Additionally, the development of tourism has attracted newcomers to mountain regions, resulting in cultural changes within mountain societies (Solé *et al.*, 2012, 2014; del Mármol, 2012).

In summary, mountains provide services and resources that extend beyond their geographical boundaries, and these assets are threatened by both climate change and socioeconomic drivers. Ensuring the sustainable development of these regions is crucial for their preservation. Given the diverse natural and human factors involved in mountainous regions, it is imperative that sustainable development policies take both inter- and trans-disciplinary approaches, examining demographic, socioeconomic, and environmental changes (Viviroli, 2020). Scholars have highlighted the importance of examining interconnected human-environment ecosystems beyond solely focusing on the biophysical aspects of adaptation (Berrang-Ford *et al.*, 2015). Rather, holistic approaches are needed. These approaches bridge the gap between social and ecological science research, and integrate the interactions between human and natural components into a unified framework (Ostrom, 2009; Virapongse *et al.*, 2016). Consequently, the use of Social-Ecological Systems (SES) approaches has gained popularity among scholars in recent years (Colding and Barthel, 2019). A 'Social-Ecological System' approach aims to integrate social -including the economic- and ecological aspects when addressing environmental challenges, and it becomes particularly useful to study complex systems.

Examining mountain systems through a SES perspective is useful because these systems involve interconnected human and natural aspects that closely interact and influence one another. Studies that combine information from both the human and natural dimensions are more likely to generate concrete management conclusions compared to those that do not (Rissman and Gillon, 2017). However, despite the increasing efforts to employ SES approaches in studying complex systems (Colding and Barthel, 2019), **studies incorporating both social and ecological data remain a minority** (Herrero-Jáuregui *et al.*, 2018; Rissman and Gillon, 2017). As for mountains, while many scholars have examined mountains from a SES perspective (e.g., Klein *et al.*, 2019b, Carey *et al.*, 2017, see examples in Appendix 1, Supplementary Material B), it is unknown whether these studies consistently integrate information from both the ecological and social dimensions of mountain systems. This is because **no study up to date has reviewed how the study of mountain social-ecological systems has been approached by scholars**. Do researchers employ frameworks to carry out mountain SES studies? Which variables do they tend to include in their studies? Are both the socioeconomic and the ecological dimensions of mountain systems consistently considered? Answering these questions can help gather knowledge from various studies and contribute to drawing conclusions on how to approach sustainable development in mountains. For instance, one may identify which mountain variables researchers considered most important for sustainable development, as well as potentially relevant variables that are frequently overlooked in the literature. Armed with this knowledge, researchers can design their social-ecological mountain system studies to incorporate neglected aspects of mountain development.

Although the approaches taken in mountain SES research are unknown, Vij *et al.* (2021) did analyze how climate change adaptation has been approached in European mountains. Their findings indicate a prevalent emphasis on biophysical and technical aspects of adaptation, often neglecting the social dimension. Similarly, socioeconomic pathways are frequently disregarded in the literature (Vij *et al.*, 2021). Rather than integrating information from both the social and ecological dimensions, the social dimension is commonly overlooked. This oversight can lead to the implementation of adaptation measures that are ill-suited to the local social context (Henstra, 2016; Glaas and Juhola, 2013), particularly when attempting to apply standardized solutions to rural and marginalized areas. This problem often occurs because far-away governing bodies often lack the necessary tools to adequately assess the compatibility of proposed measures with the interests of local communities (Ekstrom and Moser, 2013). Consequently, **maladaptive** policies arise: an adaptation policy that increases the vulnerability for the target group or external actors, impairs their adaptive capacity now or in the future, and hinders sustainable development (Schipper, 2020; Magnan *et al.*, 2016; Juhola *et al.*, 2016). To help prevent maladaptation, scholars emphasize the importance of **developing tools that help contextualize**

the social setting where adaptation measures need to be applied (Magnan *et al.*, 2016; Moser and Erkstrom, 2010). Tools addressing the influence of socioeconomic pathways, which are also frequently overlooked in the literature (Henstra, 2016; Glaas and Juhola, 2013), would be particularly valuable. Ideally, these tools should aid in identifying potential sources of maladaptation *ex-ante*, i.e., before they happen.

Conducting SES studies on mountain regions and building tools to prevent maladaptation will be useful to plan environmental policies for the sustainable development of mountain -and all- regions. For the successful implementation of environmental policies, however, the involvement of the society is also key (Yang *et al.*, 2022; Tjernström and Tietenberg, 2008; Burstein, 2003). Contrary to what might be expected, social engagement does not primarily depend on the amount of scientific evidence supporting climate change urgency (Fesenfeld and Rinscheid 2021). Instead, it is mostly driven by how climate change issues affect citizens both personally and emotionally (Brosch, 2021; Clayton *et al.*, 2015). Until recently, the prevailing belief was that low public engagement with climate change was due to a lack of information on the topic (Suldovsky, 2017). As a result, science communication tended to rely on a one-way flow of information from scientists to the public (Moser, 2010). This premise, however, dismisses important engagement barriers linked to emotions, attitudes, and beliefs (Suldovsky, 2017; Lewandowsky, 2021). Studies indicate that one of the emotional obstacles to climate change engagement is the perception of climate change as a distant and non-local threat (Tvinnereim *et al.*, 2020; Arikan and Günay, 2021; Van der Linden *et al.*, 2015). Furthermore, individuals living in rural and suburban areas, as well as those with limited purchasing power, tend to be less supportive of environmental policies (Arikan and Günay, 2021; Arndt, 2023). Thus, building free communication tools addressing the consequences of climate change at a local scale would help to overcome some of the current limitations of climate change communication.

A promising approach to address climate change engagement is through the use of Serious Games (Wu and Lee, 2015). By combining gamification techniques and learning strategies, Serious Games immerse users in the learning process while conveying target information (Abt, 1970). These tools can be designed to effectively address the behavioral and emotional components of science engagement (Connolly *et al.*, 2012; Ullah *et al.*, 2022). They excel in making education fun and engaging, which facilitates knowledge acquisition and retention (Riopel *et al.*, 2020). Often, Serious Games take the form of video games that can be played on computers, mobile phones, or consoles. Thus, they are particularly useful for educating young users, who may not learn effectively through conventional methods, but are eager to engage with technology in their daily lives. Numerous scholars have highlighted the effectiveness of Serious Games for science communication (Zhonggen, 2019; Riopel *et al.*, 2020; Clark *et al.*, 2016; Wouters *et al.*, 2013; Sitzmann, 2011), especially when purposefully designed to meet the educational needs of specific target groups (Riopel *et al.*, 2020; Ouariachi, 2019, 2017). Therefore, **building a Serious Game to illustrate how climate change can impact a local social-ecological system in a mountain area** would be useful to raise awareness among younger generations.

The objective of this thesis is twofold: firstly, to examine mountain regions, particularly the Pyrenees, from a social-ecological system perspective; and secondly, to develop a prototype of a Serious Game that can effectively communicate the scientific findings of the first part of the thesis to non-expert audiences. To address the key gaps identified earlier, the thesis consists of four chapters, each focusing on a specific issue. **Chapter 1** investigates the various approaches that scholars have taken in studying mountain SES thus far (Figure 1). To this end, this analysis identifies the frameworks, types of data, and sectors commonly considered by researchers. Additionally, it explores the variables that researchers have included in their studies. Through this analysis, we can determine the variables deemed most important by researchers, as well as identify potential gaps and unaddressed aspects in the literature. In light of the findings, the subsequent chapters aim to address some of the gaps outlined in Chapter one (Figure 1). In **Chapter 2**, our focus is on developing a set of guidelines that examine how different socioeconomic pathways can potentially conflict with the interests of local communities. These guidelines are then applied to a Pyrenean SES to provide context to the socioeconomic setting and identify potential sources of maladaptation. Moving on to **Chapter 3**, we delve into a comprehensive analysis of the social and ecological components of this same Pyrenean system. Our analysis includes 35 SES variables, encompassing aspects such as water, biodiversity, environment, climate, and socioeconomic factors. By examining the relationships between these social-ecological variables, we gain a deeper understanding of how the system in question may be influenced by both climate and socioeconomic changes. Notably, we adopt a quantitative approach to measure the magnitude of direct and indirect effects between these elements, an approach that is seldom utilized (Herrero-Jáuregui *et al.*, 2018). Lastly, in **Chapter 4**, we present the development of a prototype Serious Game that illustrates the findings from Chapters 2 and 3 (Figure 1). To this end, the game features: a) The diverse social-ecological variables and their interactions, as elucidated in Chapter 3, and b) the potential socioeconomic pathways for development, as well as the interests and goals of the local population, as uncovered in Chapter 2. The main goal of the Serious Game is thus to educate users about potential adaptation strategies in the face of global change in the Pyrenees.

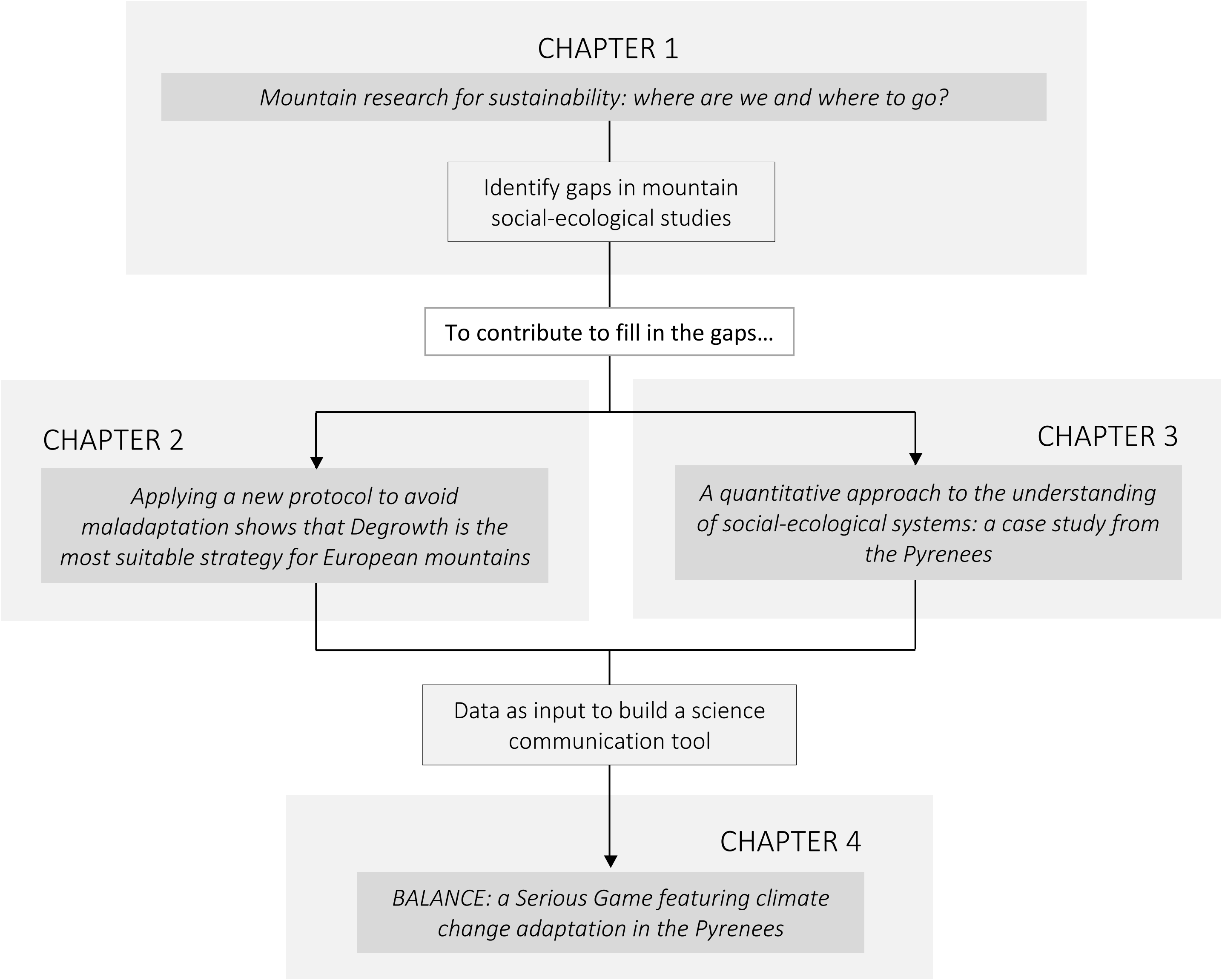

Figure 1. Outline of the steps followed during the thesis framed according to the thesis chapters. The title of each chapter is written in italics.

Ostrom’s Social-Ecological Systems framework

Several frameworks have been developed to study the interconnectedness of human and natural systems within a social-ecological (SES) perspective. Colding and Barthel (2019) identified three influential frameworks in the literature: the original framework by Berkes and Folke (2000), the multitier framework by Ostrom (2007, 2009), and the robust framework by Anderies *et al.* (2004) (*sensu* Colding and Barthel, 2019). The original framework primarily takes a descriptive approach to understanding social-ecological systems, while the multitier framework and robust framework are valuable for modeling and diagnosing these systems. Anderies' framework focuses on analyzing the resilience of social-ecological systems and provides guidance on how to study their complex dynamics. Ostrom's multitier framework, on the other hand, offers a comprehensive set of elements that are potentially relevant to the study of any social-ecological system. Briefly, Ostrom classifies the components of any social-ecological system into Resource System, Resource Units, Actors, and Governance System (Figure 2). Elements within these categories interact with each other to shape the outcomes of the system, and are also influenced by both external ecological and socioeconomic drivers (Figure 2). Later on, Epstein *et al.* (2013) and Vogt *et al.* (2015) noted the framework lacked an explicit contextualization of the ecological setting, and suggested the inclusion of another tier, namely the Ecological Rules tier.

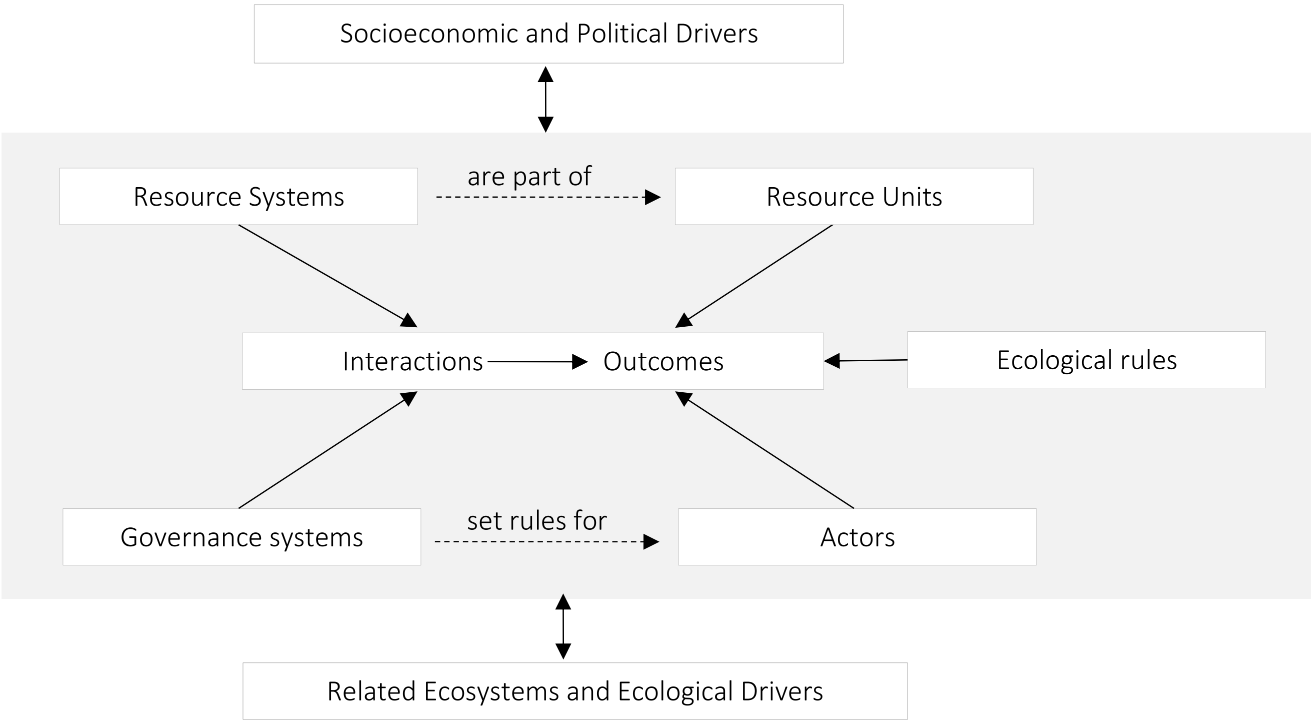

Figure 2. Structure of the first-tier elements and drivers of a social-ecological system, according to Ostrom’s framework. Modified from Ostrom (2007), Epstein *et al.* (2013) and Vogt *et al.* (2015).

Ostrom provides an extensive list of elements and attributes within each first-tier category (the complete list of second-tier elements can be found in Appendix 1, Supplementary material A). She derived this list through empirical analysis of various social-ecological systems, identifying the elements and attributes that influenced interactions among components and led to specific outcomes (Ostrom, 2007). Ostrom's framework builds upon existing knowledge of social-ecological systems, providing a common foundation for scholars from different disciplines to work with. Its characteristics make it a valuable tool for searching, organizing, and structuring information. Ostrom’s framework was used to address several of the aforementioned goals of this thesis. Its shared language and well-organized structure provided a convenient way to organize the mountain SES literature under the same scope allowing for comparisons between studies (**Chapter 1**). Furthermore, the comprehensive list of potentially relevant elements ensured that no important element was overlooked when contextualizing (**Chapter 2**) or describing (**Chapter 3**) the Pyrenean social-ecological system.

Chapter 1

Mountain research for sustainability: where are we and where to go?

Zango-Palau, A., Claramunt-López, B

Chapter 1. Mountain research for sustainability: where are we and where to go?

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Keywords

Social-ecological systems; Mountain sustainability; Global change; Trans-disciplinary research; Resource management

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Abstract

Despite mountains have socio-economic and environmental capital of significance for the entire world, natural and human communities are threatened by the climatic and socio-economic changes these regions are facing. As mountains are systems in which the human and nature dimensions are tightly interconnected, studying them as social-ecological systems (SES) has become relatively common. However, there seems to be no consensus on how to approach the study of mountain SES, and without a common structure to organize the literature, knowledge from different studies is likely to remain isolated. In here, we use Ostrom's SES framework to review the mountain SES literature under a common scope, aiming at unraveling which frameworks, approaches, domains, sectors, and SES-attributes are studied by researchers. Among the 172 reviewed works, only 25% of them employed a framework to study their system, and *ad-hoc* unique frameworks were preferred over existing ones. Despite the majority of research articles were in the domain of environmental sciences, socio-economic attributes were included more often than ecological ones, and less than half of the works included both social and ecological elements. Moreover, albeit most works had an empirical approach, field data was seldomly used. Future works should focus on collecting social and ecological data at comparable scales, as well as on developing tools to effectively integrate both dimensions in mountain SES studies. Finally, by collecting the elements considered most important by scholars, we give recommendations as to which elements to include in future studies addressing the sustainability of mountain SES.

1.1 Introduction

Mountain areas are found on every continent. They occupy approximately 25% of the world's territory and are home of ca. 25% of the population globally. Mountains have social, economic, and environmental capital of significance for the entire world, since they harbor rich natural and sociocultural diversity, and provide essential ecosystem services to up to half of the world's population (FAO, 2011; UNEP *et al.*, 2020). Mountains also provide water for about 22% of the world's population (Immerzeel *et al.*, 2019), and supply a substantial part of both natural and anthropogenic water demands (Viviroli *et al.*, 2007; Immerzeel *et al.*, 2010). Despite their geographical diversity, mountains also disproportionately contribute to the terrestrial biodiversity on Earth (Rahbek *et al.*, 2019a), hosting a diverse range of species, including many endemic, rare and threatened ones. Mountains partly or totally host approximately 30% of the total land area identified as terrestrial Key Biodiversity Areas (KBAs), and about 16.9% of the extent of the world's terrestrial protected areas network outside Antarctica is within mountains (Rodríguez-Rodríguez *et al.*, 2011). As global temperatures get higher, mountainous environments are transforming rapidly. Nearly 60% of mountainous area is under intense human pressure, predominantly at low elevations and mountain bases (Elsen *et al.*, 2020). Mountain glaciers across much of the world are retreating (Dussaillant *et al.*, 2019; Brun *et al.*, 2017), impacting the water supply for up to 1.9 billion people (Immerzeel *et al.*, 2019). These dramatic changes are expected to affect mountain hazards, such as the frequency and magnitude of flooding and landslide events (IPCC, 2019). The steep terrain in combination with extreme climatic conditions, and in some regions seismic or volcanic activity, frequently triggers landslides, rock fall, debris flows, avalanches, glacier hazards and floods (Kargel *et al.*, 2016; Kirschbaum *et al.*, 2019). Since 2000, over 200,000 people have died in water tower units (*sensu* Immerzeel *et al.*, 2019) as a result of disasters (Guha-Sapir *et al.*, 2019). Numerous people living in mountains worldwide face multiple challenges in securing sustainable livelihoods. Poverty incidence in mountain areas is high, and close to 40% of the 835 million mountain people in developing countries are considered vulnerable to food insecurity (FAO, 2015). Climate change, in combination with population growth, urbanization and economic and infrastructural developments, is likely to exacerbate the impact of natural hazards and further increase the vulnerability of these regions (Huss *et al.*, 2017; Mal 2018; Mann *et al.*, 2017; Fischer and Knutti 2015; Haeberli *et al.*, 2017). Climate change is also leading to widespread elevational shifts thought to increase species extinction risk in mountains (Elsen *et al.*, 2020). Thus, all these stressors and processes threaten the sustainability of both the natural and human communities of mountain regions, and trans-disciplinary efforts among stakeholders, policy makers, and researchers of multiple disciplines are needed to address these challenges (Grumbine and Xu, 2021; Klein, 2019a; Carey *et al.*, 2017).

Research in mountain areas has been approached in different ways. Projects may not take into account or even mention that they have been carried out in mountain areas, e.g., works that are focused on single elements, or when the «mountain» fact may not be relevant (e.g., Blumstein *et al.*, 2005). Other projects consider that whichever the element under study, it is important to include the «mountain element» because of some of mountains specific characteristics (e.g. Martínez *et al.*, 2012 López *et al.*, 2009, Barrio *et al.*, 2013). In this case, the authors may consider factors that are characteristic of mountains (e.g., slope or elevation in the case of natural communities – e.g., Richman *et al.*, 2020 -, or isolation in the case of human populations – e.g., Urban 2020 -). Finally, other projects not only take into account some «mountain factors», but also acknowledge that mountain regions can be considered «small-worlds» that share more characteristics within them than with the lowland areas that surround them, and so mountains are systems in which the various dimensions (social, environmental, and economic) are tightly interconnected (all papers listed in Appendix 1, Supplementary material B). With this in mind, considering mountains as social-ecological systems has become relatively common during the last years (Klein *et al.*, 2019b; Carey *et al.*, 2017; see examples in Appendix 1, Supplementary material B).

The Social–ecological systems' (SES) concept is a way of integrating human-environmental interactions, connecting components of both through complex system feedbacks and dependencies (Berkes *et al.*, 2003). Recent works have shown that such complex problems cannot be analyzed only with disciplinary approaches, but they have to be dealt with an integrative and trans-disciplinary way that considers the interaction between social -including the economic- and ecological systems (Newell *et al.*, 2005; Folke, 2006; Ostrom, 2007, 2009). Thus, the development of a holistic approach to identify and mitigate environmental challenges, which takes into account local and global, environmental and social contexts, was essential for advancing in the understanding on how the various elements interact in a given territory, especially because biophysical models and environmental research alone may not be enough to inform managers to take decisions to ensure the sustainability of a system (Berkes, *et al.*, 1998, 2003). A SES approach accurately reflects the chaotic real world in which human and ecological systems reciprocally interact (Folke, 2006; Alessa *et al.*, 2015), and, at least theoretically, facilitates environmental management through the application of inter- and/or trans-disciplinary concepts.

Various approaches that include both the social and the ecological systems have already been developed and applied (Young *et al.*, 2006; Binder 2007, 2013; Liu *et al.*, 2007; Herrero-Jáuregui *et al.*, 2018; Colding and Barthel, 2019). However, there seems to be no consensus in how to approach the study of SES, and scholars use different frameworks, work at different scales, and apply different methodologies to study their social-ecological systems (Herrero-Jáuregui *et al.*, 2018; Colding and Barthel, 2019). A preliminary literature review by the authors showed that this seems to be the case for studies on mountain social-ecological systems as well. Few works describing their mountain systems as SES had indeed used any framework to study them, either by applying an existing one (e.g., Al-Kalbani *et al.*, 2016, Morán-Ordóñez *et al.*, 2013) or by developing a new one (e.g., Capitani *et al.*, 2019, Perez-León *et al.*, 2020). Although this probably reflects the specificity of each case-study, the lack of a common language and organization hinders the comparison between different works (Poteete and Ostrom, 2008; Ostrom, 2007, 2009). Without a common structure to organize the literature, the knowledge from different studies remains isolated and does not accumulate (Ostrom, 2009), making it difficult to find variables relevant to the sustainability of a given social ecological system (Ostrom, 2007). The need to have a common language to structure the research has given birth to frameworks, all with different goals and objectives, but all trying to formalize a valid and standardized approach of the study of systems (Colding and Barthel, 2019). Among the different frameworks developed by researchers, one of the most extensively used ones is Ostrom's multi-tier social-ecological system's framework (*sensu* Colding and Barthel, 2019). The social-ecological system's framework (SESF) proposed by Ostrom (2007, 2009) and then complemented by others (Epstein *et al.*, 2013; McGinnis and Ostrom, 2014; Vogt *et al.*, 2015) is arguably the most comprehensive conceptual framework for diagnosing elements, interactions, and outcomes in social-ecological systems (Partelow, 2018). It provides a common language for organizing the many variables relevant in the analysis of SES into a multi-tier hierarchy that can be unfolded when needed. The SESF is now viewed both as a theoretical framework to advance collective action theory, and as a general tool to diagnose the sustainability of social-ecological systems (Partelow 2018), and it has already been used in some mountain-focused projects (e.g., Accastello *et al.*, 2019, Filbee-Dexter *et al.*, 2018, Haider *et al.*, 2020, Nigmann *et al.*, 2018). Although originally conceived as an analytical tool to study the sustainability of social-ecological systems, the SESF has also been used to characterize systems due to its comprehensive and flexible list of potential SES-elements, its ability to work at multiple scales, and its capacity to include qualitative and quantitative data (Delgado-Serrano and Ramos, 2015). These characteristics also make Ostrom's social ecological framework a useful tool to frame the mountain SES literature under a common scope.

In this work, we aim at finding patterns and trends in mountain SES. Specifically, we want to unravel which, if any, SES framework is used, which scale and approach (empiric or conceptual) is taken, which domains and sectors do researchers study, and which SES elements researchers include in their works. To classify the SES elements included in the works of researchers using different frameworks and approaches, we use the systematic and comprehensive classification of SES elements provided by Ostrom (2007, 2009). Integrating the literature under Ostrom's SES framework enables us to see patterns in the inclusion (and omission) of SES elements in mountain SES studies, letting us see what researchers deem as most important, as well as to discover potential gaps. We specifically aim at answering these questions: is there a bias in the inclusion of socio-economic versus ecological attributes? Which elements do researchers consider most important when studying mountains under a social-ecological system's perspective? Which SES elements are frequently studied together? Are there asymmetries in the literature, e.g., are there any specific SES elements which are underrepresented?

Our results will be helpful to shade light into how researchers have approached the study of mountain systems under a SES perspective so far, regarding their frameworks, approach, scale, domains, sectors, and studied SES elements. Moreover, by bringing together the work of the researchers investigating mountain social-ecological systems across scales, frameworks, and approaches, we provide some guidance as to which SES elements to include in future studies. We recommend a minimum set of SES-elements that projects addressing the sustainable management of mountain resources should include, as well as suggest sets of elements per sectors. Finally, by exposing asymmetries in the literature, we identify potential gaps of knowledge and give recommendations for future lines of research.

1.2 Methods

A bibliographic search was carried out in the ISI Web of Science database using the following syntax: «*mountain* AND ((social-ecological OR socio-ecological) AND system**». We obtained a total of 317 references that were analyzed in order to detect which were the studied resource units or resource systems, and the addressed attributes or elements. Papers mentioned in the reference list of the analyzed documents were eventually added to our database if there were clues that they referred mountains as social-ecological systems. The following data were collected for each document: authors, region, SES framework used (if any) and sector under study. Following Herrero-Jáuregui *et al.*, (2018) we also noted the approach (Empirical or Conceptual), the biophysical scale (Field, Landscape, or Remote) and the domain (Environmental, Biological, Social and Agriculture). Then, we investigated which SES elements were addressed in each study. To classify these elements, we followed the taxonomy provided by Ostrom's framework (2007, 2009). The social-ecological framework (SESF) is structured into tiers of nested and related concepts and variables. The first tiers include the Resource System (RS), Resource Units (RU), Governance System (GS), Actors (A), Social, Economic and Political Settings (S), Interactions (I), External Ecosystems (ECO), and Outcomes (O). Second-tier variables are nested within each first-tier variable. Epstein *et al.* (2013) suggested adding Ecological Rules (ER) to the list of first-tiers. First-tier and, when it was clear, second-tier attributes (Appendix 1, Supplementary material A) were assigned to all SES elements included in the studies. We decided not to include neither the SESF Interactions nor the Outcomes because they represent another category of attributes, are part of the description of the SES itself, and include elements that have already been included in the RS, RU, A, GS, CLIM, ECO and/or the ER. As expected, papers that did not use Ostrom's SES framework did not use its vocabulary or taxonomy. In this case, we tried to match as best as possible each paper's vocabulary to Ostrom's attributes. For example, when papers mentioned «*...We conducted a series of interviews-questionnaires with the local population, which enabled us to define their profile and to evaluate their perception of the landscape,...*» (Rescia *et al.*, 2008), the attribute A7 «Knowledge of SES/Mental models» was assigned to this paper. In no case we could not assign an Ostrom attribute to the object of study. Some researchers have raised awareness about the ambiguity in the interpretation of the SESF attributes (Delgado-Serrano and Ramos, 2015, Partelow, 2018). Thus, in order to minimize variation in the interpretation of Ostrom's attributes or the attributes from reviewed texts, the classification of SES attributes was carried out by the same person (Claramunt-López, the corresponding author). Papers were rejected because of one or more of the following reasons: the study was not carried out in mountains; papers were purely theoretical; and/or papers were not based on a sector (RS or RU), accepting at most «Ecosystem services» as a Sector (RS1).

With this information for each reviewed study, we investigated: number of countries/regions covered by the studies; number of papers using a framework and not doing so; number of papers using each framework (including ad-hoc unique frameworks as a category); and number of papers per approach, scale, domain, and sector. Then, following Ostrom's attribute classification, we investigated: number of attributes addressed per paper; number of attributes addressed per framework; number of papers addressing only socio-ecological attributes (GS, A, S), only ecological attributes (RS, RU, ECO, ER), and both, globally and separating by works using a framework and not using one; number and type of attributes per sector; number of papers addressing each attribute; and relationships between attributes. Two data sets were created, one with all the data, and another one selecting only the attributes that were used a number of times above the median value, in order to determine which of them were mostly addressed by the scientific community. We then created a list of attributes including the least addressed ones (below the median) and the ones that were not addressed in any of the analyzed papers. To investigate which SES elements are frequently studied together, we looked at the relationship between attributes. We built a matrix of interactions in which the cells included the number of times that each combination of attributes was found in the revised manuscripts. Several interaction networks were built: one which included all found attributes, another one in which we only included those interactions that had been addressed in 3 or more papers, and individual networks centered on these most linked attributes. For this, we used the R packages ggnet2 (Butts, 2020), network (Butts, 2020) and sna (Carter and Butts, 2020).

1.3 Results

Our final database included a total of 172 papers (Appendix 1, Supplementary material B) from 44 different countries and other trans-national regions (Himalaya, Asia, Eastern Africa, Europe, Fennoscandia, Pamir mountains, Southern Africa, and the world). Only a quarter of them (44, 25.6%) used one or more existing frameworks, whereas the rest mentioned SES in the text, but did not mention using any existing working framework. Among the ones that used a framework, fifteen different frameworks were mentioned, including *ad-hoc* unique frameworks as a category, which were actually the most used ones (31.8%), followed by the Resilience framework (13.6%) and Ostrom's SES framework (11.4%) (Figure 1; Table C1, Appendix 1, Supplementary material C).

1.3.1 Approach and Scales

The majority of the reviewed references had an empirical (67%) approach rather than conceptual (33%), and also most of them were taking a biophysical scale at the landscape level (80%), followed by field (14%) and remote (i.e. using remote sensing data, 6%) scale levels.

1.3.2 Domains and Sectors

Domains. In global, 53% of the papers were classified in the environmental domain, 29% in the social domain, 17% in the agriculture domain (including pastoralism), and only 2% in the biological domain.

Sectors (SESF Resource Systems and Resource Units) and attributes per sector. Analyzed papers evenly addressed the various sectors, with percentages that range between 11% and 18% in all cases except «Agro-pastoralism» (4%). Most studied sectors were «Biodiversity», «Ecosystem Services», «Water», «Agriculture», «Landscape», «Forest», and «Livestock» (Figure 2, top left). In general, all elements (ECO, S, ER, RS, RU, GS and A) appear for all these sectors, with a clear dominance of Actors and Governance Systems, and with the Social and Economic Drivers (S) only appearing when the sector is «Biodiversity» and «Livestock» (Figure 3). «Biodiversity» was the most linked RS/RU to other attributes (25), whereas «Forest» (15) and «Agriculture» (13) were the least ones. Works focused on «Biodiversity» mostly included the population mental frameworks (A7), climatic patterns (ECO1), equilibrium properties (RS6), and rule-making organizations (GS5) (Appendix 1, Supplementary material C, Figure C1). When addressing «Water» (Appendix 1, Supplementary material C, Figure C2) and «Ecosystem Services» (Appendix 1, Supplementary material C, Figure C3), prioritized attributes were the population mental frameworks (A7), climatic patterns (ECO1), and rule-making organizations (GS5). In the case of «Water», equilibrium properties (RS6) was also among the most addressed attributes. «Livestock» was mostly related to climate (ECO1), the population mental frameworks (A7), living population (GS3), equilibrium properties (RS6), and economic value (RU4) (Appendix 1, Supplementary material C, Figure C4). Finally, «Agriculture» (Appendix 1, Supplementary material C, Figure C5), «Landscape» (Appendix 1, Supplementary material C, Figure C6) and «Forest» (Appendix 1, Supplementary material C, Figure C7) included the population mental frameworks (A7), but «Landscape» only included equilibrium properties (RS6), «Forest» also included climatic patterns (ECO1), and «Agriculture» mostly included rule-making organizations (GS5) and economic value (RU4).

The list of the least addressed sectors (RS/RU) included some that are very close to the list of the most addressed, such as «Agroforestry» or «Farming», some that could have been included as an Interaction («Grazing»), and others that specifically addressed «sectors» that we preferred not to group with others («SDG», «Grassland», «Forest-pasture», and «River»). Except for «SDG», the rest are clearly linked to the list of the most addressed sectors, and pooling them does not add much more information than the one we can extract from the most addressed ones (not shown).

1.3.3 SES elements addressed: Ostrom's attributes

Number of attributes per paper. The number of attributes addressed in single papers ranged between only 1 and a maximum of 7 (Figure 4), with an average value of 2.5 attributes per paper, and without notable differences among sectors (Appendix 1, Supplementary material C, Figure C8) and no evidence that the more papers addressing a sector, the more attributes when pooling by sector. The average number of attributes also did not vary much between studies using a framework (2.7 attributes per study) and not using one (2.5 attributes per study) (Appendix 1, Supplementary material C, Table C1). Among the frameworks used in at least more than one study, the one that included more attributes per study was Ostrom's SESF (3.6 attributes per study), followed by Q-methodology (2.3 attributes per study) (Appendix 1, Supplementary material C, Table C1). Almost half of the works included both social and ecological elements together in their studies (83, 48%), followed by works addressing socio-economic elements exclusively (67, 38.7%), while studies addressing only ecological variables were a clear minority (23, 13.3%) (Appendix 1, Supplementary material C, Table C2). The inclusion of social and ecological variables did not vary between works employing a framework and works not using one (Appendix 1, Supplementary material C, Table C2).

Ecological Drivers attributes. Ecological drivers were included in 19.7% of the analyzed works (34 out of the 172 papers). ECO1 (Climatic patterns) was used in most cases, and ECO3 (Flows into and out of the local SES) appeared in the list of the least addressed attributes (Figure 2).

Social Economic Drivers attributes. Global social/economic drivers are the least taken into account in our database, and were included in only 12 papers (7%). Within these 12 papers, 60% addressed S5 (Markets) and 40% S1 (Economic development). Finally, only one Social and Economic Driver (S2 Demographic trends) appeared in the list of the least addressed ones (Figure 2).

Ecological Rules attributes. The attributes of the Ecological Rules were included in 18 papers (10.5%). 60% of these papers included ER1 (Physical rules) and 40% included ER3 (Biological rules) (Figure 2). Physical rules were mostly related to erosion and or run-off events, and biological rules were most related to livestock or pest management. The least addressed ER was ER2 (Chemical rules).

Resource System attributes. RS attributes were included in 41% (71 out of 172) of the analyzed references. Among them, RS6 (Equilibrium properties) was the most included (43%), indicating that many works refer to any of the disturbance attributes that may affect the RS under study (frequency of the disturbances, intensity, magnitude, etc.) (Figure 2). This is reinforced by the fact that RS10 (Ecosystem history) was the second most used RS attribute (26% of the cases); RS10 was assigned to studies that included land use change, natural disaster history, and or human use and disturbance history. With lower percentages, studies included RS3 (Size of the resource system, 13%), RS9 (Location, 10%), and RS5 (Productivity of the system, 9%). The least addressed RS attributes were RS4 (Human constructed facilities), RS7 (Predictability of the system dynamics) and RS8 (Storage characteristics).

Resource Units attributes. Resource Units and their attributes are not much referred to in our review. Only 30 (17%) mention RU attributes, probably indicating that, even though RS are formed by RU, researchers prioritized working at the RS level. Among them, a vast majority (68%) include RU4 (Economic value); and RU1 (RU Mobility) and RU7 (Spatial or Temporal distribution) are taken into account in 16% of the works. Only RU5 (Number of units) appeared in the list of the least addressed RU's (Figure 2).

Governance System attributes. Governance System's attributes were taken into account in half (51%) of the 172 analyzed papers. Among them, GS5 (Rule-making organizations) was included in 40% of the cases. GS5 includes all works in which community-based organizations, public and private sectors, and/or NGOs participate in order to manage the RS/RU (Figure 2). GS9 (Network structure) was also included in 19% of the cases, showing a relative importance of how the various governance institutions were related and how hierarchies among them could play a role. Finally, GS2 (Geographic scale of the governance system, 15%), GS3 (Population, 14%), and GS6 (Rules-in-use, 13%) represent the three other attributes that were included when governance was considered relevant in the analyzed papers. Various GS attributes appeared as least addressed: GS1 (Policy area), GS4 (Regime type), GS7 (Property-rights system), and GS8 (Repertoire of norms and strategies).

Actor attributes. These were the most addressed attributes, as over half of the works reviewed (54%) included one or more Actor attributes. Most of them (62%) gave much importance to the perceptions that actors had on the RS or the RU and how they could be related to their environment *sensu lato* (A7, Knowledge of SES/Mental models) (Figure 2). In most cases, this was carried out through *in-person* or virtual surveys. 17% of them referred to A3 (History of past experiences), which included works where, for example, land abandonment by the actors was taken into account. Both A1 (Number of relevant actors) and A2 (Socioeconomic attributes) were included in 11% of the studies. On the other hand, A8 (Importance of the resource - dependence) and A9 (Technologies available) were the two least studied Actor attributes.

Non-addressed attributes. Non addressed attributes were RS2 (Clarity of the system boundaries), RU2 (Growth or replacement rate of the RU), RU3 (Interaction among RU), RU6 (Distinctive characteristics), A4 (Location), A5 (Leadership/entrepreneurship), A6 (Norms/Social capital).

1.3.4 Relationships between attributes

The global representation of links between the SES elements shows a complex net of interactions – understood as elements or attributes studied together (Figure 5). Among the addressed attributes, thirteen were the ones that appeared linked more frequently (i.e., in 3 or more papers) than the rest: A3, A7, ECO1, GS2, GS3, GS5, GS6, GS9, RS3, RS6, RS10, RU4, and S5 (Figure 6). Four of them (S5, RS3, A3, and GS3) are linked with only one other attribute, and the rest of them present links with 3 (RU4 and RS10), 4 (ECO1, GS2, GS6 and GS9), 5 (RS6), 8 (GS5), or 9 (A7) attributes.

The most frequently linked Resource Systems attributes (RS3 -size of the RS-, RS6 -equilibrium properties-, and RS10 -Ecosystem history-) preferentially included A7 (Knowledge of SES/mental models) and ECO1 (Climatic patterns). Four out of the 5 most linked Governance Systems attributes (GS2 «geographic scale of the GS», GS3 «population», GS5 «rule-making organizations», GS6 «rules-in-use» and GS9 «network structure») were linked to A7 (Knowledge of SES/mental models) and to another GS attribute, GS5 (Rule-making organizations). There are two Actor attributes in the list of the most linked ones, A7 « Knowledge of SES/mental models» and A3 «History of past experiences», and both are linked to ECO1 (Climatic patterns) and RS6 (Equilibrium properties). Finally, it is also worth mentioning the link between RU4 «Economic value» and S5 «Markets», and the link between RU4 and the size (RS3) and ecosystem history (RS10) of the RS, and with GS5 «Rule-making organizations» (Appendix 1, Supplementary Material C, Figure C9).

1.4 Discussion

Our results show that scholars studying mountain social-ecological systems usually do not employ a framework to do so. This may indicate that some researchers are not still aware of existing SES frameworks, or that researchers are not prone to use one, even when they are as flexible and interdisciplinary as Ostrom's. As many of the reviewed works using a framework highlighted the specificity of their case study and applied *ad-hoc* unique frameworks, it may also indicate that some researchers are reluctant to apply a general one-for-all framework. Despite it has been argued that not using a framework to study a social-ecological system can cause to unintentionally miss relevant system attributes (Colding and Barthel, 2019; Ostrom, 2007, 2009), we were unable to find differences between the number of attributes addressed when employing a framework and when not using one. Similarly, studies applying a framework were equally likely to combine social and ecological variables in their studies than those not employing one. Although we cannot evaluate if relevant elements were missed in a given study, our results seem to indicate that the use of a framework *per se* does not contribute to the inclusion of both social and ecological elements together in a study, nor does it help to include a larger number of variables in mountain SES studies. It is possible that we did not find differences between studies using and not using a framework because frameworks themselves, all with their different set-ups and goals (Herrero-Jáuregui *et al.*, 2018; Colding and Barthel, 2019), vary with one another in the inclusion of SES elements. Ostrom's framework, which facilitates a comprehensive list of potentially relevant SES elements, may contribute to the consideration and thus inclusion of attributes in SES studies. However, even though in our review it may seem that works employing Ostrom's SES framework tend to address more attributes than studies using other frameworks or none, the limited number of works applying each framework did not allow us to further investigate differences between them. As the body of works applying frameworks to study mountain SES grows, future studies will be able to answer if the number or type of attributes addressed varies with the framework, and show whether there are biases in the inclusion/omission of attributes stemming from the framework used, or not.

Somehow surprisingly because of the holistic perspective of a SES approach, most of the reviewed manuscripts stating and studying mountains as SESs addressed few elements (between 1 and 7). More, of those included, there was a bias towards the inclusion of socio-economic elements over ecological ones, as previously reported (Refulio-Coronado, 2021; Herrero-Jáuregui *et al.*, 2018). In fact, less than half of the works included both social and ecological elements together in their studies. Given that SES approaches were conceived as a way to integrate social-ecological interactions into the same analysis (Newell *et al.*, 2005; Folke, 2006; Ostrom, 2007, 2009), a failure to include elements from both dimensions seems contradictory, an issue which has been raised before (Rissman and Gillon, 2017). In a review that was not mountain-focused, Herrero-Jáuregui *et al.* (2018) found that the great majority of the analyzed SES studies corresponded to research articles in the domain of environmental sciences (60%), followed by social sciences (25%) and agriculture and biological sciences (15%). They found that despite this focus on environmental sciences, studies tended to include more socio-economic variables than ecological ones, which were progressively neglected. We found very similar results regarding the domains and the inclusion of social-ecological variables studied in mountain regions. Herrero-Jáuregui *et al.* (2018) state that this suggests a greater research motivation of natural scientists to study SES, but also notice that there is an implicit risk of researchers with insufficient background in the social sciences simplifying the social dynamics of SES by incorporating just a few socioeconomic variables. At the same time, Rissman and Gillon (2017) showed that management recommendations were twice as likely to be addressed in studies incorporating both ecological and socio-economic variables. The large number of mountain studies incorporating solely socio-economic variables (almost 40%) further shows that greater efforts need to be made to include biophysical variables together with socio-economic ones in mountain SES studies (Epstein *et al.*, 2013; Rissman and Gillon, 2017). Both in mountain- and non-mountain-focused research, there is a need for change on how the territory needs to be understood. Scholars of both social and environmental sciences must find ways to connect and share their knowledge (Martin *et al.*, 2012). This will help the development of sustainability science, not only in mountains, but also for other regions (Folke *et al.*, 2016; Herrero-Jáuregui *et al.*, 2018).

The failure to include more variables in mountain SES studies probably reflects the challenges of accessing adequate data to perform trans-disciplinary SES approaches (Herrero-Jáuregui *et al.*, 2018). Despite our results show that there is a majority of empirical studies (67%), most of these empirical approaches are related to surveys or interviews to the community, and not to the obtention of environmental field data (only occurring in 14% of the cases). Another possible barrier to integrate more data in a given study is the differences of the temporal and spatial scales at which environmental and social scientists work, as well as the difficulty to find appropriate methodological tools to integrate them (Herrero-Jáuregui *et al.*, 2018; Graymore *et al.*, 2008; Firscher *et al.*, 2015; Kramer *et al.*, 2017). For example, population dynamics may only be available for large territorial scales (national or regional, at most) and at annual resolution, whereas field data are normally collected for a few years, at large territorial scales and are usually taken at higher-than-annual temporal scales. As it occurs for most of the social-ecological systems' literature (Fischer *et al.*, 2015), much of reviewed mountain studies focus on a landscape scale. Working at the landscape level may not be enough to match existing social and economic long-term data, but facilitates obtaining data about perceptions of the population about their environment (Wu, 2013). Thus, there seems to be a gap between theoretical SES conceptualization and the availability of empirical data and methodologies to effectively enable the integration of socio-economic and ecological dimensions (Herrero-Jáuregui *et al.*, 2018). New statistical tools such as Structural Equation Modelling (Filbee-Dexter *et al.*, 2018), complex systems analyses (Mao *et al.*, 2021), and neural networks and machine learning (Frey, 2020) may help move one step forward from the pure description of a system, to enable the integration of social-ecological data in order to find which may be the consequences of a given action to the whole territory, at various dimensions and spatiotemporal scales. Similarly, the use of satellite data may solve some of the problems related to obtaining data, but matching environmental and social data may still be very challenging at micro-scale in many systems. We also encourage a larger use of citizen science methodologies to obtain field data, both in the environmental and social domains (Danielsen *et al.*, 2014; Aceves-Bueno *et al.*, 2015). Citizen science projects reduce the cost of obtaining such information and have the potential to enlarge the territorial and spatial resolution of environmental data as well as collecting social data (Crain *et al.*, 2014, Ballard *et al.*, 2017), leading to a likely future «community science» approach (*sensu* Charles *et al.*, 2020).

Despite the above-mentioned limitations, our results show that mountain systems are indeed social-ecologically complex, with many elements directly or indirectly linked (Figure 5). Although this global representation includes studies from different locations, mountain regions share many characteristics, and we expect that many of the shown links globally occur, with different intensities. The most linked attributes show the complexity and reality of mountains as SES's, and point to a direction where future SES studies in mountain regions should/could go. Ostrom's SESF was initially created as a tool for a sustainable management of resources, that could take into account the social and economic dimensions of the target resource (McGinnis and Ostrom, 2014; Partelow, 2018); in the current frame of climate change highly affecting mountain regions (Huss *et al.*, 2017; Mal, 2018; Mann *et al.*, 2017; Fischer and Knutti 2015; Haeberli *et al.*, 2017), this is still more urgent and necessary. Our review clearly puts in evidence the relevance of this original objective in mountain regions, because the most connected attributes include RS6 (equilibrium properties), governance attributes that may affect this management at various levels (GS2, GS5, GS6 and GS9), the knowledge that the population has on the resource and its connections with the environment (A7), and two of the most important current drivers affecting natural systems' sustainability: the ecosystem history (RS10, analogue to land use change), and the climatic patterns (ECO1, i.e. climate change). These linked attributes arose repeatedly in studies working with different frameworks, scales, and approaches, pointing at their importance for the sustainability of mountain regions regardless of the methodology used. Thus, it can be seen as a minimum toolset of SES elements to consider, which can be adjusted to any given framework or methodology the researchers may consider more adequate for her/his specific research question. We suggest that a project aiming at including the most relevant elements for a sustainable management of mountains should include at least the above-mentioned list of SES elements.

As it occurred for mountain SES globally, certain attributes appeared more often when looking at specific sectors. The most commonly addressed sectors by the authors that see mountains as SES include «Biodiversity», «Ecosystem Services», «Water», «Agriculture», «Landscape», «Forest», and «Livestock», which are among the most threatened ecosystem services in mountain regions (Stritith *et al.*, 2020; Mengist *et al.*, 2020; Yu *et al.*, 2021). Mountains provide most ecosystem services (EEA 2016), and the most addressed attributes when addressing this sector in a social ecological frame are climate change (ECO1), governance entities that may play a role (GS5), and the mental models of the actors (A7). Ecosystem services addressed in our database include wood-based energy (Jensen-Ryan *et al.*, 2019) and carbon sequestration (Ma and Coppock, 2012), for example. It may not be surprising that, contrary to biodiversity, few studies explicitly included some of the attributes of RS6 (equilibrium properties), but we explain it by the fact that some works take a global approach to ES (e.g. García-Llorente *et al.*, 2018), making specificities difficult to address. Water is among the most important mountain ES's, and it will play a very important role in the management of mountain resources in the future (Viviroli *et al.*, 2011). Lower water availability due to climate change may lead to conflicts for water use, not only in the mountains but also in the lowlands, which are the main users of water (Viviroli *et al.*, 2011; Fuller and Harhay, 2010). Not surprisingly, the most addressed attributes when water is the target sector are the same as with «Biodiversity», i.e. the mental models of actors (A7), climatic patterns (ECO1), rule-making organizations (GS5), and equilibrium properties (RS6). This indicates that managing water in a global change scenario must take into account the local population and the different actors that may play a role, be interested on, or be affected by, changes in water use or availability. For instance, McNeeley *et al.* (2016) showed how a bottom-up approach to understand drought complemented the more classical top-down one, and suggested that social-ecological contexts defined by both manager-types are important to understand how drought was experienced by locals. Again, Postigo (2014) suggested that the sustainable management of a glacier in the Peruvian Andes may be better addressed strengthening institutions and fostering local knowledge renewal.

Contrary to what Rissman and Gillon (2017) found in a systematic review of SES research, we found biodiversity to be equally addressed in comparison to other elements in mountain SES studies. This is perhaps due to the fact that mountains are biodiversity hot-spots and host many endemic species (Payne *et al.*, 2020). Mountains are also among the most threatened ecosystems by climate change (Hock *et al.*, 2019), specially at high elevations, where changes in temperature are higher (Hock *et al.*, 2019). This probably reflected in our data, since climate patterns (ECO1) and equilibrium properties (RS6, which includes frequency, timing, extent and magnitude of disturbances, as second-tier attribute) are both addressed when Biodiversity is the target sector. More, our analyses also suggest that when dealing with biodiversity and climate change, it's important to include the knowledge of the SES by the stakeholders (A7), as well as who is in responsible (or partially responsible) of local rules (GS5) affecting biodiversity, or which sectors may need to play a higher role when managing biodiversity in mountains. For example, Cottrell *et al.* (2019) show how taking into account these attributes can help manage the mountain pine beetle (*Dendroctonus ponderosae*) in western USA.

Understandably because these are the most closed sectors to markets, it's in both «Livestock» and «Agriculture» sectors when the economic value of the RS/RU appears. In terms of Governance Systems, authors dealing with «Agriculture» seem to include more often the organizations that may participate in the rule-making (GS5), whereas those focused on «Livestock» take into account the population (GS3). «Livestock»-focused works also mostly include the climatic patterns (ECO1) and the equilibrium properties (RS6), probably because many of them deal with traditional and migratory pastoralism, which follows seasonality and can therefore be affected by changes on climate predictability derived from climate change (Aryal *et al.*, 2014; Gentle and Thwaites, 2016). Both sectors also include the actors' mental frameworks (A7), their socio-economic attributes (A2), and their dependence on the RS-RU (A8).

Out of the 49 SESF attributes considered in this paper, only 13 were never used in none of the reviewed manuscripts. The fact that these attributes did not appear in our database does not necessarily mean that they are not relevant in mountain regions. We may have missed some papers, or it may indicate that papers focusing on them do not take into account mountains as SES and/or just do not mention it in their texts. Table C3 (Appendix 1, Supplementary Material C) shows some examples of these «forgotten» attributes addressed in mountain-focused papers that do not mention «social-ecological systems» (or similar) in their texts. Despite mountains offer new opportunities for entrepreneurs (Covaci and Brejea, 2020; Martini *et al.*, 2020), we found no papers dealing with leadership or entrepreneurship (A5). The urgent need for diversification of the winter tourism (Bausch and Gartner, 2020; Hoy *et al.*, 2011), the higher availability of internet services in remote areas, the increase of work-from-home possibility in many sectors after the COVID19 pandemic (Bick *et al.*, 2021), and the incentivization of circular and local economies in many regions of the world (Heshmati, 2016; Urbinati *et al.*, 2017), offer a plethora of new business models that seem not to be addressed yet by the scientific community. We advocate for the inclusion of entrepreneurship in SES approaches, because all the above-mentioned points may have an impact in the whole region. For example, promoting the use of local wood for heating can be seen as a good adaptive strategy under a circular economy development pathway (Pan *et al*., 2015), but the logging can have detrimental effects on large mammal populations inhabiting local forests (Bowman *et al.*, 2010; Brodie *et al.*, 2015), which in its turn may affect grassland biodiversity by limiting or removing the effect of grazing (Riesch *et al.*, 2019; Tälle *et al.*, 2016). Similar to what occurs with entrepreneurship, our results confirm that, at least in mountain research, authors citing mountains as SES do not take much into account the global Socio-Economic and Political Drivers (S), which mostly act at macro-scale, but act also at the micro-scale through their influence in GS attributes, which are among the most addressed ones. Not considering the global economic and political agenda is hardly realistic in a globalized world, as globalization can have impacts on the connectedness, intensity, and speed of interactions among variables of any social-ecological system (Young *et al*., 2006). Moreover, as globalization is a relatively recent phenomena, the lack of past experience makes it even more difficult to anticipate the potentially wide range of consequences linked to it (Young *et al*., 2006). Thus, we strongly recommend future researchers to combine variables related to local governance with global socio-economic and political drivers in order to successfully develop effective adaptation strategies in the long run.

1.5 Conclusions

Despite they are tightly connected with the lowlands, mountain regions are physically, socially, and often culturally distinct from them, and their current state is the legacy of thousands of years of interactions between humans and nature (Olsson *et al.*, 2000; Telbisz *et al.*, 2016). The network of interactions that make up this socio-ecological system is an exceptional framework for deepening the application of SES approaches. However, mountain SES research is still a work in progress, and in our analysis, we identified potential caveats and opportunities for future research. Future development must be focused on collecting empirical data at finer spatial and temporal scales, as well as on developing analytical tools and advancing frameworks to effectively integrate both socio-economic and ecological variables in SES research. Additionally, we encourage researchers to incorporate relevant but understudied attributes in their future mountain SES studies, such as entrepreneurship and global Socio-Economic and Political Drivers, in order to prevent negative effects of a priori good adaptive solutions. To ensure no relevant attributes of a given system are missed, we encourage researchers to apply Ostrom's framework, as it facilitates a list of potentially important SES attributes to consider (Ostrom, 2007, 2009). There are actually no rules to add or change attributes to the framework, and far from being a flaw, this flexibility enables to adapt the framework to any system and needs (Ostrom, 2007, 2009; Delgado-Serrano and Ramos, 2015). The fact that we were able to classify all the attributes addressed in the mountain SES literature under the same scope confirms that the SESF does not seem to miss any relevant attribute when applied to mountain research.

Figures

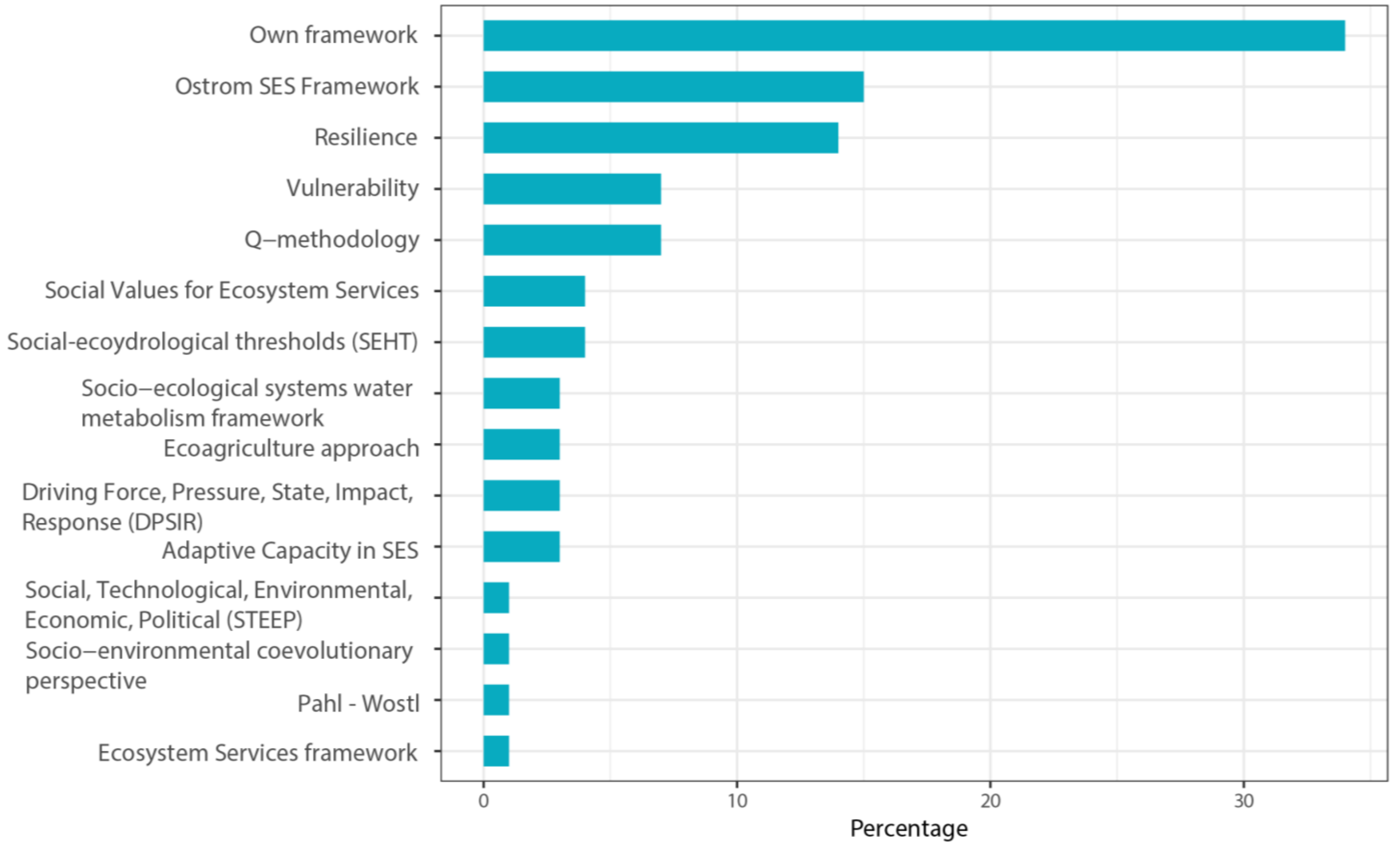

Figure 1. Percentage of frameworks used by scholars in the reviewed works (n=172)

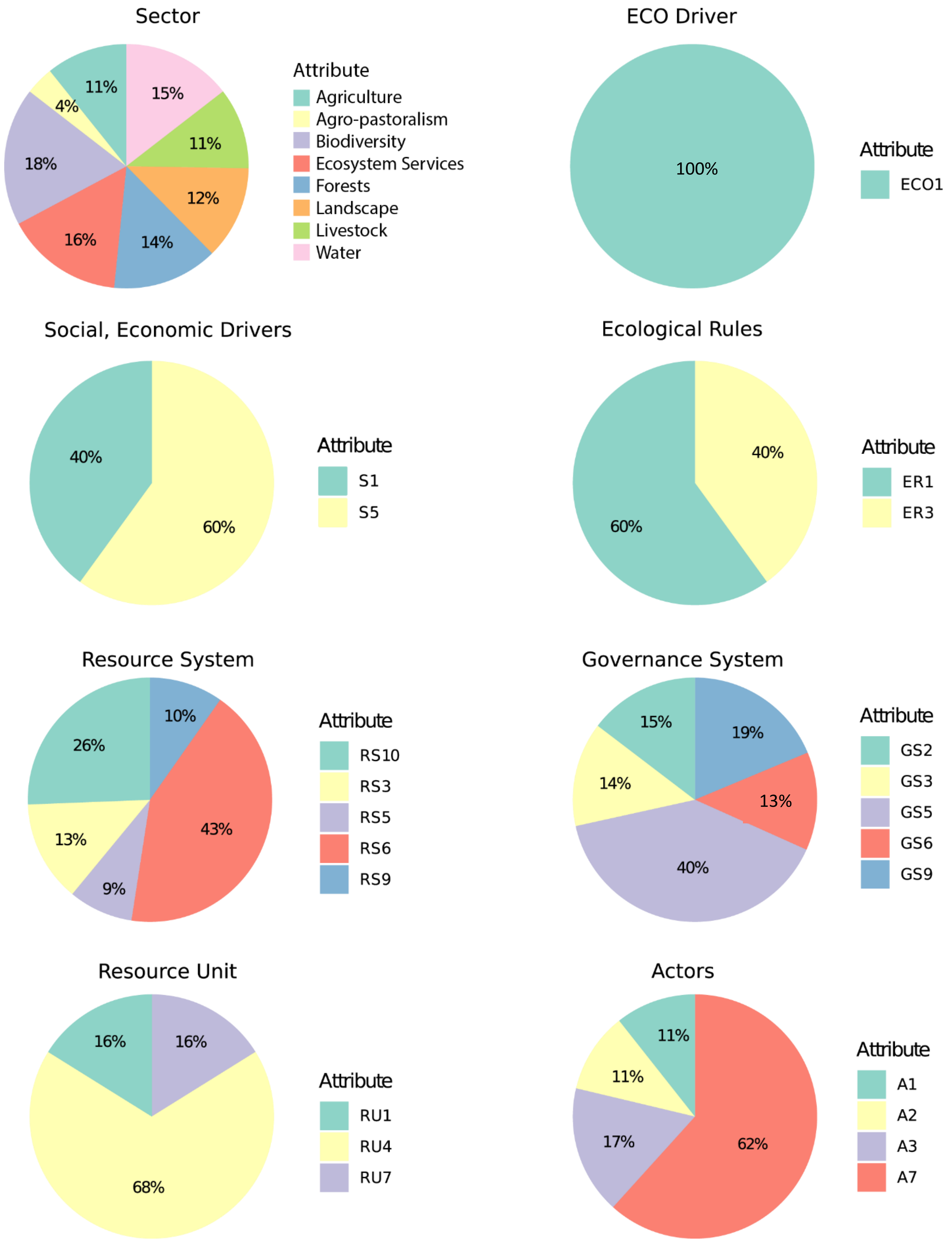

Figure 2. Percentage of papers that addressed each sector (top left), and the attributes of the ecological drivers, the social and economic drivers, the ecological rules, the resource units and systems, actors, and governance systems.

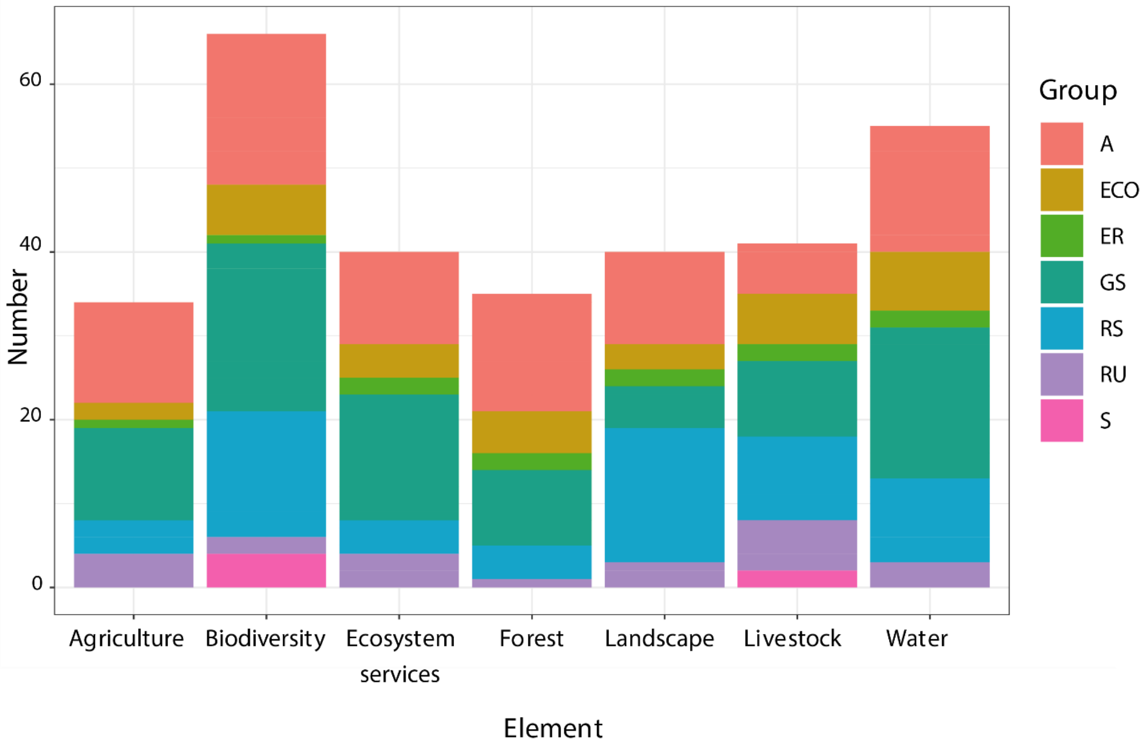

Figure 3. Number of SES attributes addressed in the reviewed manuscripts when addressing each sector (Element) (N=172) (A: Actors, ECO: Related Ecosystems, ER: Ecological Rules, GS: Governance System, RS: Resource System, RU: Resource Unit, S: Socio-economic and Political Drivers)

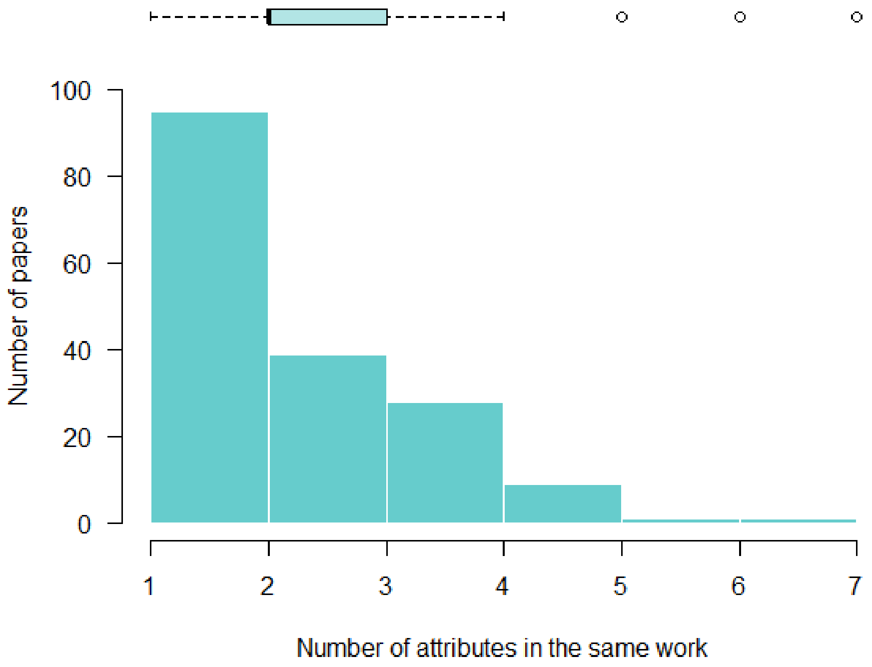

Figure 4. Number of SES attributes addressed in each individual revised manuscript.

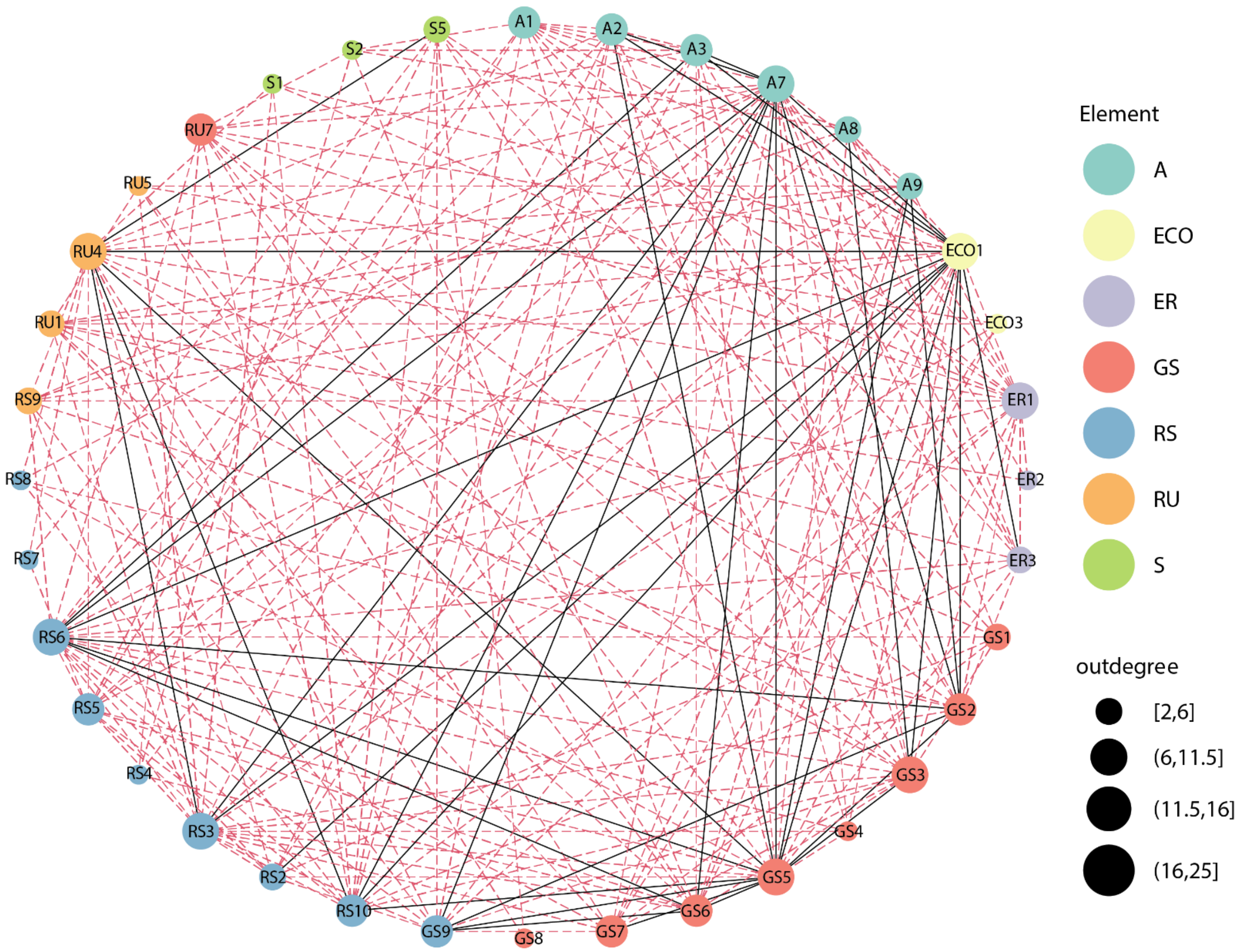

Figure 5. Links between pairs of SES attributes. Dashed red lines indicate connections appearing in less than three papers, and solid black lines show that the two connected attributes appear together in three or more papers. The size of the circles (Outdegree) is proportional to the times that each attribute has been addressed in the revised papers. (A: Actors, ECO: Related Ecosystems, ER: Ecological Rules, GS: Governance System, RS: Resource System, RU: Resource Unit, S: Socio-economic and Political Drivers)

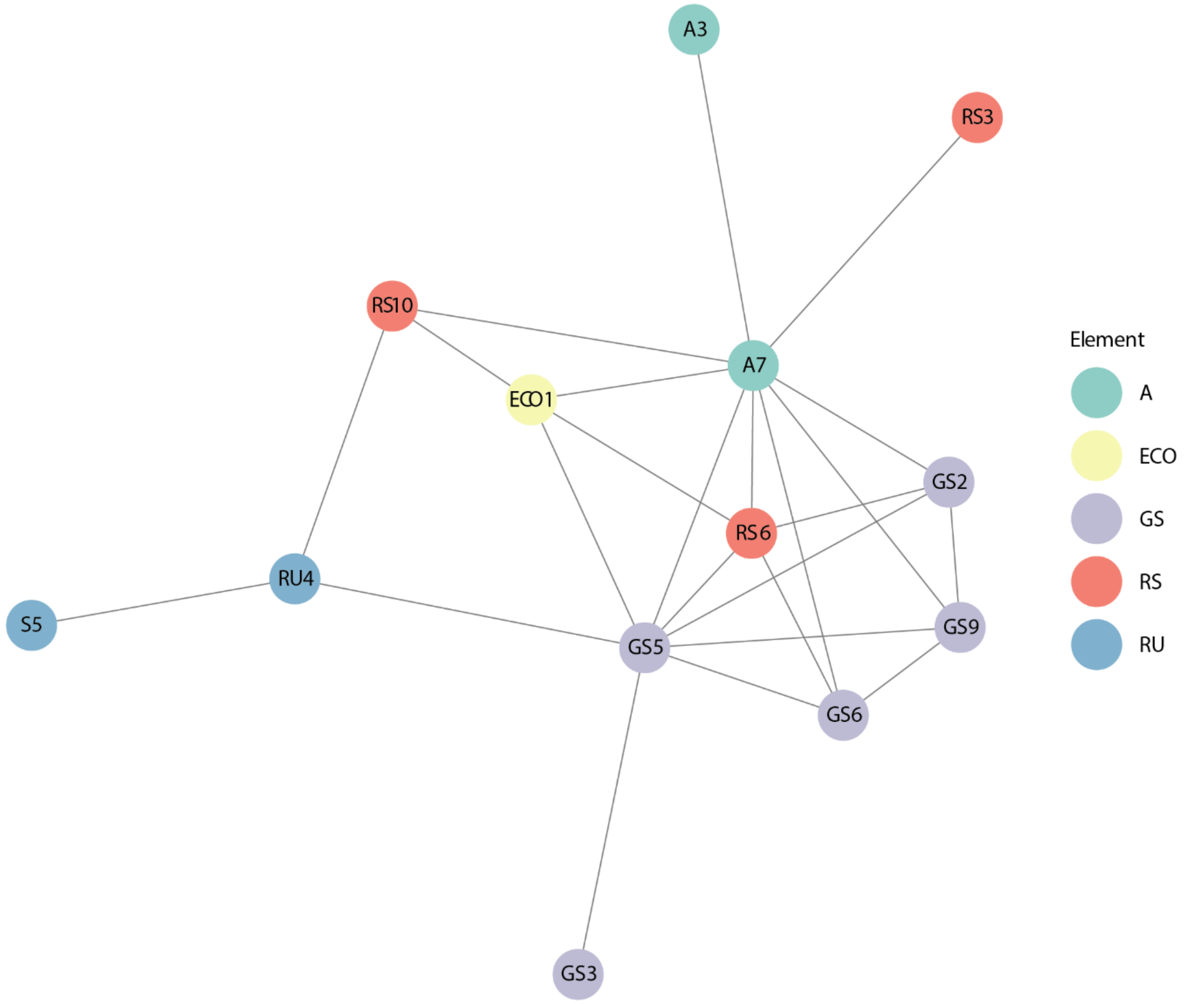

Figure 6. Links between the pairs of attributes that are mostly addressed together in the same manuscript. (A: Actors, ECO: Related Ecosystems, GS: Governance System, RS: Resource System, RU: Resource Unit)

Chapter 2

Applying a new protocol to avoid maladaptation shows that Degrowth is the most suitable strategy for European mountains

Zango-Palau, A., Rivera-Ferre, M., López-i-Gelats, F., Claramunt-López, B.

Chapter 2. Applying a new protocol to avoid maladaptation shows that Degrowth is the most suitable strategy for European mountains

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Keywords

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Abstract

Maladaptation occurs when actions taken to adapt to global change end up increasing vulnerability, instead of reducing it. This process often occurs when multiple drivers affecting a system's vulnerability are not considered. To prevent maladaptive actions, it is important to consider both these drivers and the potential conflicting interests at different territorial scales. Unfortunately, existing guidelines for assessing the risk of maladaptation are not context specific. To address this, we developed a set of guidelines that can establish a link between drivers, trends of change, adaptation actions, and potential conflicts of interest. The suggested guidelines allows for context-specific assessment, making it easier to detect adaptation actions that could become maladaptive by either increasing vulnerability or causing negative externalities. It also helps to identify potential conflicts among mental frameworks at the local territorial scale and between these frameworks and development pathways, normally decided for large territorial scales. As a case study, we applied these guidelines to the Pyrenees mountain range. The results show that some adaptation actions, such as promoting local varieties of crops, would be welcomed by all locals, while others, such as revitalizing the building sector, would displease the majority and turn maladaptive. Our application to the Pyrenees also suggests that *Degrowth* is the development pathway that better fits the locals' interests, and *Business-As-Usual* has the worst fit. Our guidelines are flexible and modifiable, making them applicable to any social-ecological system.

2.1 Introduction

There is a pressing need for adaptation in the face of global environmental change. However, some adaptation measures have not only failed to address the challenges effectively but have also exacerbated the vulnerability of some systems. Maladaptation, as defined by Juhola *et al.* (2016), occurs when intentional adaptation policies or measures actually increase vulnerability for targeted or external actors, eroding the preconditions for sustainable development and intensifying society's overall vulnerability to climate change-related issues, both now and in the future. This highlights the alarming reality of unintended increases in vulnerability resulting from the implementation of inadequate adaptation actions. Magnan *et al.* (2016) proposed four key dimensions to help assess the risk of maladaptation: processes, multiple drivers, temporal scales, and spatial scales. The events leading to increased vulnerability depend on changing drivers and the sensitivity of the system to these drivers, both dynamic and static (Turner *et al.*, 2003). These multiple drivers include the climatic and socioeconomic dimensions (Zavaleta *et al.*, 2018). Finally, both the temporal and spatial scales at which maladaptation occurs must be defined (Cash *et al.* 2006). As Granberg and Glover (2013) pointed out, an adaptation action can be beneficial at a local scale, but can cause negative externalities if a wider spatial scale is considered (Work *et al.*, 2019). Similarly, short-term solutions can become maladaptive in the long term (Burby, 2006).

Maladaptation can manifest in multiple ways, depending on the specific focus. For instance, it can manifest as an alarming increase in greenhouse gas emissions (Hopkins, 2014), unfairly burdening vulnerable groups (Albizua *et al.*, 2019), incurring exorbitant opportunity costs (Macintosh *et al.*, 2013), undermining incentives to adapt (Barnett and O'Neil, 2010), or creating dependencies that reduce future adaptive capacity (Barnett and O'Neil, 2012). Maladaptation can also be categorized based on its impact on different groups affected by adaptive actions (Schipper, 2020; Juhola, 2016), including rebounding vulnerability, where the target group's vulnerability increases due to adaptive actions (Piggott McKeller *et al.*, 2020); shifting vulnerability, where the actions inadvertently make another group vulnerable (Neset *et al.*, 2019); and negative externalities, which are adverse outcomes stemming from these actions that are not necessarily linked to climate change (Sovacool *et al.*, 2015). These classifications underscore the complexity and urgency of addressing maladaptation to ensure that adaptation efforts align with the goals of building resilience and sustainable development in the face of global environmental challenges.

Climate change strategies should not be evaluated separately from broader development plans when assessing maladaptation (Juhola *et al.*, 2016). It is crucial to recognize the intrinsic interconnection between climate change effects, adaptation strategies, and socioeconomic and political agendas (Kriegler *et al.*, 2012; Berkhout *et al.*, 2014). Maladaptation often occurs when the social context of the region where adaptation actions are implemented is ignored (Schipper, 2020; Magnan *et al.*, 2016), and many documented cases of maladaptation have resulted from imposing one-size-fits-all solutions on local communities without first conducting context-appropriate assessments (Rahman *et al.*, 2019; Kennedy *et al.*, 2010). For example, Albizua *et al.* (2019) demonstrated that a modernization agenda driving mountain agricultural policy in Navarre (Spain) favoured large-scale market-driven farmers over small-scale diversified farmers, resulting in irrigation systems that displaced the latter. This privatization of water resources meant that farmers lost autonomy over their products, practices, and prices, thereby limiting their ability to respond to future changes in climate and market interests. Similarly, Magnan *et al.* (2016) showed that government adaptation efforts in pastoral regions in Afar (Ethiopia) focused on reductionist approaches that considered climate change as the sole driver of vulnerability. Consequently, the government promoted irrigation agriculture by reinforcing technological improvements; however, the main drivers of vulnerability for such pastoral communities were socioeconomic stressors. Addressing the socioeconomic context and behavioural motivations of the local population has been proven to be crucial to prevent maladaptation (Henstra, 2016). However, vertical policy incoherence often exists between the national adaptation agenda and the interests and goals of local communities (Henstra, 2016; Glaas and Juhola, 2013). High-level decisions are typically made at the national or regional level, leaving local communities at a disadvantage due to the legal and regulatory controls imposed by higher levels of governance (Ekstrom and Moser, 2013). A lack of public participation in decision-making processes reinforces power imbalances and contributes to a sense of marginalization among local communities. The extent to which local communities can lead processes of change ultimately depends on the degree to which national and local governments prioritize building long-term relationships with them (Klinsky *et al.*, 2017). However, conflicts of territorial scales often arise (Cash *et al.*, 2006). To avoid such conflicts, the existence of different interests at multiple territorial scales must be acknowledged. At the local level, actions should consider the (usually conflicting) interests and values of the inhabitants that coexist in a given territory (Pahl-Wostl, 2007); and at the regional/national level, the development plans of policymakers, usually driven by socio-economic and political interests, must consider both the large-scale context(s) and the local interests (Haasnoot *et al.*, 2013; Kriegler *et al.*, 2012; Berkhout *et al.*, 2014). Finally, much focus has been placed on identifying and classifying the outcome of a maladaptive action a posteriori. However, far less attention has been paid to developing practical strategies that avoid maladaptation *ex-ante*, i.e., before it happens. Scholars argue that potential sources of maladaptation should be checked prior to strategy implementation; thus, scientific efforts should focus on developing practical guidelines to assess the risk of maladaptation (Asare-Nuamah *et al.*, 2021; Schipper, 2020).

Mountains offer a prime example of how to prevent maladaptation caused by conflicts of interest at different territorial scales. Accounting for territorial-scale mismatches is particularly difficult in complex socio-ecological systems (SES), such as mountains (Klein *et al.*, 2019a). The inherent complexity of these systems, with multiple social and ecological elements affecting one another (Klein *et al.*, 2019a), adds to conflicting management interests at multiple territorial scales. Moreover, in recent decades, mountains have undergone profound transformations due to their exposure to many social and ecological drivers of change (Mitchley *et al.*, 2006; MacDonald *et al.*, 2000; Vaccaro and Beltran, 2007), but most mountain regions are far from decision-making centres. Hence, establishing appropriate adaptation measures for these regions is complicated because they must be context-based and consider a myriad of factors at play (Adger *et al.*, 2006). Developing successful strategies for mountains is necessary not only for mountain dwellers, but also because these social-ecological systems provide multiple ecosystem goods and services for the entire population (Viviroli *et al.*, 2003; EEA, 2016; Benayas *et al.*, 2007; Wilson *et al.*, 2012; Mármol and Vaccaro, 2015; Smith *et al.*, 2014; Martín-López *et al.*, 2019; Rahbek *et al.*, 2019a; Dean *et al.*, 2021). However, a recent review of climate change adaptation strategies in European mountain regions showed that studies primarily focus on the biophysical and technical aspects of strategy implementation and rarely on critical aspects regarding the human dimension of adaptation (Vij *et al.*, 2021). Two decades ago, Marsden (1999) pointed out that rural areas worldwide were becoming less self-sufficient and more influenced by socioeconomic drivers. General guidelines to prevent maladaptation were developed by Hallegatte (2009), Barnett and O'Neill (2010), and Magnan (2016). These guidelines advocate for the development of adaptation actions that, for instance, "ensure economically and socially equitable initiatives" (Barnett and O'Neill, 2010), or that "integrate local social characteristics and cultural values about risk and the environmental dynamics" (Magnan, 2016). However, as the same authors acknowledge, these are general, non-context-specific guidelines, and a practical methodology to help detect and prevent maladaptation has yet to be developed. The next step is to develop guidelines suited to assessing the risk of maladaptation in specific contexts (Magnan, 2016).

This study offers a new framework for decision-making that includes multiple scales, the perspectives of locals, territorial development planning strategies, and the complexity of mountain social-ecological systems. Drawing on the social-ecological systems framework (Ostrom, 2007, 2009) and the contextual vulnerability framework (Adger, 2006; Okpara *et al.*, 2016), we present a set of practical guidelines that can be applied to any region and use them in the Pyrenees Mountains as an example. We propose these step-by-step guidelines to help detect potential maladaptive actions arising from conflicts at multiple territorial scales: first, within local actors with different views on how the mountain region should be developed, and second, between these local actors and development-planning options.

2.2 Methods

2.2.1 Conceptual framework

The Socio-Ecological Systems (SES) framework developed by Ostrom (2007, 2009) is widely regarded as the most comprehensive SES framework to date (Partelow, 2018). Ostrom's SES framework encompasses both ecological and socio-economic elements and attributes of the system, organizing them into Actors (A), Governance System (GS), Resource Systems (RS), and Resource Units (RU). These elements and attributes are influenced by external drivers, both socioeconomic (S) and ecological (ECO). The framework provides a comprehensive multitier list of potentially relevant SES elements, making it a valuable tool for avoiding the unintentional omission of important aspects in any given system (Colding and Barthel, 2019; Ostrom, 2007, 2009). The Vulnerability framework has been extensively utilized to analyse how exposure to change affects the sensitivity and adaptive capacity of complex systems (Vallejo-Rojas *et al.*, 2016; Butler, 2016; Maru *et al.*, 2014; Adger, 2006). The assessment of a system's vulnerability can be approached from various perspectives (Adger, 2006). Contextual Vulnerability emphasizes that a system's vulnerability is influenced not only by biophysical drivers but also by its socio-economic and political context (Okpara *et al.*, 2016). O'Brien *et al.* (2007) argued that the contextual vulnerability approach is particularly suitable for analysing complex mountain systems. Maladaptation processes often occur when multiple drivers that influence a system's vulnerability are neglected, including social, cultural, and economic drivers (Magnan *et al.*, 2016; Schipper, 2020). Therefore, maladaptation is closely linked to vulnerability.

The integration of these two frameworks has previously been employed to evaluate the resilience of local agricultural systems to climate change (Vallejo-Rojas *et al.*, 2016). However, such integration is limited to the local scale and does not specifically focus on its broader application in guiding adaptation decisions. In this study, we propose that combining SES and Vulnerability frameworks can enhance our understanding of the driving factors behind contextual vulnerability and enable us to assess the influence of social, economic, and ecological factors on the maladaptation process (Figure 1). For successful adaptation, the goals and interests of local communities, captured by their co-existing mental models, must align with the aims of these development plans (Albiuza *et al.*, 2019; Magnan *et al.*, 2016). Mental models refer to the cognitive frameworks or internal representations that individuals use to understand, interpret, and explain the world around them, and they can influence how people perceive and respond to various situations (Easterby-Smith, 1980). Mental models can take various forms, such as images, concepts, or narratives, and can vary significantly among individuals, groups, and cultures.

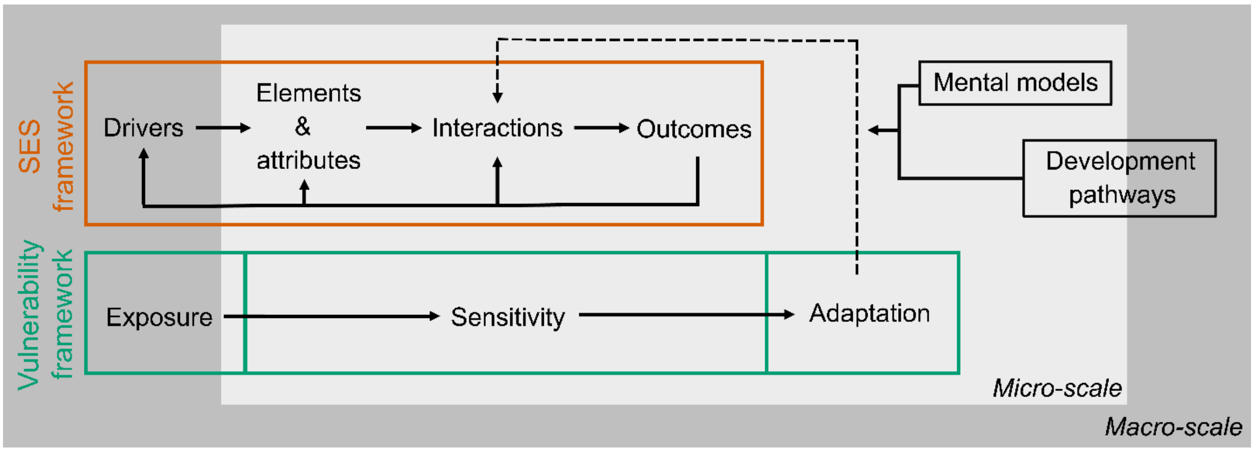

Figure 1. Diagram conceptualizing the integration between the Vulnerability framework (green) and the Socio-Ecological System (SES) framework (orange). The micro- and macro-scales of action for both frameworks are represented by light and dark grey squares, respectively. The Vulnerability framework comprises of three primary elements: exposure, sensitivity, and adaptation. Exposure refers to the magnitude and nature of changes that affect a system; sensitivity describes the system's response to those changes; and adaptive capacity measures the system's ability to cope with such changes (Adger, 2006). However, describing these elements in complex systems can be challenging (Adger, 2006; Vallejo-Rojas *et al.*, 2016). To address this challenge, Ostrom's SES framework has proven useful in analyzing the complexity of a system by systematically identifying its social and ecological components (Partelow, 2018). In the Vulnerability framework, the concept of Exposure aligns with the Drivers element in the SES framework, as both represent external elements that influence the system on a macroscale. The trends and attributes of the SES framework, along with their interactions and outcomes, correspond to the Sensitivity element of the Vulnerability framework, as they represent the impacts on the system. Finally, Adaptation aims to modify the interactions between the system drivers and elements to achieve the desired outcomes. Development pathways are employed to address system adaptations by aligning them with macro-scale socioeconomic trends.

2.2.2 Decision-making guidelines to implement adaptation action in a context of complexity

We propose a methodology for implementing context-specific adaptive actions. To avoid maladaptive outcomes, we assess the relationships among adaptation actions, locals' mental frameworks, and development pathways. This allows us to assess how priorities at national/regional territorial scales may affect locals and potentially cause negative externalities (Juhola, 2016). The guidelines follow four steps, organized as key questions that consider the different aspects of the vulnerability of the system under study.

- Q1: Which are the main drivers describing the changes in our system? Answering this question generates an organized list of drivers following the SES framework. It helps to identify the components of 'multiple drivers' to assess the risk of maladaptation.
- Q2: How are the SES elements and attributes changing? For each SES element and attribute, the trend of change (increasing/decreasing) is assessed. This allows to describe the first component of their sensitivity, as well as to understand the processes derived from the impacts of the drivers.
- Q3: Which interactions and outcomes result from these trends in changes in elements and attributes? By answering this question, the remaining SES framework elements are considered in the analysis, as well as the sensitivity of the elements in the Vulnerability framework. This step allows the establishment of the final link between drivers and how the system responds to their impact.
- Q4: What adaptation options are available, and how do they interact with existing development options and the mindset of the local population? This question addresses the Adaptation step in the Vulnerability framework. Answering the final question helps to identify context-specific adaptation actions that can be implemented to address the impacts of the drivers. Then, their potential to turn maladaptive is assessed by identifying how they fit with the local mental models and global development pathways, allowing to understand conflicts between these scales.

2.2.3 Application of the guidelines to the Pyrenees

The Pyrenees serve as a suitable case study because of their resemblance to other mountainous regions in Europe (and some worldwide) and the shared pressures they face as a result of global change (EEA, 2016). Over the course of the 20th century, European mountains have progressively become integrated into globalized markets, leading to cultural, occupational, and demographic changes (Perlik, 2019).

Furthermore, mountains are expected to experience more pronounced impacts from climate change than lowland areas (Adler *et al.*, 2022). These drivers have contributed to the evolving role of mountains in society (Mitchley *et al.*, 2006; MacDonald *et al.*, 2000; Vaccaro and Beltran, 2007). In recent decades, territorial planning in the Pyrenees has focused on nature conservation and recreational activities, while rural communities have shifted from primary-sector-oriented economies toward the services sector (Vaccaro and Beltran, 2007, 2009). This transition has given rise to diverse discourses among the local population regarding a region's future development (López-i-Gelats, 2009). The conflicting interests between locals, the development priorities imposed by higher levels of governance, and the challenges posed by climate and socioeconomic changes make the implementation of adaptation actions complex. Previous studies have highlighted the existence of conflicting mental frameworks in the Pyrenean region (López-i-Gelats, 2009), providing an ideal context for identifying which adaptation actions may give rise to conflicts and have the potential to become maladaptive. To answer to Q1 and Q2, i.e., to characterize the system and to determine its elements and attributes as well as its exposure and sensitivity, a literature review (Grant and Booth, 2009) was carried out to obtain the following information:

- Population dynamics in the Pyrenees. Population numbers, origin (newcomers, locals), movements, communications and infrastructure, settlement location and size, and degree of education.

- Economic trends in the Pyrenees region. Tourism and tertiarization of the economy (tourism offer, economic importance), agriculture, and livestock (production trends, abandonment, and incentives).

- Management policies applied at local (local agreements, communal management, cooperatives) and global (Spanish and European legislation) scales, management trends over time, and environmental policies (both local and global).

- Biodiversity. Areas under some degree of protection, Natural Parks, and National Parks; Reintroduction programs; general population trends of species linked to agriculture, grasslands, meadows, and forests; trends in species richness and diversity estimators; landscape heterogeneity.

- Climate change. Estimated impacts of climate change on the economy, particularly winter tourism and landscape.

Seventy documents were used to identify the main elements (Actors, Government System, Resources, and Resource Units) and the drivers of exposure (Ecological, Socio-economic, and Political) characterizing the Pyrenean socio-ecological system (SES). To understand the sensitivity of these elements and their attributes to the identified drivers, we investigated the trends of change (Q2). In cases where information regarding a specific element or attribute in the Pyrenees was unavailable, data from the Spanish or European mountain regions were used. Experts were consulted in cases where no literature-based data were accessible. The findings for addressing Q1 and Q2 are presented in Table 1. The subsequent step involved identifying a list of adaptation actions being implemented in the Pyrenees and influenced by the interactions and outcomes associated with the identified trends (Q3, Table 2). We examined the system's capacity to adapt by addressing the alignment of these adaptation actions within various global development pathways and the mindset of the local population (Q4). To analyse the coexisting mindsets, we employed the four mental frameworks already identified in the Pyrenees (López-i-Gelats, 2009): the Conservationist, who prioritizes the ecological assets of the mountains; the Entrepreneurial, who seeks to combat depopulation and promote economic growth through innovation, with a focus on the current main drivers of economic growth (tourism and construction); the Agriculturalist, who emphasizes the promotion of agriculture, particularly extensive livestock farming; and the Endogenous Development discourse, which argues that an economic emphasis on mass tourism has detrimental effects on the local economy and society, advocating for economic diversification based on the system's assets. As for the development pathways, three commonly described and well-documented development pathways were used: *Degrowth*, *Circular Economy*, and *Business-As-Usual* (Table A1, Appendix 2).

The next step involved assessing the compatibility of each adaptation action from Table 2 with each mental framework of the local population (Table 3) and potential development pathways (Table 4). In both tables, we assigned the fit of each interaction as positive (+), neutral (0), or negative (-). A positive action-mental framework interaction indicates that the implementation of that action aligns with the preferences of the local mental framework. Conversely, a negative interaction suggests that the local mental framework is not supportive of the implementation of that action, whereas a neutral interaction signifies that the mental framework does not have a specific stance on the implementation of that action. Similarly, a positive action-development pathway interaction indicates that the respective development strategy is likely to adopt and implement the given action; a negative interaction indicates that the development strategy would impede, limit, or reduce the implementation of that action; and a neutral interaction implies that the development strategy would not take action in that regard. The final step involved assessing potential conflicts between the development pathways and mental frameworks for each action by combining the results from the previous two tables, as shown in Table 5. When both the pathway and mental framework exhibit the same response toward an action (either positive or negative), the outcome of the interaction is considered positive (+). Conversely, if a pathway is in opposition to the desires of the mental framework or does not take action on the matter that the mental framework holds an opinion about, the outcome is considered negative (-). Finally, any action for which the mental framework was unaffected was classified as neutral (0).

2.3 Results

2.3.1 *Q1: Which are the main drivers describing changes in our system?* System's exposure

A total of 25 main elements and attributes were identified to describe the system: 7 for Actors (A), 5 for Governance (G), 8 for Resource System (R) and 5 for Resource Units (RU); and a total of 9 main drivers of change were also identified: 4 ecological drivers (ECO) and 5 social-economic and political drivers (S) (Table 1).

The ecological drivers in the region are linked to climate change, which is already evident in the Pyrenees. The disappearance of permanent snow due to a temperature increase (ECO1), especially the maximum values, and the overall shortening of the winter season (ECO1) are among the clearest examples (Calbó, 2016; Kreyling and Henry, 2011; IPCC, 2014). In addition, there is a decrease in precipitation (ECO1), and models predict a change in the rainfall regime towards fewer events but of greater intensity (Calbó, 2016; IPCC, 2014; Beguería *et al.*, 2009; López-Moreno *et al.*, 2008). Finally, an increase in extreme events (ECO1) increases the risk of landslides, floods, and/or avalanches (Stott *et al.*, 2016; Peñarrocha *et al.*, 2002; Sillmann and Roeckner, 2008).

The identified socioeconomic and political drivers stem from the integration of mountain regions into the globalized economy (Vaccaro and Beltran, 2009; Mármol and Vaccaro, 2015), causing an economic shift towards the services sector, that is, tertiarization of the economy (S1) (Marín-Yaseli *et al.* 2003; García-Martínez *et al.* 2009; López-i-Gelats *et al.* 2011; Sancho-Reinoso, 2013). There is also an internal migration towards the towns of the valleys (S2), which leads to a gradual abandonment of small medium-to-high elevation rural towns and a concentration of the population in the valleys (S2) (García and Mateu, 2003; Gutiérrez, 2001; Alados *et al.*, 2014). However, the overall population of the Pyrenees is currently stable (S2) (IDESCAT, 2020) and may even increase after the COVID19 pandemic. Finally, there has been an increase in environmental policies and the promotion of protected natural areas in the entire Pyrenean region (Pallares-Blanch, 2012; IDESCAT, 2020).

2.3.2 *Q2: How are the SES elements and attributes changing*? System's sensitivity

The main trends identified for Actors, Governance System, Resource System and Resource Units are the result of the effects of the ecologic and the socioeconomic and political drivers on the elements of the system. Thus, many of the changes are related to a progressive tertiarization of the economy following global market interests (Table 1), i.e. there is a shift from the primary sector towards tourism and services (A1) (Mármol *et al.*, 2018; Mármol, and Vaccaro 2015; Vaccaro and Beltran, 2009; Tulla, 2003). This is linked to an increase in entrepreneurship through the establishment of cooperatives and micro-enterprises (A1, A5), associative networks (GS3), new systems of production (such as organic farming or traditional crops), and distribution circuits (A1, GS3, RS1, RS5) (Mármol *et al.*, 2018). Similarly, population migration towards larger cities (RS4) has facilitated a higher degree of education (A1) and the integration of newcomers into mountainous regions (A1, A2) (Gutiérrez, 2004; IDESCAT, 2020; Solé *et al.*, 2012). Despite efforts to promote agriculture and livestock through subsidies (GS8) (EC, 2020; Lasanta and Marín-Yaseli, 2007; GENCAT, 2020a, 2020b, 2020c. 2020d), which mainly depends on the European Common Agricultural Policy, there is a growing degradation of agricultural ecosystems (RS1, RS4). This has driven the simplification of agricultural practices and livestock (Poyatos *et al.* 2003; Mottet *et al.* 2006; López-i-Gelats *et al.*, 2016), and degradation of communal management, mainly forests and alpine pastures (GS6, RS1) (Gil, 2000; Iriarte, 2002). This causes an increase in forest biomass and species linked to forests (RS1, RU2, RU6, RU7) (Sanjuán *et al.*, 2018; Cohen, 2011; Poyatos, 2003; Roura-Pascual, 2005), including natural livestock predators (RU3), whereas the number of species linked to agricultural systems decreases (RU7) (Delibes-Mateos, 2009; Gortázar *et al.*, 2000; Cortés-Avizanda *et al.*, 2015; Benayas *et al.*, 2007; MacDonald *et al.*, 2000). Similarly, the growing realization of the value of nature, both as natural heritage and potential economic value through tourism attraction, has implied an increase in conservation policies (GS5) (IDESCAT, 2020; López-i-Gelats, 2009; Pallares-Blanch, 2012). Thus, protected natural areas have been promoted in the entire Pyrenees region (RS1), up to the point where 47% of the total area in the High Pyrenees is under some degree of protection (Pallares-Blanch, 2012; IDESCAT, 2020). Similarly, wildlife reintroduction programs have been implemented (RU6 and RU7) (Palazón, 2017; Boitani and Linnell, 2015; Margalida *et al.*, 2003).

Climate change severely impacts overall water availability, especially in snow areas (RS1) (López-Moreno *et al.*, 2008; EEA, 2016; Pons *et al.*, 2010; Beniston *et al.*, 2018), and thus the economic viability of ski resorts (A1, A2) (Sánchez-Pulido *et al.*, 2016; Clarimont, 2008; Pons *et al.*, 2015). The regional public administration opted for a public purchase of the ski resorts and for valorization of the winter tourism infrastructure (López Palomeque, 2009) that is currently materialized in the candidature for the 2030 Olympics winter games. Thus, although these subsidies allow ski resorts to survive, most have had to make large investments, for example, for artificial snowmaking (Spandre *et al.*, 2019; Pons *et al.*, 2015). In addition, some resorts have opted for a diversification of offers to become mountain resorts offering a range of recreational activities throughout the year (Fraguell *et al.*, 2016). There has also been a clear commitment to the promotion of mountain tourism (snow and river tourism, agritourism, and nature tourism) with positive results, especially for summer tourism (Fraguell *et al.*, 2016).

2.3.3 *Q3: Which interactions and outcomes result from these trends of change in the elements and attributes?* Completing the system's sensitivity

A total of 16 current and potential adaptation actions and patterns were identified as the interactions (I) and outcomes (O) between the elements and attributes of our system (Table 2). Investments to improve resource management (I5) have been developed extensively in the region. A general increase in entrepreneurship has been observed; for example, activities aimed at the diversification of tourism to decrease the current focus on winter tourism have been carried out, targeting relatively unexploited niches of adventure tourism and rural and eco-friendly tourism (Morata, 2007; Mármol and Vaccaro, 2015). Similarly, efforts to localize product distribution and consumption are made through an increase in the direct selling of local products (Mármol *et al.*, 2018). Moreover, some livestock farmers also opt to shift to an extensification of the activity to reduce production costs, whereas others, taking advantage of subsidies to promote organic farming, decided to shift to organic production (GENCAT, 2020a, 2020b, 2020c, 2020d; Lasanta and Marín-Yaseli 2007). In parallel, there are different initiatives to promote nature conservation, such as reintroduction programs and an increase of protected areas (Palazón, 2017; Boitani and Linnell, 2015; Margalida *et al.*, 2003; Vaccaro, 2005). Networking activities (I8), such as the promotion of land stewardship agreements, are also starting to be carried out in the region, as are self-organizing activities (I7), such as increasing collective endeavors. There is also an evident effort to promote information sharing (I2) among farmers by promoting local varieties/traditional crops, which are better adapted to drought and thus may be better suited to climatic adversities linked to climate change (Scialabba and Müller-Lindenlauf, 2010; Olesen and Bindi, 2002; Mármol and Chopo, 2014). Finally, lobbying activities (I6) are present in the region through the prevalence of snow tourism and efforts to revitalize the building sector (López-i-Gelats *et al.*, 2009). Among the outcomes, social performance measures (O1) are identified through the overall loss of traditional knowledge due to the use of more intensive production practices as well as through the demographic changes occurring in the region (IDESCAT, 2020). Ecological performance measures (O2) can be identified through the landscape consequences of land abandonment (MacDonald *et al.*, 2000; Sanjuán *et al.*, 2018).

2.3.4 *Q4: What adaptation options are available and how do they interact with the existing development options and the mindset of the local population?* Putting together mental frameworks and development pathways

In the last step, an independent assessment of the fit between the actions (Table 2) and mental frameworks or development pathways must be conducted (Tables 3 and 4, respectively). Afterwards, both resulting tables must be crossbred to analyze the fit between the mental frameworks and development pathways (Table 5).

(Q.4.a) Crossing local mental frameworks and adaptation actions

The Agriculturalist and Endogenous development mental frameworks have a very similar fit with the actions, agreeing in 81,25% of the cases and both favoring collective actions and strategies linked to promoting farming activities with the goal of decreasing the current focus on winter tourism (Table 3). The Conservationist and Entrepreneur take opposite sides for most actions (68.75%) but share similarities with Agriculturalist and Endogenous development for some actions. For example, the Conservationist agrees both with the Agriculturalist and the Endogenous development on promoting organic farming and the extensification of livestock activity, but the Entrepreneur disagrees with both actions. On the other hand, the Entrepreneur, the Agriculturalist, and the Endogenous development agree on promoting counter-urbanization, but the Conservationist is against it. In total, the Entrepreneur agrees with the Agriculturalist and the Endogenous development in 37.5% of the occasions, whereas the Conservationist has a higher percentage of agreement with both, 50% with the Endogenous development and 56.25% with the Agriculturalist (Table 3).

(Q.4.b) Crossing global development pathways and adaptation actions

Degrowth and *Business-As-Usual* disagreed in virtually all actions (93.75%) and took opposite sides for more than half of them (56.25%), with *Degrowth* favoring more social and environment-oriented actions, such as land stewardship agreements, conservation initiatives, and organic production, whereas *Business-As-Usual* promotes activities aimed at maximizing productivity, such as the prevalence of snow tourism and revitalizing the building sector (Table 4). *Circular Economy* is an intermediate position between the other two, taking a position of neutrality for many actions (43.75%) and pushing only for those activities that bring opportunities for a business change towards a circular production-consumption model.

(Q.4.c) Crossbreeding mental frameworks and development pathways: addressing the conflict of scales

Once we assessed the fit between adaptation actions and mental frameworks and development pathways, we crossed the two tables to identify which development pathways aligned best with the different local mental frameworks (Table 5). Overall, *Degrowth* is the best fitting development strategy, with positive interaction outcomes in 60,1% of the cases, negative ones in 28,1%, and neutral ones in 12,5%. The worst-fitting development pathway for the region is *Business-As-Usual*, with 62,5% of the interactions with a negative outcome, 26,6% with a positive outcome, and 12,5% neutral. The *Circular Economy* strategy is in an intermediate position between the other two, with 46,9% of the interactions with a negative outcome, 42,2% with a positive outcome, and 12,5% a neutral outcome. *Degrowth* is seen as the most favorable development strategy for the Conservationist (11+ vs 1-), the Endogenous development (12+ vs 2-) and the Agriculturalist (12+ vs 3-) mental frameworks, but it is the least favorable for the Entrepreneur (4+ vs 11-) (Table 5). Expectedly, *Business-As-Usual* is the most favorable development pathway for the Entrepreneur (10+ vs 6-), but the least convenient for the other three (Conservationist:0+ vs 12-, Agriculturalist:3+ vs 11-, and Endogenous development:4+ vs 11-). *Circular Economy* is not clearly favorable or unfavorable for most of the mental frameworks (Conservationist: 5+ vs 7-, Agriculturalist: 8+ vs 6-, Endogenous development: 9+, 6-) but it is unfavorable for the *Entrepreneur*: 5+ vs 11-.

Under the *Circular Economy* and the *Business-As-Usual* approaches to certain actions, there are cases in which all the mental frameworks are displeased. For instance, a *Business-As-Usual* approach neither acting upon the loss of traditional knowledge nor trying to push for sustainable tourism displeases all mental frameworks. Similarly, the *Circular Economy*'s neutral position regarding the revitalization of the building sector and the counter-urbanization process also disfavors everyone. In a few cases, a *Degrowth* or *Circular Economy* approach to certain actions satisfies all mental frameworks without disfavoring anyone: promotion of local varieties and traditional crops, increasing direct selling of local products, and trying to stop out-migration (Table 5). However, for most adaptive actions, there is conflict between perspectives (and interests). Thus, following a *Circular Economy* or a *Degrowth* pathway, there is disagreement between mental frameworks in all but the three aforementioned actions. In the *Business-As-Usual* approach, there is a disagreement between the interested parties for all actions, but one: increasing entrepreneurship. Contrary to the *Degrowth* pathway, which usually satisfies the majority, several adaptation actions developed under the *Business-As-Usual* development pathway satisfy only one mental framework (Entrepreneur), such as pushing for the prevalence of snow tourism or revitalizing the building sector. However, despite *Degrowth* being the best strategy in this case, it is also worth mentioning that certain actions under the *Degrowth* approach do not satisfy the majority of mental frameworks. For instance, decreasing entrepreneurship or disfavoring counter-urbanization fits only with the mindset of Conservationist, displeasing the rest.

2.4 Discussion

Acknowledging the local context in which adaptation actions need to be implemented is key to preventing maladaptation (Schipper, 2020; Magnan *et al.*, 2016). Here, we develop and apply guidelines that can help contextualize the social background under which adaptation actions will be implemented. Specifically, these guidelines help to identify potential sources of conflict arising from a mismatch between global development planning and local communities' interests, a common documented source of maladaptation (Henstra, 2016; Glaas and Juhola, 2013). The guidelines have been effective in enabling the user to globally assess which development pathway would better fit the local mental models in a given context, and identifying which specific actions have better resonance with the local views. Thus, it helps to identify which mental models are favored under which pathway and where a conflict between them may arise. Given that the guidelines help to understand the social response towards forcing global development strategies into local settings, it is a useful tool to identify sources of maladaptation *ex-ante* (Asare-Nuamah *et al.*, 2021; Moser and Ekstrom, 2010), and so can be a tool to help prevent maladaptation. The guidelines are especially helpful in contexts where resources are limited, conflict of scales between local communities and global actors and trends are evident, and/or when maladaptation processes already exist. In such contexts, the mismatch between national-level strategies, international trends, local interests, and mental models might lead to a maladaptive dynamic that could further exacerbate the vulnerability of the population to shocks and changes. Thus, it is essential to actively seek an understanding of local mental models and how they fit within the development pathways available to promote their successful adaptation to global changes. This is an important element of community resilience, which should be considered when planning development activities.

The guidelines are sufficiently flexible to fit smoothly with diverse classifications of the local population or diverse development pathways. Therefore, these guidelines can be applied in different social-ecological systems with varying local population groups and where different development pathways may be implemented. Furthermore, some aspects of the guidelines can be adjusted to meet the needs of future users. For example, the current guidelines are designed to penalize inaction. When creating the Crossbreeding Table (Table 5), if a development pathway does not take action on something that a mental framework has an opinion about, the outcome of the interaction is negative. For instance, in our case, the *Circular Economy's* neutral stance regarding many actions (Table 4) results in a significant number of interaction outcomes with negative values (Table 5). While inaction on something may not be as detrimental as taking actions in the opposite direction, we decided that categorizing levels of positivity or negativity might add complexity and potential bias to the analyses. However, these quantitative levels can easily be implemented if desired by the user, by assigning numeric values to each cell.

Studies on maladaptation have shown that generalizing the locals' mindsets can be counterproductive (Albizua *et al.*, 2019; Neset *et al.*, 2019); therefore, the more detailed the social groups are, the less likely they are to encounter unintended conflicts. However, increasing detail also increases the complexity of the analysis. Thus, a balance between the level of detail and complexity must be found. In our guidelines, actor groups and their response to an action can endlessly vary. Subdivisions within discourses are encouraged, as these can help identify potentially marginalized groups at early stages and give them a voice throughout the decision-making process (Sibiya *et al.*, 2022; Marini Govigli *et al.*, 2020). Nonetheless, conflicts within a mental framework are inevitable. For example, in the Pyrenees, Conservationists generally support extensive livestock management practices because they are more compatible with nature preservation and may contribute to a more heterogeneous and biodiverse landscape (Wolff *et al.*, 2001; Chiarello, 2000). However, some Conservationists may have a negative view of extensive practices because they require the use of a larger land area compared to intensive practices (Kremen, 2015; Ekroos *et al.*, 2016). Therefore, for the sake of simplification, if the outcome of an interaction is associated with a particular sign for an action, it does not imply that there are no deviations from it. It means that after weighing the pros and cons, a position must be set. Nonetheless, these considerations are important in order to avoid the generalization of the local mental models.

The presented guidelines assume an equal distribution of decision-making power and constituents among mental framework actors, with no data on population numbers within each mental framework considered. Whether or not this would significantly affect the final decision or specific activities goes beyond the scope of this paper. However, weighting could be implemented in certain steps of the guidelines. For example, when summarizing the overall outcomes of each development pathway (Table 5), participatory weighting can be applied to each mental framework. In addition, some actions may currently have much more economic, ecological, and social impact than others. While weighting actions based on their current relevance can be considered, caution must be taken, as this approach could potentially slow down adaptation. Weighting based on the present static scenario tends to favor well-established assets while potentially hindering the exploration of new ones. For example, in the Pyrenees, economic weighting based on the current importance of an action might lead policymakers to prioritize winter tourism, given its primary economic role (Spandre *et al.*, 2019; Pons *et al.*, 2015). However, the sustainability of snow-based tourism is uncertain in the mid-term (Steiger *et al.*, 2019; Sánchez-Pulido *et al.*, 2016). Such a measure could thus be counterproductive and prevent the transition to a more diversified, resilient economy (Fraguell *et al.*, 2016).

The application of the guidelines to the Pyrenees region revealed that certain adaptation actions are more prone to conflict than others. For example, revitalizing the building sector or maintaining snow tourism are actions with high opportunity costs, as they only align with one of the local mental frameworks. Continuing these actions could lead to maladaptation and negatively impact the local population. In contrast, actions like promoting short distribution circuits for local products or cultivating local crop varieties have a higher likelihood of success, as they are generally well-received. Other actions rise a lot of conflict, such as increasing collective management or diversifying tourism towards adventure tourism. The outcomes of these actions can potentially shift vulnerability from one group to another, depending on how they are implemented. Therefore, careful consideration is required to address potential conflicts and ensure equitable outcomes (Schipper, 2020; Juhola, 2016).

Among the development pathways, the *Degrowth* approach aligns well with the local social context. *Degrowth* has been proposed as a suitable strategy for local economies to integrate into global capitalist systems (Rooney & Vallianatos, 2021). However, under a *Degrowth* pathway, vulnerability shifts towards the entrepreneurial mental framework, whose needs may be overlooked. Therefore, compensation measures for this affected group should be considered (Eriksen *et al.*, 2021). The crossbreeding table helps to identify specific actions that carry the risk of shifting vulnerability towards this mental framework. While *Degrowth* generally fits well with the local context, other pathways may better align with locals' interests for certain actions. For example, the *Business-As-Usual* approach, which limits or reduces nature conservation areas, aligns better with most mental frameworks. However, it is important to note that rural tourism in this region is closely linked to protected areas (Pallares-Blanch, 2012; Mármol & Vaccaro, 2015). Considering the progressive disappearance of snowy areas due to climate change (López-Moreno, 2005; Pons *et al*., 2010; Beniston *et al*., 2018), promoting nature conservation could be a viable long-term strategy (Fraguell *et al*. 2016; Pons, 2014). However, effective communication and ensuring that conservation strategies do not interfere with locals' interests are crucial. In cases where the interests of locals are compromised, effective compensation measures should be included in the agenda (West *et al*., 2006; Siegele *et al*., 2009).

Overall, the *Business-As-Usual* pathway is the least suitable for the Pyrenean region, as it aligns only with the entrepreneurial mental framework. Adopting such a pathway leads to shifting vulnerability, high opportunity costs, and negative externalities. Other studies examining the plausibility of sustainable development under the *Business-As-Usual* pathway also concluded that it would fail to meet sustainability goals, such as SDGs or Aichi targets (Harrison *et al.*, 2019). The social-contextualization guidelines demonstrate that, at least for the Pyrenees region, *Business-As-Usual* is not environmentally sustainable and fails to accommodate the needs of the majority of local mental frameworks.

2.5 Conclusions

As the world is facing global environmental change, the development of effective adaptation strategies is crucial. However, identifying appropriate actions can be challenging and there is a risk of maladaptation. To mitigate this risk, we created step-by-step guidelines to facilitate the understanding of processes that may lead to maladaptation. These guidelines establish connections among drivers, trends of change, adaptation actions, and potential conflicts of interest. These guidelines enable the assessment of how global development pathways may intersect with the interests of the local population. Applying these guidelines to the Pyrenees case study revealed potential sources of maladaptation, including shifting vulnerability, high opportunity costs, and negative externalities. Our findings indicate that a *Degrowth* development pathway, although not currently implemented in the region, aligns better with the local discourse. In contrast, the *Business-As-Usual* pathway often contradicts the interests of locals, favoring actions that displease them while hindering those actions that would be welcomed. The Pyrenees case study serves as an example of the mismatch between the visions of local communities and development pathways dictated by global trends. Therefore, it is essential to assess the risk of maladaptation using tools, such as the one developed here, which can help identify and prevent actions that are likely to generate conflicts. Importantly, these guidelines were intentionally designed to be flexible and applicable to other systems.

Tables

Table 1. Trends in the Socio-ecological system (SES). List of main SES components identified for the Pyrenees region classified following Ostrom (2007), with their respective references. For Actors, Governance System, Resource System and Resource Units, current trends of increase/decrease and ID numbers to link each element to an interaction/outcome in Table 2 are provided. Ostrom's (2007) notation for each SES component is provided in brackets.

SES-group	SES Component affected	ID	Trend	References
Actors (A)	Population that works in the tertiary sector (A1)	1	Increase	Mármol *et al.*, 2018; Mármol and Vaccaro 2015; Vaccaro and Beltran, 2009; Tulla, 2003
	Population working in agriculture (A1)	2	Decrease	Mármol and Vaccaro, 2015; Vaccaro and Beltran, 2009; García-Martínez *et al.*, 2009
	Organic production farmers (A1)	3	Increase	Fraysse, 2019; CCPAE, 2020; Guirado *et al.*, 2011
	Newcomers and population with more «urban» values (A1, A2)	4	Increase	IDESCAT, 2020; Carrasco and Alonso, 2010; Chevalier, 1993; Mármol, 2012; Solé *et al.*, 2012
	People with higher education (A1)	5	Increase	Gutiérrez, 2004; IDESCAT, 2020
	Cooperatives and microenterprises (A1, A5)	6	Increase	Local experts
	Ski resorts (A1) and profitability of ski resorts (A2)	7	Decrease	Sánchez-Pulido *et al.*, 2016; Clarimont, 2008; Pons *et al.*, 2015; Lasanta, 2007b ; Moreno-Gené *et al.*, 2020
Governance System (GS)	Associative network (GS3)	8	Increase	Local experts
	Direct sales, alternative products and distribution circuits (GS3)	9	Increase	Mármol *et al.*, 2018
	Communal management of pastures and forests, informal agreements (GS6)	10	Decrease	Gil, 2000; Iriarte, 2002; Vaccaro and Beltran, 2007
	Subsidies to agriculture and organic production (GS8)	11	Increase	GENCAT, 2020a, 2020b, 2020c. 2020d; Lasanta and Marín-Yaseli 2007
	Local nature conservation policies (GS5)	12	Increase	IDESCAT, 2020; Pallares-Blanch, 2012
Resource system (RS)	Lowland meadows with alpine biodiversity (RS1)	13	Decrease	Sanjuán *et al.*, 2018; Ascaso *et al.*, 2020
	Forested area (RS1)	14	Increase	Sanjuán *et al.*, 2018; Cohen, 2011; Poyatos, 2003; Roura-Pascual, 2005
	Local/traditional crops (vineyards) and products (cheese) (RS1, RS5)	15	Increase	Mármol *et al.*, 2018; Mármol and Vaccaro, 2015; del Mármol and Chopo, 2014
	Snow areas (RS1)	16	Decrease	López-Moreno, 2005; Pons *et al.*, 2010; Beniston *et al.*, 2018; EEA, 2016
	Water (may affect livestock, agriculture, biodiversity and humans) (RS1)	17	Decrease	López-Moreno *et al.*, 2008; Beguería *et al.*, 2003; EEA, 2016
	Areas with agriculture/livestock (RS1, RS4)	18	Decrease	MacDonald *et al.*, 2000; García-Martínez *et al.*, 2009; Mármol and Vaccaro 2015; Vaccaro and Beltran, 2009
	Small villages (RS4)	19	Decrease	García and Mateu 2003; Gutiérrez, 2001
	Areas under some degree of protection (RS1)	20	Increase	IDESCAT, 2020; Vaccaro, 2005; Vaccaro and Beltran, 2009
Resource units (RU)	Forest biomass (RU2)	21	Increase	Sanjuán *et al.*, 2018; Cohen, 2011; Poyatos, 2003; Roura-Pascual, 2005
	Number of ungulates, medium size carnivores and scavengers (RU2)	22	Increase	Delibes-Mateos, 2009; Margalida *et al.*, 2003; Gortázar *et al.*, 2000; Cortés-Avizanda *et al.*, 2015
	Natural predators of livestock and social consequences (RU3)	23	Increase	Palazón, 2017; Boitani and Linnell, 2015; Margalida *et al.*, 2003; Piédallu *et al.*, 2016
	Number of forest wild species and reintroduced species (RU6, RU7)	24	Increase	Palazón, 2017; Boitani and Linnell, 2015; Margalida *et al.*, 2003; Pereira et al, 2015
	Wild species linked to agricultural or farming environments (RU7)	25	Decrease	Benayas *et al.*, 2007; MacDonald *et al.*, 2000; Queiroz *et al.*, 2014 ; O'Rourke *et al.*, 2016

Social and economic drivers	Integration into a globalized economy (S1)	Vaccaro and Beltrán, 2009; Mármol and Vaccaro, 2015
	Tertiarization of the economy (S1)	Marín-Yaseli *et al.* 2003; García-Martínez *et al.* 2009; López-i-Gelats *et al.* 2011; Sancho, 2011; Sancho-Reinoso, 2013
	Decrease of rural population (S2)	García and Mateu 2003; Marín-Yaseli *et al.* 2003; García-Martínez *et al.* 2009; Gutiérrez, 2001; Alados *et al.*, 2014
	Estabilization of the population (S2)	IDESCAT, 2020
	Increase of environmental policies (S4)	IDESCAT, 2020; Pallares-Blanch, 2012; Vaccaro, 2005
Ecological divers	Winter shortening (ECO1)	IPCC, 2014; Calbó, 2016; Kreyling and Henry, 2011
	Temperature increase (ECO1)	IPCC, 2014; Calbó, 2016
	Precipitation decrease (ECO1)	IPCC 2014; Beguería *et al.*, 2009; López-Moreno *et al.*, 2008; Calbó, 2016
	Increase of extreme events (ECO1)	Stott, 2016; Peñarrocha *et al.*, 2002; Millán, 2014; Sillmann and Roeckner, 2008

Table 2. Interactions/Outcomes. List of current adaptive actions identified in the Pyrenees region as a result of Interactions and Outcomes between the Socio-Ecological System (SES) components and drivers identified in Table 1. SES-framework notation (Ostrom, 2007) for each interaction/outcome, ID of SES component(s) they are linked to, and a description of each action are provided.

Current actions and activities	Interaction/ Outcome	ID of SES elements related	Explanation of the action
Extensification of the livestock activity	I5	3, 18	Strategy of going from intensive livestock production to extensive one, reducing livestock density and costs of production by reducing external inputs (such as N).
Loss of local traditional knowledge and practices	O1	4	Loss of traditional knowledge and practices (such as transhumance, traditional land restoration practices, or traditional water, soil and pest management knowledge) in favor of more intensive, technological and productive practices.
Promotion of local varieties/traditional crops (NUS)	I2/I6	11, 15	Promotion of neglected and underutilized species (NUS), native edible plants from the region that were traditionally cultivated but have been displaced by an agricultural focus on market demands
Shifting to organic production for livestock farming	I5	11	Favoring a farming system that prioritizes sustainability, biodiversity and maintaining soil fertility over increasing productivity
Increasing direct selling of local products (distribution)	I5	9	Promotion of short distribution circuits and local consumption of goods produced in the region
Increasing number of collective endeavors	I3/I7	8	Promotion of local associations (such as School of shepherds or Land bank initiatives) to facilitate land management and decision making
Increasing entrepreneurship	I5	6, 10	Promotion of new business and business models from any sector, linked to the emergence of new job opportunities
Diversification of tourism towards adventure tourism (excluding ski)	I5	1, 7, 16, 17	Switching from snow tourism towards nature-based adventure tourism, with activities such as rafting, kayaking or mountain bike, but excluding ski. The focus of this type of tourism is on individual leisure and business potential, and thus it does not imply any sort of restrictions of access, activities or number of tourists.
Diversification of tourism towards rural/eco-friendly tourism	I5	1, 7, 16, 17	Switching from snow tourism towards eco-friendly activities (like birdwatching or mushroom picking) and agrotourism (linked to farming activities both in the production of goods, such as cheese, and/or as accommodation of tourists in farms). The focus of this type of tourism is on ensuring nature and culture preservation, and thus it implies access restrictions, as well as limitations on the number of tourists and activities developed.
Prevalence of snow tourism	I6	7	Maintenance of snow-based tourism (mainly ski resorts), through artificial snowmaking if necessary
Revitalization of the building sector	I5/I6	1	Promoting construction, mainly linked to seasonal accommodation for tourists
Increase of nature conservation areas, projects and initiatives	I5	12, 20, 21, 22, 23, 24	Increasing the amount and extension of protected areas, as well as any initiative or project related to nature conservation, such as wildlife reintroductions.
Promoting initiatives of land stewardship	I8	10,	Agreements between local landlords and stewardship entities (not involving the government) with the aim of sustainably managing the land, maintaining its ecosystem services and preserving nature. The workforce is mainly composed by volunteers or by technicians funded by public or private grants.
Land abandonment (landscape scale)	O2	2, 13, 14, 18, 21, 22, 23, 24, 25	The abandonment of any form of land management.
Demographic changes-counterurbanization	O1	4, 5	Demographic process in which people from urban areas migrate and establish in rural areas
Demographic changes-Outmigration	O1	2, 19	Migration of people from mountain regions to other regions, usually large, cities located in the lowlands

Table 3. Mental frameworks. Fit between actions carried out in the Pyrenees and the mental framework coexisting in the region: Conservationist, Entrepreneur, Agriculturalist and Endogenous development (López-i-Gelats *et al.*, 2009). Sign '+' indicates that the mental framework is pleased with the development of such action, sign '-' means it is displeased, and a '0' means the mental framework does not have a specific position regarding the implementation of this action.

	Conservationist	Entrepreneur	Agriculturalist	Endogenous development
Extensification of the livestock activity	+	-	+	+
Loss of local traditional knowledge	-	+	-	-
Promotion of local varieties/traditional crops (NUS)	0	+	+	+
Organic production for livestock farming	+	-	+	+
Increasing direct selling of local products (distribution)	+	+	+	+
Increasing number of collective endeavors	0	-	+	+
Increasing entrepreneurship	0	+	0	+
Diversification of tourism towards adventure tourism (excluding ski)	-	+	0	+
Diversification of tourism towards rural/eco-friendly tourism	+	-	+	+
Prevalence of snow tourism	-	+	-	-
Revitalization of the building sector	-	+	-	-
Increase of nature conservation areas, projects, and initiatives (e.g., wildlife reintroduction)	+	-	-	0
Promoting initiatives of land stewardship	+	-	+	+
Land abandonment (landscape scale)	+	-	-	-
Demographic changes- counterurbanization	-	+	+	+
Demographic changes- Outmigration	0	-	-	-

Table 4. Development pathways. Fit between actions carried out in the Pyrenees and the proposed Development pathways: Degrowth, Circular Economy, and Business-As-Usual (for specific definitions, see Table A1, Appendix 2). A '+' action-Development pathway interaction means that this development strategy would likely implement such action, a '-' means it would stop, limit, or reduce it, and a '0' means it would not act upon it.

	Degrowth	Circular Economy	Business-As-Usual
Extensification of the livestock activity	+	0	-
Loss of local traditional knowledge	-	-	0
Promotion of local varieties/traditional crops (NUS)	+	+	-
Organic production for livestock farming	+	+	-
Increasing direct selling of local products (distribution)	+	+	0
Increasing number of collective endeavors	+	0	0
Increasing entrepreneurship	0	+	+
Diversification of tourism towards adventure tourism (excluding ski)	-	0	+
Diversification of tourism towards rural/eco-friendly tourism	+	+	0
Prevalence of snow tourism	-	-	+
Revitalization of the building sector	-	0	+
Increase of nature conservation areas, projects and initiatives (e.g., wildlife reintroduction)	+	0	-
Promoting initiatives of land stewardship	+	0	-
Land abandonment (landscape scale)	-	-	-
Demographic changes- counterurbanization	-	0	+
Demographic changes- Outmigration	-	-	0

Table 5. Crossbreeding table. Table depicting the outcome of the interaction between development pathway and mental framework for each of the actions. If both the development pathway and mental framework had the same response towards an action (both positive or both negative), the outcome was assigned a '+' (colored green). If development pathway and mental framework had opposing signs, the outcome was assigned a '-' (colored red). If a development pathway had a 0 regarding an action the mental framework had an opinion about (either positive or negative), the outcome was considered '-'. Finally, any action for which the mental framework was not affected was always considered neutral and assigned a '0' (colored yellow). Cons. = Conservationist; Entr. = Entrepeneur; Agr. = Agriculturalist; En. Dev. = Endogenous Development

Development pathways	Degrowth				Circular Economy				Business-As-Usual			
Mental frameworks	Cons.	Entr.	Agric.	En. dev	Cons.	Entr.	Agric.	En. dev	Cons.	Entr.	Agric.	En. dev
Extensification of the livestock activity	+	-	+	+	-	-	-	-	-	+	-	-
Loss of local traditional knowledge	+	-	+	+	+	-	+	+	-	-	-	-
Promotion of local varieties/traditional crops (NUS)	0	+	+	+	0	+	+	+	0	-	-	-
Shifting to organic production for livestock farming	+	-	+	+	+	-	+	+	-	+	-	-
Increasing direct selling of local products (distribution)	+	+	+	+	+	+	+	+	-	-	-	-
Increasing number of collective endeavors	0	-	+	+	0	-	-	-	0	-	-	-
Increasing entrepreneurship	0	-	0	-	0	+	0	+	0	+	0	+
Diversification of tourism towards adventure tourism (excluding ski)	+	-	0	-	-	-	0	-	-	+	0	+
Diversification of tourism towards rural/eco-friendly tourism	+	-	+	+	+	-	+	+	-	-	-	-
Prevalence of snow tourism	+	-	+	+	+	-	+	+	-	+	-	-
Revitalization of the building sector	+	-	+	+	-	-	-	-	-	+	-	-
Increase of nature conservation areas, projects and initiatives (e.g. wildlife reintroduction)	+	-	-	0	-	-	-	0	-	+	+	0
Increasing initiatives of land stewardship	+	-	+	+	-	-	-	-	-	+	-	-
Land abandonment (landscape scale)	-	+	+	+	-	+	+	+	-	+	+	+
Demographic changes- counterurbanization	+	-	-	-	-	-	-	-	-	+	+	+
Demographic changes- Outmigration	0	+	+	+	0	+	+	+	0	-	-	-

Chapter 3

A quantitative approach to the understanding of social-ecological systems: a case study from the Pyrenees

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Chapter 3. A quantitative approach to the understanding of social-ecological systems: a case study from the Pyrenees

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Abstract

Mountains are social-ecological systems exposed to multiple climatic and socioeconomic drivers, making them good candidates for study from a social-ecological (SES) perspective. Focusing on a Pyrenean SES, we use piecewise structural equation modeling and network analysis to quantitatively describe the relationships between water resources, biodiversity, and the social and economic elements of the system. Our results show that the current economic focus and dependency on tourism severely impact water resources and biodiversity. Future climatic scenarios will aggravate the pressures on hydrology and may threaten winter tourism. Actions to alleviate the pressures on water and biodiversity and to increase socioeconomic resilience are a priority. We argue that such actions will have to include both a diversification of the region's touristic offer and of the economy, coupled with a more sustainable use of water resources. Our findings also highlight the importance of using quantitative approaches in the study of social-ecological systems, which can become important tools to improve sustainable resource management.

3.1 Introduction

Climate change severely threatens mountain ecosystems, particularly at high elevations (Hock *et al.* 2019). Mountains provide many ecosystem services to human populations living in and outside them (Palomo, 2017; Hock *et al.*, 2019). Foremost amongst these services at a global scale is freshwater supply. In Mediterranean countries, where summers are hot and dry, human settlements depend heavily on mountain water resources (Beguería *et al.*, 2003; Grima and Campos, 2020). The joint effects of climate and land use change have already prompted a general decrease in water yield and runoff in Mediterranean rivers over the last decades (Beguería *et al.*, 2003). Mountain regions also greatly contribute to the Earth's biodiversity. They are considered biodiversity hotspots, home to a wide range of endemic, rare, and threatened species (Rahbek *et al.*, 2019a). Mountains comprise roughly 30% of the terrestrial area identified as Key Biodiversity Areas (KBAs), and a large portion of mountain areas is under protection (Rodríguez-Rodríguez *et al.*, 2011). Elevational and phenological changes in mountain species due to climate change exacerbate their risk of extinction (McCain and Garfinkel, 2021; Vitasse *et al.*, 2021), and cause a radical reorganization of ecological communities and food webs (Lurgi *et al.* 2012).

In parallel to environmental challenges, mountain regions are undergoing important socio-economic changes (Hock *et al.* 2019), with impacts on ecosystem services and the associated upstream and downstream human settlements (Palomo, 2017). In particular, Mediterranean alpine systems in Europe have experienced difficulties adapting to these changes. The agricultural sector has become increasingly marginalized (Ustaoglu and Collier, 2018), and local economies have gradually shifted their focus to the service sector, mostly tourism, for local economic development (Mármol and Vaccaro, 2015; Heberlein *et al.*, 2002). This has additionally prompted the integration of mountain regions into increasingly urbanized and globalized societies (Vaccaro and Beltran, 2009). Consequently, both local depopulation due to agricultural abandonment and growing urban development to accommodate tourism coexist in the same space. Farmland abandonment, urbanization, and the establishment of protected areas and ski resorts have led to important demographic and socio-professional changes (Jiménez-Olivencia *et al.*, 2021; Pallarès-Blanch *et al.*, 2014; Vaccaro and Beltran, 2009) and to important impacts on the surrounding environment (Beguería *et al.*, 2003; Jiménez-Olivencia *et al.*, 2021).

To adapt to such socioeconomic and environmental changes, mountain territories and communities are experiencing a profound reorganization process. To properly address the challenges that these territories are facing, interdisciplinary approaches such as Social-Ecological Systems (SES) are especially relevant. They bridge the gap between social and ecological research by integrating interactions between humans and nature, as well as the drivers influencing them, under a common framework (Ostrom, 2009; Virapongse *et al.*, 2016; Klein *et al.*, 2019a).

SES approaches have been applied in a wide range of fields of knowledge and sectors (e.g., water management: Cabello *et al.*, 2015; conservation: Allen *et al.*, 2021; agriculture: Guerrero *et al.*, 2019; tourism: Adrianto *et al.*, 2021; fisheries: Botto-Barrios *et al.* 2020; Elsler *et al.*, 2021), bringing their own perspectives, frameworks, and methodologies. For instance, qualitative approaches have focused on applying the SES framework to diagnose problems in common-pool resource use (e.g., Cole and Browne, 2015), or to describe innovative solutions for sustainable agri-food systems (e.g., Guerrero *et al.*, 2019). Quantitative approaches, on the other hand, collect SES data using different methods and use them in a variety of analyses and theoretical or empirically-based models, including Agent-Based Models, Fuzzy Cognitive Mapping, hydrological models, network analysis or Structural Equation Modeling (Bengochea Paz *et al.*, 2020; Elsler *et al.*, 2021; Heckbert *et al.*, 2013; Hafezi *et al.*, 2020; Cabello *et al.*, 2015; Allen *et al.*, 2020; Noble *et al.*, 2021). Regardless of the methodology used, Rissman and Gillon (2017) showed that studies incorporating both the socio-economic and ecological dimensions of systems were twice as likely to arrive at management recommendations than those that did not. Considering both dimensions is not only fundamental to understanding the current state of ecosystems, but also to supporting the design of sustainable development strategies. However, mountain SES studies frequently fall short of analyzing a comprehensive set of potentially relevant SES elements, and often do not consider both the socio-economic and ecological dimensions in the same study (Zango-Palau and Claramunt-López, under review).

In the Pyrenees, studies investigating how water resources, biodiversity, and upstream communities affect each other in a quantitative manner are lacking. To fill this gap, this work aims to quantify how a comprehensive set of social-ecological factors, including hydrological, land-use, climatic, environmental, biodiversity, and socio-economic elements, interact with each other in order to obtain a holistic picture of the current functioning of this SES. Our objective is to assess how changes in one variable can affect multiple variables simultaneously through both direct and indirect paths. Moreover, by quantitatively measuring such effects, we aim to identify the relative importance of each variable in driving changes to other variables. For example, this analysis can help understand what the main economic focus of the region is, and how heavily the current economic model depends on it. Ultimately, we can assess the direct and indirect paths that affect resource availability and biodiversity in the region. By shedding light on how these social-ecological variables are intertwined and influence one another, we suggest potential adaptation strategies for a sustainable development of the region.

3.2 Methods

3.2.1 Study site

The study area includes the upper part of the Segre River watershed in Catalonia, from its Pyrenean headwaters to the Oliana Reservoir, covering a surface area of approximately 1993 km^2 between Alt Urgell and La Cerdanya counties. Water from the Segre upper basin is used for domestic consumption, agriculture and livestock farming, aquaculture, snowmaking, and industrial activities, as well as non-consumptive uses, such as recreation and hydropower (Confederación Hidrográfica del Ebro, 2015). The area has been suffering from depopulation since the 1960s, in favor of more industrialized areas. From the 1990s onwards, immigration has been the main factor preventing the resident population from declining (Pallarès-Blanch *et al.*, 2014, Guirado González, 2014). Since the 1980s, the region has shifted towards an economy focused on the services sector, although agriculture and intensive livestock farming are still present in the region. While Alt Urgell has a more diversified economy, La Cerdanya has specialized into tourism and hosts five ski resorts.

3.2.2 Elements of the social-ecological system

We used Ostrom's SES framework tiers (Ostrom, 2009; Vogt *et al.*, 2015) to identify the elements of our system. Thanks to the multitier collection of elements provided by this framework, information can be searched systematically, preventing missing potentially relevant elements of the system (Delgado-Serrano and Ramos, 2015; Ostrom, 2009). Using public databases (see Appendix 3, Supplementary material A – Data sources and processing, and Supplementary material B – Missing data imputation), we collected hydrological, climatic, biodiversity, land-use, and remote sensing-derived environmental data, as well as socio-economic variables from the study area. This resulted in a total of 35 variables measured annually from 2000 to 2020 (Table 1). Due to the absence of consistent socio-economic data for the region before the year 2000, the timespan of the study had to be restricted to this period. The dataset generated for the current study and the scripts used are available from the corresponding author upon request.

3.2.3 Building the social-ecological network

We hypothesized a network structure based on 67 direct relationships among the 35 social-ecological variables of the system, based both on the available literature (see Appendix 3, Supplementary material C – Hypotheses; and Supplementary material D – Model evaluation, Table D2) and the authors' expert knowledge of the system. All statistical analyses were performed in R version 4.3.0 (R Core Team, 2021), using RStudio version 2023.03.1.

We used the *piecewiseSEM* package to statistically test the set of hypothesized relationships between the variables (Lefcheck, 2016). Structural Equation Modeling (SEM) is a powerful statistical technique that enables the analysis of relationships among variables. By assembling multiple regression models, it connects all variables into a single network, facilitating the testing of multiple hypotheses at once. Moreover, this approach enables the quantification of both direct and indirect relationships, as variables in the network can act as predictors and responses at the same time. A notable advantage of using *piecewiseSEM*, as opposed to traditional SEM, is that it breaks down the analysis into smaller pieces (sub-models). This flexibility not only allows for a much more manageable handling of non-normal data or other violations of model assumptions, but also makes it possible to conduct the analysis with smaller sample sizes.

We specified and tested the individual regression models for each response variable (Appendix 3, Supplementary material C – Hypotheses, Table C2). Continuous response variables were fitted using linear regressions. Count data were fitted using generalized linear models (GLMs) with a Poisson distribution. Under and overdispersion in GLMs were tested using the function *testOverdispersion* from R package *DHARMa* (Hartig and Hartig, 2017), and when encountered, quasipoisson or negative binomial responses were used to account for it. Due to the use of time series data, there could be temporal autocorrelation in some of the response variables. In such cases, autocorrelation was accounted for by running a generalized least squares (GLS) model with first-order autocorrelation (1 year lag). When the assumptions of the GLS were not met, 1-year-lagged residuals were included as an additional predictor in the original model. The assumptions of the linear models were validated using the *gvlma* package (R Core Team, 2021). When encountered, heteroscedasticity was accounted for in the GLS model. The goodness of fit of the linear models was based on the model's R^2 and the global model's significance, as well as the significance of each individual relationship tested. For the generalized linear models, it was assessed based on the pseudo-R^2 (*1-(Residual Deviance/Null Deviance)*) and the significance of each individual relationship tested. Finally, for the generalized least squares models, the goodness of fit was evaluated by measuring the correlation between the observed values and the fitted values of the response variable, as well as the significance of each individual relationship specified in the model.

To test if our data fit the hypothesized network configuration, all the individual models for each response variable were joined into a single global model using the function *psem()* from the *piecewiseSEM* package (version 1.2.1, Lefcheck, 2016). A d-separation test was run to find correlations among variables that were unaccounted for. Correlations that could have a potential causal link were included in the individual models when: 1) the model assumptions remained unaffected; 2) the model fit improved. When the inclusion of the correlated variable in the model affected the relationship with the other variables, we considered those for which the causal link with the response was more robust. All remaining relationships were specified as correlated errors in the model. Goodness of fit of the global SEM model was assessed using the test of directed separation using Fisher's C statistic and its associated p-value.

Due to the disparity in units and ranges between all included variables, the standardized estimates for each pairwise relationship from the model were used to create a matrix encompassing all interaction coefficients (Table 2). A quantitative social-ecological network depicting the relationships among all variables in our SES was represented using the *igraph* package (Csárdi and Nepusz, 2006) and edited using Adobe Illustrator CC19 to display the variable types and modules.

3.2.4 Modularity of the social-ecological network

The resulting network of interactions between social-ecological factors and their corresponding interaction coefficients, revealed by path analysis (see section *Building the social-ecological network*), was analyzed using complex network tools. All relationships with p-values < 0.1 were considered for this analysis. We quantified the degree of each node as the number of links it had to other nodes in the network. Modularity analyses are useful for identifying groups of variables that are tightly linked together (modules) and variables that act as connectors between the different modules of the system. This can be helpful, for instance, to identify optimal paths to apply changes in one variable, as well as to see which variables would trigger changes across the entire system if they changed. The modularity analysis was carried out following the simulated annealing optimization approach to partition the network into connected sub-groups or modules proposed by Guimerà and Amaral (2005), which aims at maximizing the modularity function:

$$M = \sum_{s=l}^{N_M} \left[\frac{l_s}{L} - \left(\frac{d_s}{2L} \right)^2 \right] . (1)$$

where N_M is the number of modules, L is the number of links in the network, l_s is the number of links between nodes in module s, and d_s is the sum of the degrees (number of links to or from that node) of the nodes in module s. The partition of nodes into subsets of the nodes in the network that maximizes M constitutes the modules of the network. In addition to module membership, this approach also allows us to calculate measures of within-module connectivity and participation coefficients, which quantify the degree of connectivity of each node within its own module and the rest of the network, respectively. Within-module connectivity, or simply 'connectivity' from now on, is calculated thus:

$$z_i = \frac{k_i - \underline{k_{si}}}{\sigma_{k_{si}}} (2)$$

where k_i is the number of links of node i to other nodes in its module s_i, $\underline{k_{si}}$ is the average of k over all the nodes in s_i, and $\sigma_{k_{si}}$ is the standard deviation of k in s_i. Participation coefficient is defined as:

$$P_i = 1 - \sum_{s=1}^{N_M} \left(\frac{k_{is}}{k_i} \right)^2 (3)$$

Where k_{is} is the number of links of node i to nodes in module s, and k_i is the total degree if node i. Large values of P_i (close to 1) indicate that node i has its links uniformly distributed across all modules in the network, whereas P_i close to 0 indicates that all its links fall within the module it belongs to. We calculated modularity M, the corresponding modular partition of nodes (modules), z_i's, and P_i's using the *rnetcarto* library in R (Doulcier and Stouffer 2015; Guimerà and Amaral 2005) on the quantified version of our network (i.e., considering the regression coefficients from path analysis as interaction strengths). Given the stochastic nature of the simulated annealing approach, we ran 100 replicates of the *netcarto* algorithm and kept the best partition obtained amongst them (i.e., the one yielding the largest modularity score M – Eq. 1).

To assess the importance of nodes within the network, we quantified node-level betweenness centrality. Node betweenness is defined as the fraction of shortest paths between any pair of nodes in the network that traverse it. We quantified this measure for each node in network v as:

$$C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}} (4)$$

where *s*, *v*, and *t* are elements of the set *V* of nodes in the network; σ_{st} is the number of shortest paths from node *s* to node *t*; and $\sigma_{st}(v)$ is the number of those paths that traverse node *v* (Freeman 1979). The larger the $C_B(v)$, the larger the fraction of shortest paths that traverse it, and hence, the more central it is in the network.

Based on their connectivity (z) and participation (P) coefficients, nodes were classified as (1) ultra-peripheral, (2) peripheral, or (3) connectors (Guimerà and Amaral 2005). Ultra-peripheral nodes establish almost all their links within their module ($z<2.5$; $P\approx0$), peripheral nodes form at least 60% of their links within their module ($z<2.5$; $0 < P \leq 0.625$), and connectors make at least 50% of their connections in other modules (<2.5; $0.625 < P$).

Finally, we explored the importance of the magnitudes of the relationships in driving modularity results, i.e. we assessed whether a qualitative version of the network and a quantitative one would result in the same modules. For both versions of the network, only the relationships found through the piecewiseSEM analysis explained above were used. In the qualitative version, instead of using the magnitude of the relationships, we only considered the presence/absence of a relationship (1 or 0); in the quantitative version, the path coefficients resulting from the piecewise SEM analysis were used.

3.3 Results

A good fit was found between the data and the hypothesized network configuration (Fisher's C statistic=1172.25, AICc=1122.32, df=1156, p-value=0.363, 578 independent claims), with a total of 37 significant (p-value<0.05) and 5 marginally significant (p-value<0.1) relationships out of the 67 hypothesized relationships (Table 2, Figure 1, Figure 3). The results for all the hypothesized individual relationships, as well as the model specifications of linear, generalized linear, and generalized least square models, can be found in Table D1 and Table D2 (Appendix 3, Supplementary material D), respectively.

3.3.1 Relationships between socio-economy, biodiversity, and water

Main economic focus of the region

Total GDP of the region is heavily influenced by the services sector GDP (coefficient=0.85, p-value<0.01), mildly by the agriculture sector GDP (coefficient=0.10, p-value<0.01) and barely by the *resident population* (coefficient=1e-4, p-value=0.02). Both *agriculture GDP* and *services GDP* are mainly influenced by occupation in their corresponding sectors (coefficient *occupation agriculture*=0.81, p-value<0.0; coefficient *occupation services*=0.15, p-value=0.03). *Resident population* is negatively affected by *second homes* (coefficient=-0.11, p-value<0.01) but positively by *tourism establishments* (coefficient=0.16, p-value<0.01). Both seasonal populations increase *second homes*, which has a negative effect on the *resident population*. This results in an indirect negative influence of seasonal populations on *total GDP*. However, there are three additional paths connecting *winter seasonal population* and *total GDP*, all with positive effects (Figure 1).

Paths from the current economic model to water resources and biodiversity

While most socio-economic variables have only direct connections with other socio-economic variables, all population related variables and *occupation agriculture*, act as connectors between socioeconomic variables and biodiversity through their influence on land-use variables (*urban areas* as well as *meadows, bushes, and fields*). Similarly, *summer seasonal population* affects the total *water consumption* (coefficient=0.59, p-value=0.04), which in turn strongly influences hydrological variables (effect on *summer flow*: coefficient=-1.45, p-value<0.01; effect on *annual volume*: coefficient=-0.42, p-value=0.03). As a consequence, direct and indirect paths starting from socio-economic variables reach all endpoints of the network, ultimately affecting *total GDP*, biodiversity variables, or *water volume* (Figure 1).

Effects of climatic variables on biodiversity and water resources

Maximum temperatures, through their effect on almost all environmental variables, have an indirect effect on water resources by affecting *summer* (but not *winter*) *flow*, which ultimately influences the water volume in the Oliana reservoir. In contrast, no climatic variable affects any biodiversity variable. Both *summer* (coefficient=-0.57, p-value<0.01) and *winter maximum temperatures* (coefficient=-0.48, p-value=0.03) negatively influence the snow variables. Similarly, neither *summer* nor *winter precipitation* affect any variable of the system (Figure 1).

3.3.2 The modular structure of the Pyrenean SES

The modularity analysis revealed a total of seven modules (Figure 1a): 1) the *total GDP and services* module; 2) the *tourism and population* module; 3) the *agriculture* module; 4) the *butterfly* module; 5) the *water* module; 6) the *land use and birds* module*;* and 7) the *winter snow* module. A simpler pattern, with only five modules, emerges for the qualitative network, in which the magnitudes of the interactions are not taken into account (Figure 1b). *Resident population* and *tourism establishments*, which are grouped with the other tourism variables in the quantitative network, join the *total GDP and services* module in the qualitative network (Figure 1b, module A). The seasonal populations and *second homes* are assembled with *urban areas*, *roads*, and *bird abundance* in the qualitative network (Figure 1b, module B). The *agriculture* module and the *butterfly* module unify into one in the unweighted network (Figure 1b, module C). Finally, in the qualitative network, *summer flow* is isolated from the rest of the water variables (Figure 1b, module D), and groups with a large module including all climatic and environment variables instead (Figure 1b, module E).

Regarding the links between the variables, *summer flow* and *meadows, bushes, and fields* present the highest degree (6 links), followed by *urban areas* (5) (Figure 1). *Meadows, bushes, and fields* appears to be the most dominant node regarding nodes' centrality in the network (i.e., betweenness) (Figure 2a), probably because this variable conveys the paths from socioeconomic or land use variables to all butterfly variables. The same occurs with *urban areas*, as many paths from the socioeconomic part of the network converge to *urban areas* before reaching the biodiversity endpoints located in two different modules. In contrast, despite its high degree and connectivity (Figure 2b, Figure 2c), *summer flow* shows a relatively low betweenness (Figure 2a). This indicates that this variable is highly interconnected within its own module, but plays a relatively minor role in connecting different modules.

Finally, with only three links, *summer seasonal population* connects three different modules: the *tourism and population* module, the *water* module, and the *land use and bird* module (Figure 1a). Despite being an exogenous variable with among the lowest betweenness and degree values (Figure 2a, Figure 2c), *summer seasonal population* is a vital connector at both local (within module) and regional (between modules) levels (Figure 2b). In fact, *summer seasonal population* is the only variable classified as a connector, while the rest are all peripheral or ultra-peripheral nodes.

3.4 Discussion

3.4.1 The region's economic model and its vulnerabilities

The socio-economic system in the Segre upper basin of the Pyrenees strongly relies on the services sector to maintain economic growth, particularly on tourism in both summer and winter. Specifically, agrotourism is the main tourist activity in less touristy counties in the Catalan High Pyrenees, such as Alt Urgell, whereas popular destinations such as La Cerdanya rely on a more intensive, snow-oriented tourist model (Campillo Besses and Font Ferrer, 2004; Lasanta *et al.*, 2013). It is also evident that both tourism establishments and the number of second homes are influenced by seasonal populations, albeit in different ways. Second homes increase with the number of visitors in both seasons, with a predominant effect of summer visitors. Indeed, in recent decades, many Pyrenean districts have witnessed an increase in the number of second homes due to the growing appeal of the region to urban dwellers seeking mountain retreats for occasional use during weekends and summer holidays (Vaccaro and Beltran, 2009).

In contrast, only the winter seasonal population seems to have a significant positive relationship with the number of tourism establishments. This clearly indicates the region's focus on snow tourism to boost economic growth in recent decades (Lasanta *et al.*, 2013), although there has been a recent increase in summer-related activities. Ski resorts in the region are currently not economically profitable *per se*, but they generate benefits by boosting local economies (Campillo Besses and Font Ferrer, 2004; Lasanta *et al.*, 2013). Unfortunately, we could not find any data on snow depth or snowmaking for ski resorts in the region, and snow cover, the only available data related to snow, is not a reliable measure of snow depth (Niu and Yang, 2007), and much less of snow available for skiing. Thus, we were unable to establish a relationship between snow and ski resort profitability. However, the results show that maximum temperatures in both summer and winter have a negative influence on snow cover in their respective seasons. Due to the increased temperatures caused by climate change, Pyrenean ski resorts rely heavily on artificial snowmaking rather than natural snowfall (Moreno-Gené *et al.*, 2020). Snowmaking is costly and financially unviable in the long run under climate change scenarios and causes significant environmental impacts related to water and energy consumption (Moreno-Gené *et al.*, 2020; Spandre *et al.*, 2019). These drawbacks, along with growing competition from other European resorts (e.g., the Alps), threaten the long-term sustainability of ski resorts in the region (Steiger *et al.*, 2017).

The economic importance of the services sector aligns with the overall shift from a traditional agro-silvo-pastoral economy to a tourism-based economy observed in the Catalan Pyrenees since the second half of the 20th century (del Mármol and Vaccaro, 2015; Guirado González, 2014; Pallarès-Blanch *et al.*, 2014). As anticipated, the primary sector and its influence on the local economy are diminishing (del Mármol and Vaccaro, 2015; Guirado González, 2014). The marginalized economic role of this sector in the region's current development model is evident from the limited influence of agriculture's contribution to the total GDP, as well as the fact that all agriculture variables are grouped separately from the total GDP. Subsidies to agriculture and cattle farming also fail to significantly promote employment in the sector or contribute to its GDP (Lasanta and Marín-Yaseli, 2007; Muñoz-Ulecia *et al.*, 2021). Farmers' salaries do not contribute to occupational growth in agriculture, and the negative relationship between these two variables may be attributed to the technification of the agricultural sector, which requires personnel with higher qualifications. Kalie Pauw *et al.* (2007) found that technological advances in agriculture had a negative impact on agricultural employment in South Africa, a phenomenon that could also be occurring in our region. Furthermore, the resident population, which has a modest influence on the region's GDP, is positively affected by tourism establishments. Tourism has played a vital role in mitigating the economic recession in the Pyrenees region and has significantly contributed to countering depopulation (Pallarès-Blanch *et al.*, 2014). However, this trend highlights the ongoing dependence on external elements of the system, namely, visitors and tourists, to sustain the local society and economy.

3.4.2 Threats to water resources and biodiversity

The hydrological system is directly and indirectly influenced by various SES elements. Direct connections to the hydrological system encompass elements related to water demand (water consumption), land use (forest cover), and environmental variables (evapotranspiration and snow cover). The high degree of connectivity of summer flow indicates its significant importance within the water module, and it also highlights the vulnerability of the hydrological system to water scarcity during summer. Apart from forested areas, most of the linked variables are grouped in the same module as summer flow, indicating their strong influence on it. Interestingly, when the magnitude of the interactions is not considered, the influence of water consumption on summer flow diminishes, and summer flow is grouped in a different module from water consumption and other water variables.

As for the indirect effects, both summer and winter temperatures affect the hydrological system through their effects on environmental variables. Snow cover is highly variable among years in mountain areas, and there is a general reduction in solid precipitation compared to liquid precipitation in winter, as well as earlier snowmelt linked to climate change (Gössling and Hall, 2006; Sanmiguel-Vallelado *et al.*, 2017). The positive effect of both summer and winter snow cover on summer flow, but not on winter flow, reflects the usual seasonal pattern found in Pyrenean rivers: low discharges in winter, when snowpacks above 1600 m.a.s.l. act as water reservoirs, and higher discharges in spring due to snowmelt (López-Moreno and García-Ruiz, 2009; Revuelto *et al.*, 2017).

Contrary to our expectations, we found a positive effect of both evapotranspiration (ET) and forest cover on summer flow. It is possible that an increase in snowmelt due to rising temperatures causes more discharges in early spring, masking the negative effects of forest cover or ET on flow (Buendia *et al.*, 2016; Vicente-Serrano *et al.*, 2015). We tried to account for the influence of snow on summer flow, but the only available data related to snow was snow cover. The lack of information on snow depth or rates of snowmelt is most likely behind the inability of our model to capture the total effect of snow on flow changes.

Our biodiversity variables are only affected by land-use variables, particularly forested areas and those related to human expansion. Both urban areas and roads have a strong negative effect on bird abundance. The high betweenness of *urban areas* shows its strategic role in mediating the effects of tourism-related variables on *bird abundance*. Moreover, *summer seasonal population* has the highest participation in the network and influences the *land use and bird* module and the *water* module. This highlights how tourism can indirectly play a role in habitat loss and fragmentation (Dri *et al.*, 2021; Payne *et al.*, 2020) and affect water availability (Hof and Schmitt, 2011; Confederación Hidrológica del Ebro, 2015). In contrast, forested areas have a strong positive effect on bird abundance. In the Pyrenees, as well as in many European mountains, agricultural and livestock abandonment has led to widespread afforestation processes, changing habitat composition (MacDonald *et al.* 2000). Some studies have reported that afforestation and the loss of grassland habitats have had a negative overall outcome for bird biodiversity in other European mountains. For instance, a study on Greek mountains found that bird diversity and richness were negatively affected by afforestation (Zakkak *et al.* 2014). However, a study of the impact of managed afforestation in open grasslands in Ireland showed an overall positive effect on bird species richness (Graham *et al.*, 2013). Similarly, a study in Galician Spanish mountains found 13 bird species benefited from the afforestation of abandoned farmlands, while only four species were negatively affected (Regos *et al.*, 2015). Despite the absence of a significant association between forested areas and bird richness or diversity, the observed positive effect on abundance implies a potentially beneficial influence of afforestation on this taxonomic group as a whole.

As expected, all butterfly biodiversity variables increase with the extension of meadows, bushes, and fields, which are favorable habitats for this group (Bubová *et al.*, 2015). These habitats are slightly endangered by roads (Stefanescu *et al.*, 2011) but they are mainly affected by direct forest expansion linked to encroachment (MacDonald *et al.*, 2000). Thus, although forests demonstrate a positive association with bird abundance, they have a detrimental effect on all butterfly biodiversity variables. Butterflies are mildly affected by the abandonment of agricultural and livestock practices. Medium to low grazing by livestock and traditional agricultural practices contribute to insect and plant diversity and the maintenance of a heterogeneous landscape (MacDonald *et al.*, 2000), and the progressive abandonment of these practices can endanger these species (Balmer and Erhardt, 2000). When looking at the qualitative unweighted network, the importance of some relationships is over- or underestimated. Forested areas group in a different module than bird abundance, thus underestimating their importance. The opposite occurs for butterflies, as occupation in agriculture groups with all biodiversity variables in the same module, overestimating its effects. The emergence of different modules in the unweighted network highlights the relevance of considering the magnitude of the interactions when analyzing social-ecological networks, to ensure that the relevance of both direct and indirect effects is properly captured.

We did not find any effect of climatic variables on biodiversity. However, this does not mean that the species groups under study are not impacted by climate change. Mountain butterfly populations in Europe and other regions are shifting their habitat ranges in response to the rapidly changing climate (Rödder *et al.*, 2021; McCain and Garfinkel., 2021). Moreover, a study carried out in four European mountain regions, including the Pyrenees, reported an overall 7% decline in bird species, and a 10% decline in mountain bird specialists (Lehikoinen *et al.*, 2019). Similar to our study, Nogués-Bravo *et al.* (2007) did not find a relationship between their diversity variables and temperature changes, as these relationships are difficult to capture. However, alpine habitats that are essential for these species are highly vulnerable to climate change (Seddon *et al.*, 2016). The Millennium Ecosystem Assessment (2005) found that changes in land-use and land cover have been the main drivers of terrestrial biodiversity changes in the last half of the century. However, Ostberg (2015) reported that the effects of climate change have now reached the levels of those caused by land-use/land-cover changes. Thus, future biodiversity forecasts should aim to capture the concomitant and potentially synergic effects of both these drivers in the study region (Santos *et al.*, 2021).

3.4.3 Recommendations for a sustainable management of resources

Warmer winters, earlier snowmelt, decreases in precipitation, and more frequent and severe droughts are expected to change the intra-annual streamflow variations in the Pyrenees (López-Moreno and García-Ruiz, 2009; Sanmiguel-Vallelado *et al.*, 2017). According to projections, water demand for domestic supply will increase from 28.07 hm^3/year in 2013 to 38.70 hm^3/year in 2033 in the Segre basin, partly due to seasonal population and services supply (Confederación Hidrográfica del Ebro, 2015). Under these projections of drought coupled with increased water demand, focusing on tourism may have conflicting outcomes. On the one hand, it can help revitalize the economy. This has been the solution to slow the demographic recession in Alt Urgell and even revert it in Cerdanya (Guirado González, 2014). On the other hand, it aggravates the pressure on water resources and biodiversity. The centrality of *urban areas* and the high participation of *summer seasonal population* in the SES highlight these elements' ability to reach multiple endpoints, causing multiple cascading effects that may be difficult to balance out.

Although we did not find a relationship between winter tourism and water consumption, water extraction for snowmaking threatens water resources in mountains (Reynard, 2020; Steiger *et al.*, 2022) and is expected to increase with climate change (Rixen *et al.*, 2011; López-Moreno *et al.*, 2014). Our results do reflect, however, that water resources are strongly influenced by visitors in summer, when droughts are more likely (López-Moreno and García-Ruiz, 2009). A diversification and deseasonalization of tourism, promoting spring and autumn visitors, could dampen the negative effects of an unreliable snowpack on the local economy (Moreno-Gené *et al.*, 2020) and summer peaks in water demand. However, promoting tourism in the less popular seasons does not necessarily imply fewer visitors in hot summer months, nor in the ski season. Thus, diversification of the touristic offer should nonetheless go hand in hand with increasingly needed strategies to reduce water consumption (Calianno *et al.*, 2018; Foris and Pleşca, 2017).

The region's single focus on tourism has been coupled with the progressive marginalization of the agriculture and livestock sectors. This affected both farmers' income, which heavily depends on subsidies (Muñoz-Ulezia *et al.*, 2021), and the extension of meadows and fields, which contribute to maintaining habitats for butterflies, albeit mildly (Bubová *et al.*, 2015). Promoting a development strategy singly focused on tourism and exacerbating these imbalances between sectors does not seem to be a sustainable economic strategy. An economic model based almost exclusively on a sector can be risky and diminish the socio-economic stability and resilience of a region (Dissart, 2003; Kaulich, 2017), as the COVID19 pandemic has recently shown (Pinilla *et al.*, 2021). A general diversification of the economy, not only of tourism, would thus be necessary to strengthen the economic basis of the region. Agriculture focused on local varieties adapted to a dry climate (i.e., there are currently some initiatives to recover old varieties of potatoes, apples, and vineyards), as well as extensive livestock farming, are assets that could be further promoted to establish a more resilient and diverse economy. Despite policies such as the Common Agricultural Policy (CAP) attempting to encourage employment in the sector (Muñoz-Ulecia *et al.*, 2021), many farmers have already opted for diversification of their activities. In the Catalan Pyrenees, diversification of farming households towards tourism entails that less of the farmers' well-being is secured through farming itself (López-i-Gelats *et al.*, 2011). Thus, an increased diversification of the activities carried out in the farm usually precedes the abandonment of most, if not all, agricultural practices. To prevent this, it is important that agricultural policies aim at readdressing diversification: instead of diversifying towards activities other than agriculture, the focus should be on strengthening and expanding agricultural practices themselves (López-i-Gelats *et al.*, 2011). However, a word of caution. Although we were unable to quantify water extraction for agriculture, irrigated agriculture is water-demanding and will likely be threatened under climate change scenarios (Haro-Monteagudo *et al.*, 2020). Additionally, intensive agriculture or livestock practices do not contribute to the maintenance of essential habitats for biodiversity, rather the opposite (Dudley and Alexander, 2017). Thus, promoting locally adapted crops as the ones mentioned above would increase their survival under climate-change scenarios, contributing to both food security, farmers' income, and water use efficiency. It is key that the promoted agricultural practices align with nature conservation planning to prevent downsides in agricultural policy implementation. All these context-specific agriculture measures highlight the importance of properly integrating CAP instruments with both scientific expertise and local policies and knowledge (Muñoz-Ulecia *et al.*, 2021).

It is worth noting that, while one pattern may emerge at the scale of the social-ecological system, trends can differ among and within counties. For example, depopulation has affected mostly small and isolated villages, and the population has been concentrated in larger and more touristic municipalities located in valley bottoms (Guirado González, 2014; Pallarès-Blanch *et al.*, 2014). Working at the watershed scale as we did, these spatially explicit patterns within parts of the study area were missed. In this respect, we were limited by the absence of better data. In fact, the main challenge encountered during this study was the lack of some data on a suitable temporal scale and scope, as well as missing data. Similarly, not all variables were available on the same spatial scale (Table 1), which certainly influenced the magnitude of the relationships between them. Scale mismatch is one of the challenges faced by multidisciplinary approaches to environmental management, such as Social Ecological Systems science, and monitoring standards must be developed to homogenize scales among disciplines and facilitate the acquisition of integrated databases (Virapongse *et al.*, 2016). Gathering detailed socioeconomic data, especially at a monthly scale to match monthly environmental data, would be extremely helpful to study interactions in complex social-ecological systems in a quantitative manner.

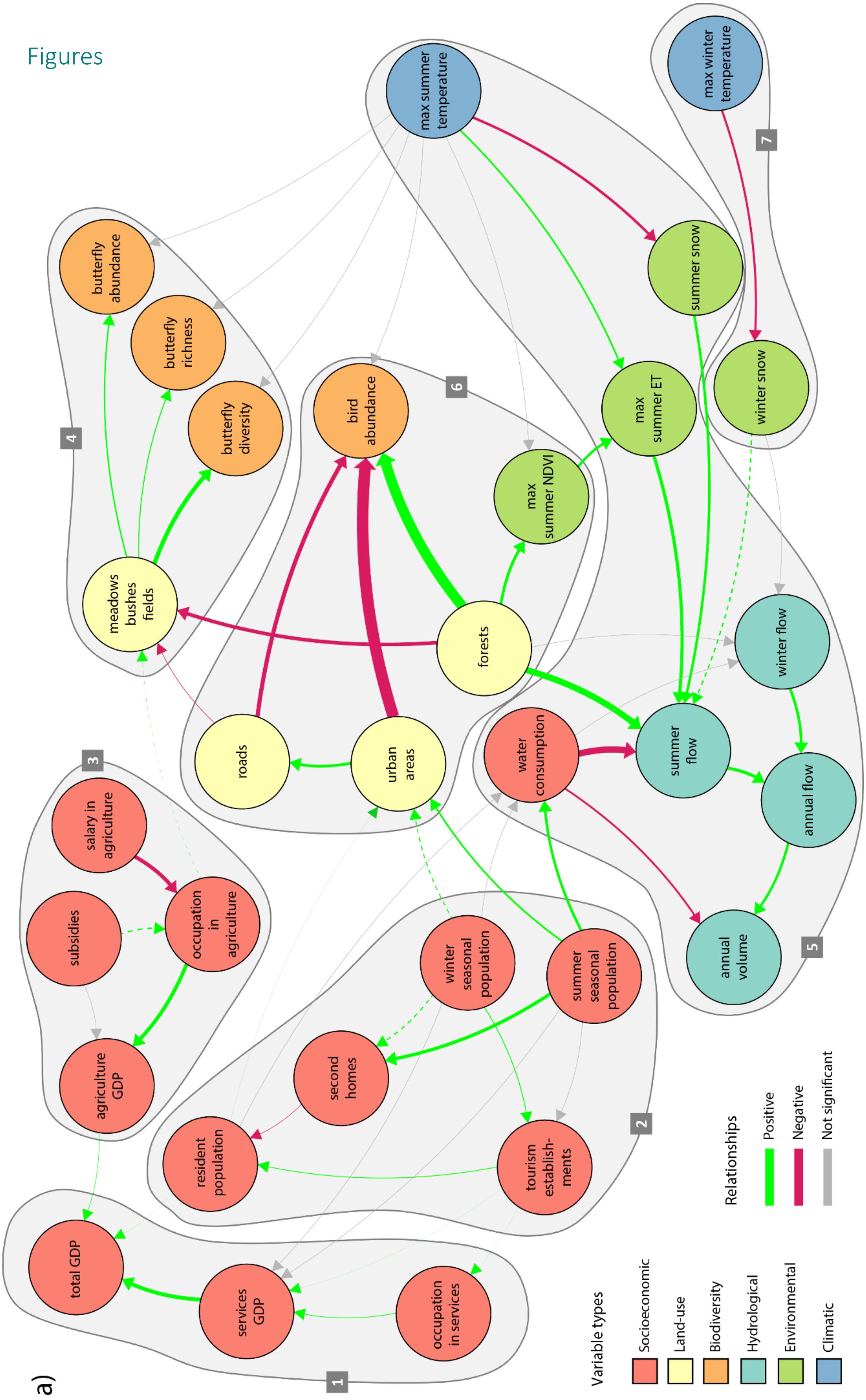
A word of caution regarding future predictions: we have modeled the relationship between social-ecological elements based on data from the last two decades, but there is no way of knowing if these relationships will hold with the same magnitude and sign, or even the same direction, if changes beyond the ranges used to model the interactions occur.

Finally, we demonstrate that estimating the magnitude of the relationships is key to ensuring that direct and indirect paths are not under- or overestimated. Thus, periodically quantifying changes in the relationships between social-ecological system elements would be highly recommended. Moreover, developing tools to facilitate computing the cascade effects of changes in elements of the network, as well as incorporating feedback loops (Herrero-Jáuregui *et al.*, 2018), would bring invaluable information to management planners and researchers alike.

3.5 Conclusions

Taking the Pyrenees as a case study, we have been able to quantitatively characterize a complex network of interacting social-ecological elements. We have shown how such an approach helps understand the direct and indirect relationships among interacting elements, potentially supporting decision-making. In the Pyrenees, promoting all-year-round tourism coupled with strategies to reduce water consumption could contribute to alleviating the current pressure on water resources and biodiversity, while at the same time reducing the dependence on snow tourism. Moreover, efforts to effectively promote employment in the primary sector could help distribute economic wealth among sectors, increasing the system's economic and social resilience. Extensive livestock practices can also favor the maintenance of essential habitats for biodiversity. However, as rainfed agriculture and intensive practices can threaten both biodiversity and water resources, local crops adapted to a dry climate and extensive practices should be promoted. Extrapolated to other mountain systems, our findings highlight the importance of considering social and ecological factors holistically to improve economic and environmental resource management. Furthermore, our results emphasize the need to quantify the magnitude of relationships between the elements of the ecosystem to ensure that both direct and indirect effects between variables are properly captured. Future efforts should aim at gathering socioeconomic information at appropriate temporal and spatial scales to match environmental data, as well as at developing tools to facilitate the incorporation of feedback loops and computing cascade effects on such complex networks.

Figures


a)
1
2
3
4
5
6
7
total GDP
services GDP
occupation in services
resident population
second homes
tourism establish-ments
winter seasonal population
summer seasonal population
agriculture GDP
subsidies
occupation in agriculture
salary in agriculture
meadows bushes fields
butterfly abundance
butterfly richness
butterfly diversity
roads
urban areas
forests
bird abundance
max summer NDVI
max summer ET
max summer temperature
summer snow
winter snow
max winter temperature
water consumption
summer flow
winter flow
annual flow
annual volume
Variable types
Socioeconomic
Land-use
Biodiversity
Hydrological
Environmental
Climatic
Relationships
Positive
Negative
Not significant

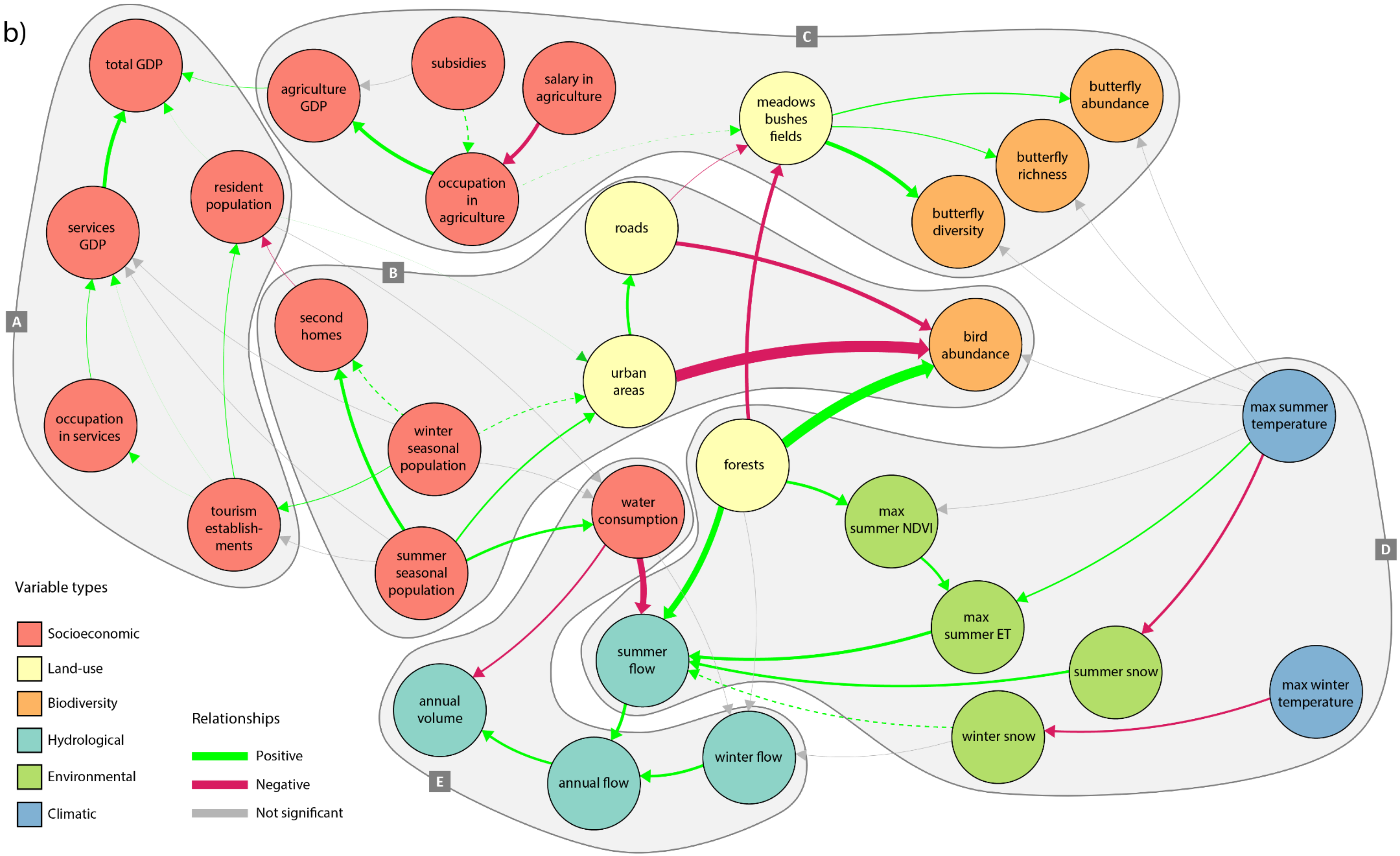
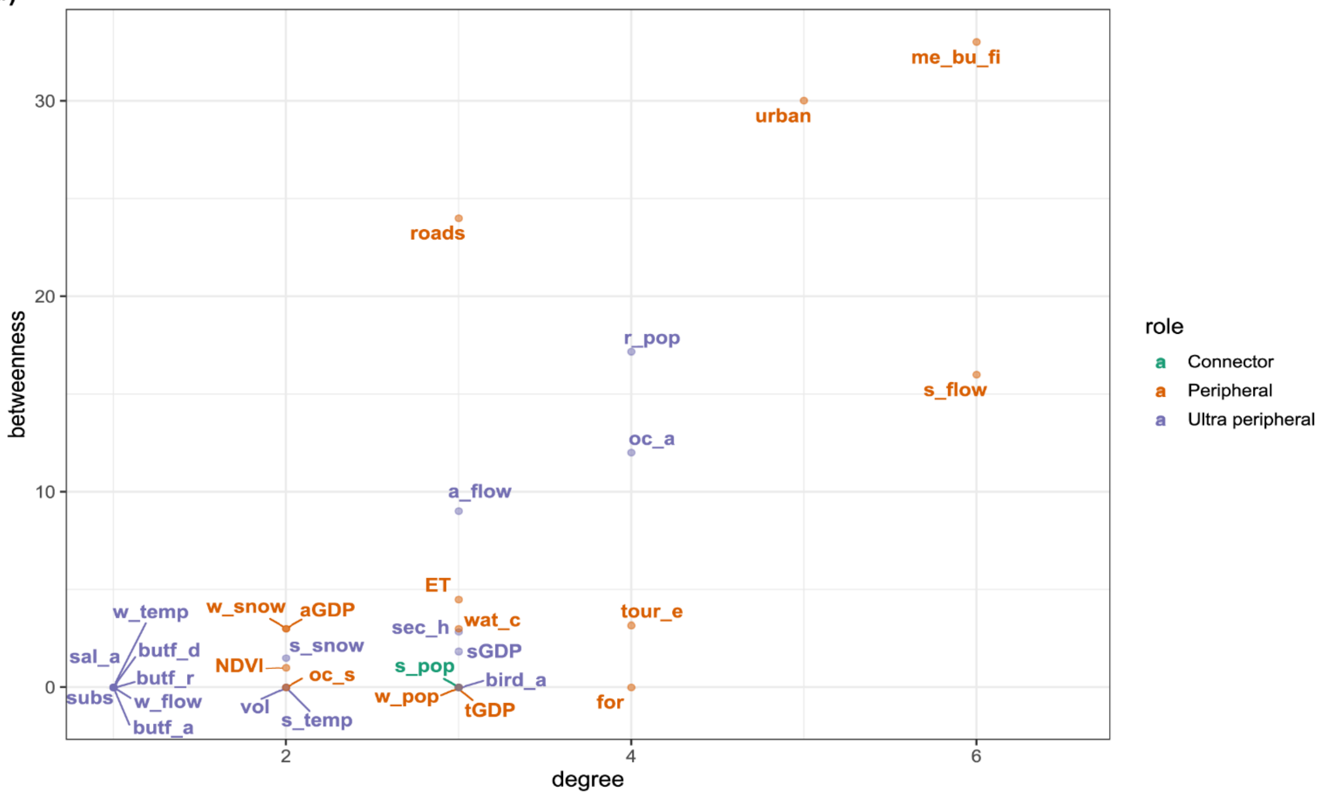


Figure 1. Integrated social-ecological network of a mountain ecosystem showing the relationships between 31 social-ecologic variables inferred through structural equation modeling. For clarity, the four variables without any significant (p-value<0.05) or marginally significant (p-value<0.1) relationship with another variable were omitted. Arrows indicate the relationships between variables. Dotted arrows indicate marginally significant relationships (p-value<0.1). For significant and marginally significant relationships, arrow width is proportional to standardized weight coefficients. Shaded background areas indicate **a)** the seven modules (labeled with numbers) that emerged when considering relationship magnitudes, i.e., quantitative network; and **b)** the five modules (labeled with letters) that emerged when only considering presence or absence of a relationship, i.e. qualitative network. Modules were calculated following the simulated annealing optimisation approach to partition the network into connected sub-groups (see details and formulas in Methods, section 2.4 - Modularity of the social-ecological network).

a)


betweenness
degree
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w_temp
w_snow
aGDP
sec_h
wat_c
tour_e
sal_a
butf_d
s_snow
sGDP
NDVI
oc_s
s_pop
butf_r
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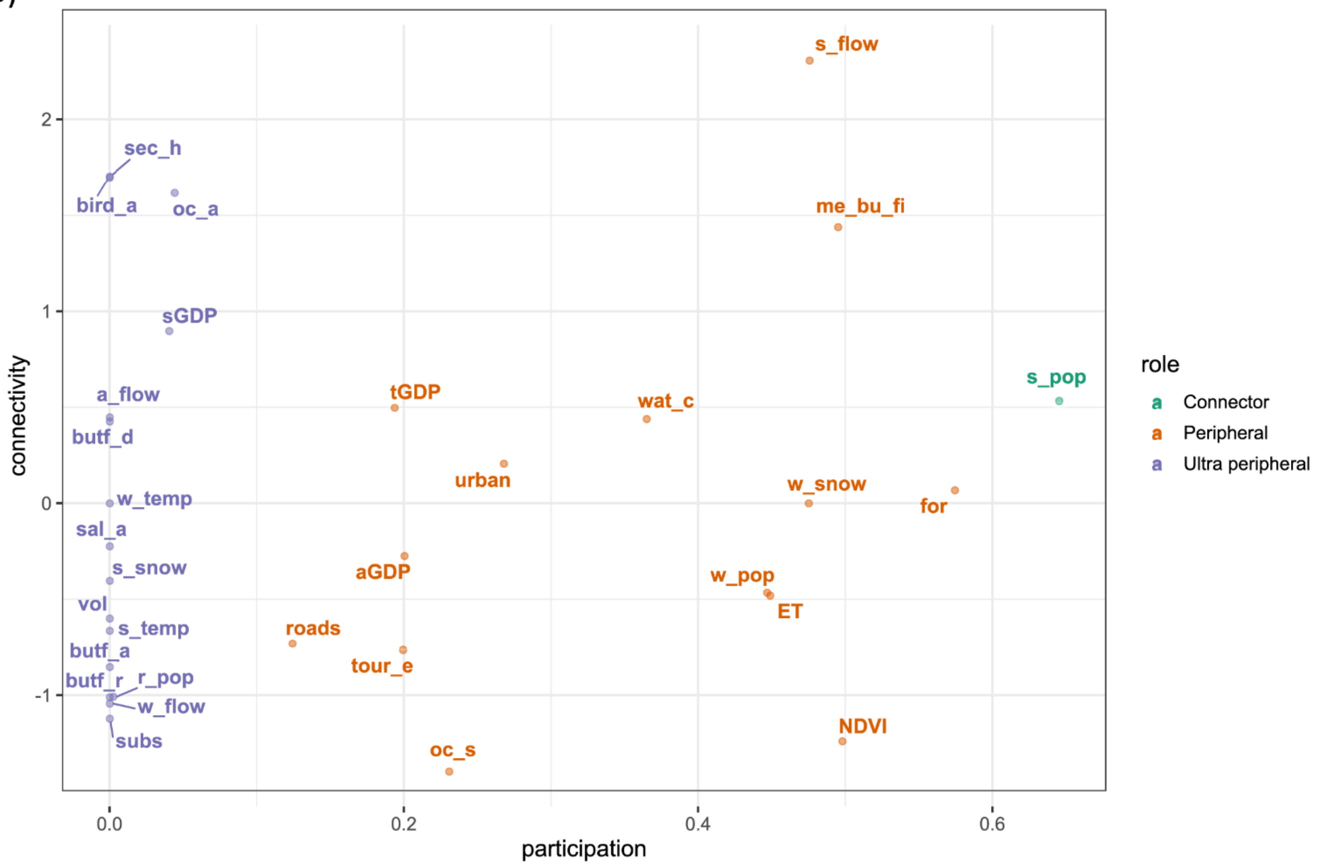
b)


connectivity
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2
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s_flow
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me_bu_fi
sGDP
s_pop
a_flow
tGDP
wat_c
butf_d
urban
w_temp
w_snow
for
sal_a
s_snow
aGDP
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ET
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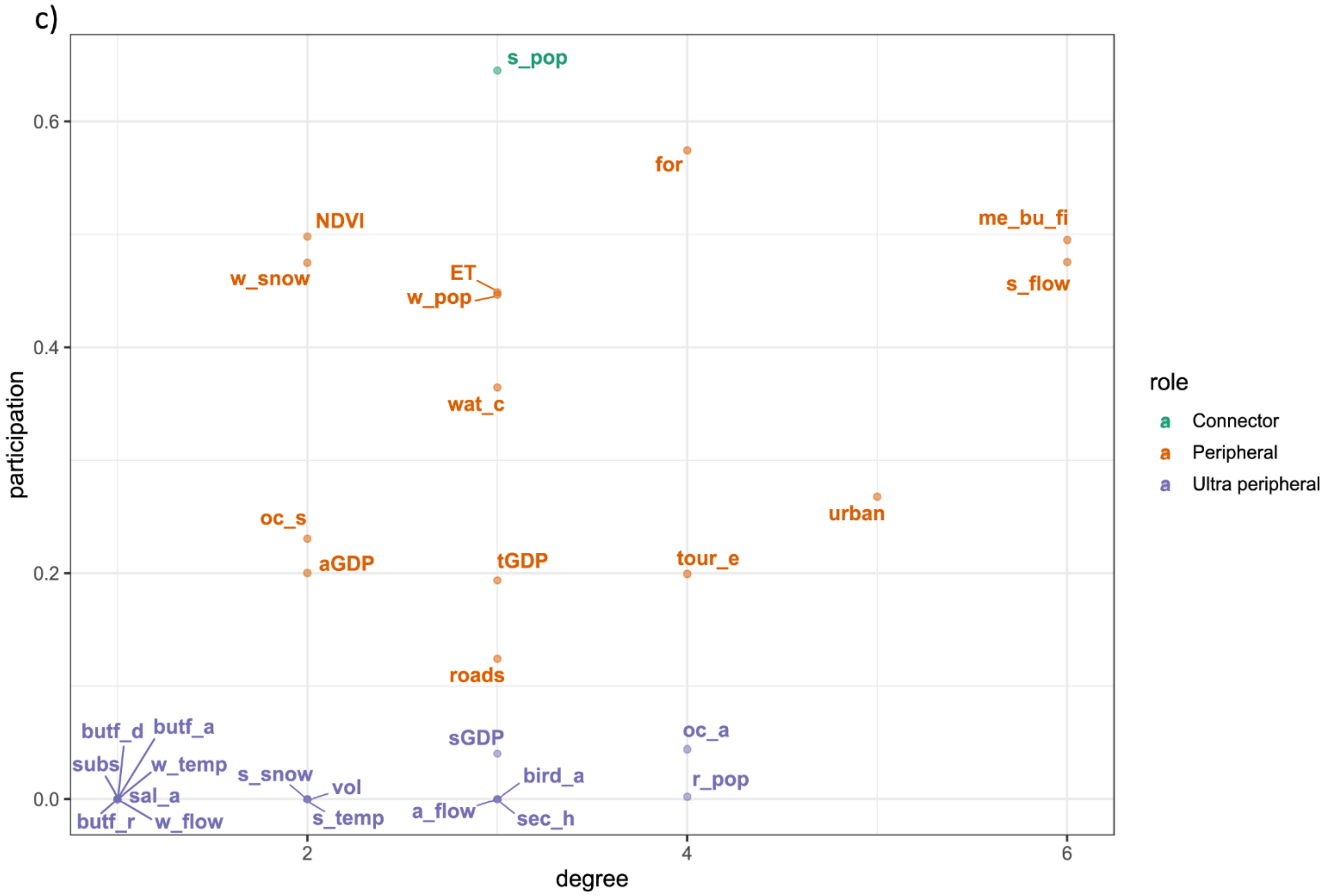

Figure 2. Relationship between **a)** betweenness and degree; **b)** connectivity and participation; and **c)** participation and degree for each one of the 31 variables included in the modularity analyses. For clarity, the four variables without any significant (p-value<0.05) or marginally significant (p-value<0.1) relationship to another variable were excluded from these analyses. Betweenness quantifies the importance of a node within the network by assessing its role connecting pairs of nodes with each other through the shortest possible path; degree indicates the number of links a node possesses; connectivity quantifies the degree of connectivity of each node within its own module; and participation indicates a node's degree of connectivity with the rest of the network (see Methods, section 2.4 - Modularity of the social-ecological network, for further details and mathematical formulas). The peripherality of nodes was calculated based on the quantitative network, i.e. considering relationship magnitudes. Abbreviations: vol for annual volume, a_flow for annual flow, s_flow for summer flow, w_flow for winter flow, s_temp for max summer temperature, w_temp for max winter temperature, ET for max summer ET, NDVI for max summer NDVI, s_snow for summer snow, w_snow for winter snow, urban for urban areas, me_bu_fi for meadows, bushes, and fields, for for forests, bird_a for bird abundance, butf_a for butterfly abundance, butf_r for butterfly richness, butf_d for butterfly diversity, tGDP for total GDP, aGDP for agriculture GDP, sGDP for services GDP, oc_a for occupation in agriculture, oc_s for occupation in services, sal_a for salary in agriculture, w_pop for winter seasonal population, s_pop for summer seasonal population, r_pop for resident population, tour_e for tourism establishments, sec_h for second homes, subs for subsidies, and wat_c for water consumption.

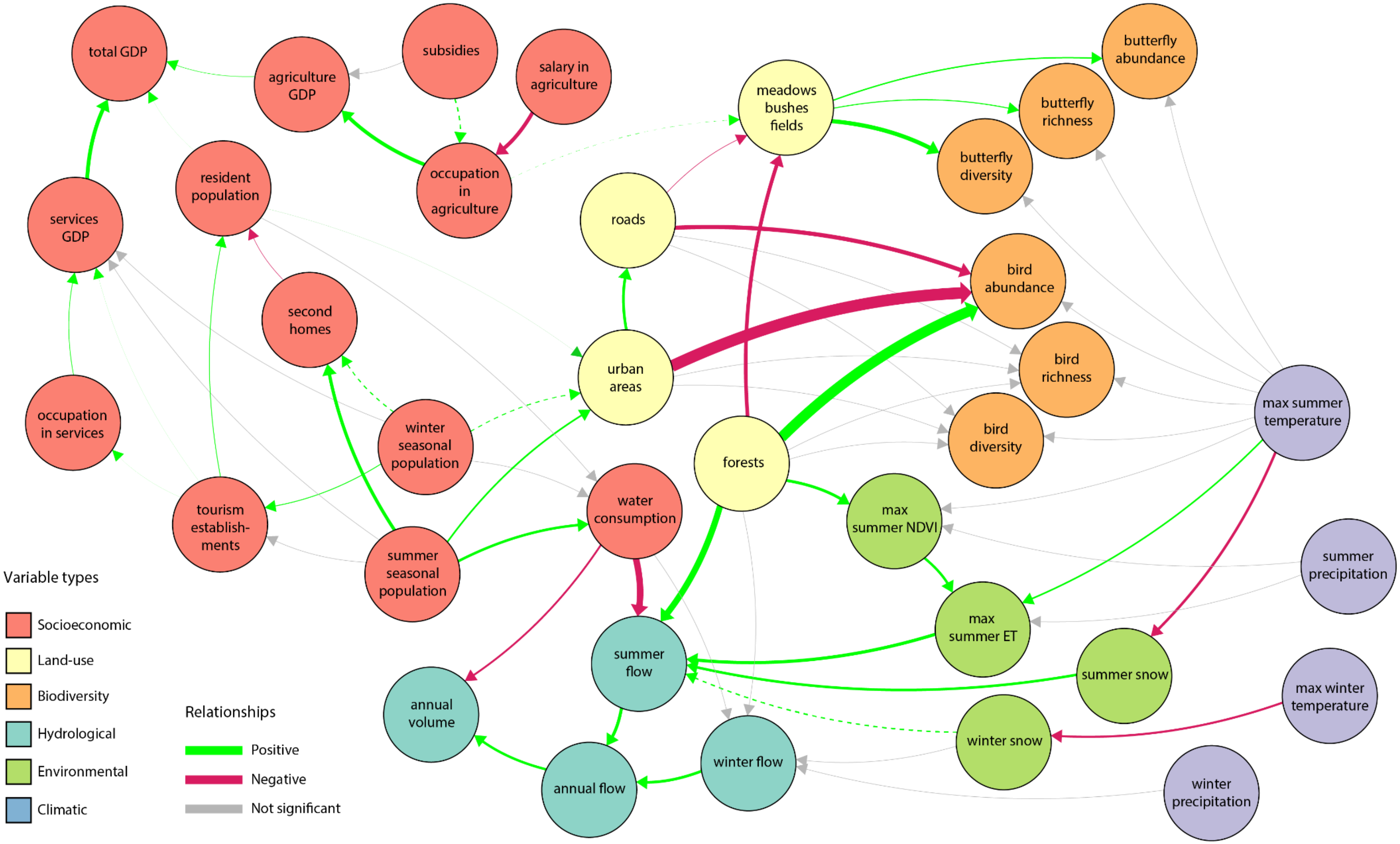

Figure 3. Integrated social-ecological network of a mountain ecosystem showing the relationships between 35 social-ecologic variables inferred through structural equation modeling. Arrows indicate the relationships between variables. Dotted arrows indicate marginally significant relationships (p-value<0.1). For significant and marginally significant relationships, arrow width is proportional to standardized weight coefficients.

Tables

Table 1. Description of the variables used in the path models, with Ostrom's social-ecological system notation provided in brackets. For all seasonal variables, summer corresponds to the months April to September, while winter goes from October to March. For details on data sources see Appendix 3, Supplementary material A – Data sources and processing.

Variable name	Type of variable	Description	Units	Spatial scale
annual volume (RS3)	Hydrological	Annual volume stored in the Oliana Reservoir	hm3	Oliana
annual flow (RU1)	Hydrological	Average annual streamflow from 6 gauging stations	m3/s	Watershed
summer flow (RU1)	Hydrological	Averaged streamflow during summer months	m3/s	Watershed
winter flow (RU1)	Hydrological	Average streamflow during winter months	m3/s	Watershed
max summer temperature (ECO1)	Climatic	Averaged maximum temperature of summer months	°C	Alt Urgell and Cerdanya
max winter temperature (ECO1)	Climatic	Averaged maximum temperature of winter months	°C	Alt Urgell and Cerdanya
winter precipitation (ECO1)	Climatic	Accumulated precipitation during winter months	mm	Alt Urgell and Cerdanya
summer precipitation (ECO1)	Climatic	Accumulated precipitation during summer months	mm	Alt Urgell and Cerdanya
max summer ET (RU1)	Environmental	Averaged maximum evapotranspiration during summer months	/	Alt Urgell and Cerdanya
max summer NDVI (RS5)	Environmental	Averaged maximum NDVI during summer months	mm	Alt Urgell and Cerdanya
summer snow (RS3)	Environmental	Mean number of pixels classified as "snow" during summer months	Number	Alt Urgell and Cerdanya
winter snow (RS3)	Environmental	Mean number of pixels classified as "snow" during winter months	Number	Alt Urgell and Cerdanya
roads (RS3)	Land-use	Total annual surface classified as road and railway infrastructure	km2	Alt Urgell and Cerdanya
urban areas (RS3)	Land-use	Total annual surface classified as urban areas or residential complex	km2	Alt Urgell and Cerdanya
meadows, bushes, and fields (RS3)	Land-use	Total annual surface classified as meadows, shrubs, bushes, or fields (irrigated or rainfed, abandoned or not)	km2	Alt Urgell and Cerdanya
forests (RS3)	Land-use	Total annual surface classified as forest, regardless of forest type	km2	Alt Urgell and Cerdanya
bird abundance (O2)	Biodiversity	Sum of maximum number of individuals from all species found in two spring censuses	Count	Alt Urgell and Cerdanya
bird richness (O2)	Biodiversity	Number of species found per transect on average, based on 4-16 transects (average transect per year of 12.7)	Count	Alt Urgell and Cerdanya
bird diversity (O2)	Biodiversity	Shannon Biodiversity Index per transect, based on 4-16 transects (average transect per year of 12.7)	/	Alt Urgell and Cerdanya

butterfly abundance (O2)	Biodiversity	Number of butterfly species found per transect calculated based on weekly species count data from one transects	Count	Transect
butterfly richness(O2)	Biodiversity	Number of butterfly individuals found per transect calculated based on weekly species count data from one transects	Count	Transect
butterfly diversity (O2)	Biodiversity	Shannon Biodiversity Index of butterflies per transect calculated based on weekly species count data from one transects	/	Transect
total GDP (O1)	Socio-economic	Total Gross Domestic Product per year	Millions of euros	Lleida
agriculture GDP (O1)	Socio-economic	Gross Domestic Product per year devoted to agriculture	Millions of euros	Lleida
services GDP(O1)	Socio-economic	Gross Domestic Product per year devoted to the services sector	Millions of euros	Lleida
occupation in agriculture (O1)	Socio-economic	Number of workers employed in agriculture (including livestock)	Number	Lleida
occupation in services (O1)	Socio-economic	Number of workers employed in the services sector	Number	Lleida
salary in agriculture (O1)	Socio-economic	Annual salary earned by permanent employees in the agriculture sector	euros/year	Spain
winter seasonal population (GS3)	Socio-economic	Result of subtracting the exits of the resident population leaving the municipality to the entries of non-resident population for the winter season.	Number	Alt Urgell and Cerdanya
summer seasonal population (GS3)	Socio-economic	Result of subtracting the exits of the resident population leaving the municipality to the entries of non-resident population for the summer season.	Number	Alt Urgell and Cerdanya
resident population(GS3)	Socio-economic	Total population registered as resident	Number	Alt Urgell and Cerdanya
tourism establishments (RS4)	Socio-economic	Number of rural tourism establishments and hotels	Number	Alt Urgell and Cerdanya
second homes (RS4)	Socio-economic	Number of secondary residences	Number	Alt Urgell and Cerdanya
Subsidies (GS6)	Socio-economic	Total public expenditure on subsidies to agriculture	thousands of euros	Catalonia
water consumption (RU1)	Socio-economic	Total declared water consumption for domestic uses, industry, or services	thousands of m3	Alt Urgell and Cerdanya

Table 2. Matrix with the independent and dependent variables of the regressions present in the network, with standardized path coefficients from the piecewiseSEM analysis, indicating the strength of the relationship between variables. Colored cells indicate correspondence with hypothesized relationships: blue, the hypothesized relationship was found; red, the relationship was not found; Bold standardized coefficients indicate marginally significant relationships (p-value<0.1). For clarity, columns (dependent variables) receiving no effect and rows (independent variables) causing no effect were removed from the matrix.

Dependent Independent	annual volume	annual flow	summer flow	winter flow	max summer ET	max summer NDVI	summer snow	winter snow	roads	urban	meadows bushes fields	bird abundance	bird richness	bird diversity	butterfly abundance	butterfly richness	butterfly diversity	total GDP	agriculture GDP	services GDP	occupation in agriculture	occupation in services	resident population	tourism establishments	second homes	water consumption
annual flow	0.567	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
summer flow	0	0.697	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
winter flow	0	0.612	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
max summer temperature	0	0	0	0	0.36	0	-0.57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
max winter temperature	0	0	0	0	0	0	0	-0.48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
winter precipitation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
summer precipitation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
max summer ET	0	0	0.729	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
max summer NDVI	0	0	0	0	0.561	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
summer snow	0	0	0.58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
winter snow	0	0	**0.304**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
roads	0	0	0	0	0	0	0	0	0	0	-0.11	-0.94	0	0	0	0	0	0	0	0	0	0	0	0	0	0
urban	0	0	0	0	0	0	0	0	0.613	0	0	-2.62	0	0	0	0	0	0	0	0	0	0	0	0	0	0
meadows bushes fields	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.295	0.216	0.941	0	0	0	0	0	0	0	0	0
forests	0	0	1.411	0	0	0.639	0	0	0	0	-0.82	2.347	0	0	0	0	0	0	0	0	0	0	0	0	0	0
agriculture GDP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.104	0	0	0	0	0	0	0	0
services GDP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.852	0	0	0	0	0	0	0	0
occupation in agriculture	0	0	0	0	0	0	0	0	0	0	**0.046**	0	0	0	0	0	0	0	0.815	0	0	0	0	0	0	0
occupation in services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.148	0	0	0	0	0	0
salary in agriculture	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.85	0	0	0	0	0
winter seasonal population	0	0	0	0	0	0	0	0	0	**0.222**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.185	**0.252**	0
summer seasonal population	0	0	0	0	0	0	0	0	0	0.39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.747	0.59
resident population	0	0	0	0	0	0	0	0	0	2E-04	0	0	0	0	0	0	0	1E-04	0	0	0	0	0	0	0	0
tourism establishments	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.021	0	0.023	0.161	0	0	0
second homes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.11	0	0	0
subsidies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.301**	0	0	0	0	0
water consumption	-0.42	0	-1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Chapter 4

BALANCE: a Serious Game featuring climate change adaptation in the Pyrenees

Zango-Palau, A., Jolivet, A., Lurgi, M., Claramunt-López, B.

Chapter 4. BALANCE: a Serious Game featuring climate change adaptation in the Pyrenees

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Keywords

Serious games; Environmental education; Social-ecological systems; Climate change; Mountain sustainability; Sustainable resource management.

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Status

Manuscript in preparation.

Abstract

Serious Games (SG) are potent tools for addressing emotional barriers to climate change engagement. This study aims to conceptualize and develop a SG to effectively raise awareness and communicate the findings of two research studies focused on climate change adaptation in a social-ecological system in the Pyrenees. To achieve this, we first performed a literature review to identify key features of successful SG regarding scope, graphics, narrative, gameplay, and development process. Guided by these identified key features, we created the prototype of BALANCE, a SG that immerses players in the role of a manager responsible for making decisions on which social-ecological elements should change to maintain development goals and keep the local population satisfied. The game incorporates a system to collect in-game decision data as a first step to creating a future database to study the users' decision-making processes in the context of climate change adaptation. Moreover, the game has been designed to be flexible and easy to modify. This allows to customize the game's complexity based on the target audience, as well as to create new versions of the game to feature different social-ecological systems. A future version is going to include, among others, conducting playtesting sessions with students to evaluate mechanics and identify potential errors, designing a multiplayer option to enhance user discussion, and establishing a remote data storage system to retain gameplay data securely.

4.1 Introduction

Global climate change is considered one of the greatest world-wide threats for our societies in the near future (Poushter and Huang, 2019). Governments and societies use the concept of "climate emergency" to highlight the massive resources allocation needed to face climate change impacts (Climate Emergency Declaration 2020). While considerable efforts have focused on long-term institutional actions, the critical aspect of raising awareness among the population should not be underestimated (Clayton *et al.*, 2015). Climate change concern has been shown to increase citizens' support towards environmental policies and pave the way for the development of a sustainable society (Rhodes *et al.*, 2017; Berglund and Matti, 2006). A clear example of that is the Fridays For Future movement, which shifted voter's behavior towards environmentalist parties and has become an opportunity to implement climate policies with citizen support (Venghaus *et al.*, 2022). Moreover, climate change concerns also drive personal responsibility and encourage behavioral changes towards sustainable habits, such as the adoption of energy-efficient appliances (Jakučionytė-Skodienė and Liobikienė, 2022). It is essential that citizens perceive climate change as a pressing issue that deserves priority of action.

Despite the overwhelming scientific evidence supporting the reality of climate change, misinformation on the topic is still common (Treen, 2020; Farrell, 2019), and some people continue to harbor skepticism or denial regarding climate change issues (Capstick *et al.*, 2015). Moreover, influential politicians have been known to deny climate change and promote disinformation campaigns (Selby, 2019; Marquardt *et al.*, 2022). In addition, and contrary to expectations, climate change awareness does not primarily depend on how well informed the population is (Kahan *et al.*, 2012). Instead, worldview, cultural, and personal values play a significant role in climate change denialism (Lewandowsky, 2021; Clayton *et al.*, 2015). Even in countries where climate change is perceived as a legitimate concern, it is often perceived as a distant threat, both temporally and spatially. Thus, many believe it primarily affects others in faraway places, and seldom impacts oneself (Schultz *et al.*, 2014; Tvinnereim *et al.*, 2020). A recent study has shown that threats directly affecting the individual raise more climatic concern and awareness than distant or planetary threats (those acting at a world-wide scale) (Arikan and Günay, 2021). In Western Europe, support for climate change policies also varies with income and spatial dimension, i.e., people living in rural and suburban regions, as well as those with limited purchasing power, exhibit lower support due to fears of income losses (Arndt *et al.*, 2023). Due to all these reasons, climate change awareness and willingness to act are limited.

Low climate change engagement may result partly from ineffective methods to communicate scientific topics (Moser, 2010). Traditionally, communication efforts were based on the *information deficit model*, which argues that low population engagement arises from a lack of knowledge on the topic (Suldovsky, 2017; Bucchi, 2008). Thus, this approach primarily focuses on providing scientific information to engage the public. However, the *information deficit model* overlooks critical psychological barriers, such as personal norms, motivation, emotional connection, skepticism, or ideology (Gifford, 2011; Whitmarsh, 2011). More recent trends acknowledge that both human psychology and the complexity of scientific information play a role in climate change awareness. Three barriers have been identified as key to increasing climate change engagement: cognitive (understanding), affective (caring), and behavioral (acting) (Lesnikowski, *et al.*, 2015; Clayton *et al.*, 2015). Overcoming these barriers requires not only delivering relevant information but also employing communication methods that evoke personal and emotional interest in the receiver.

Serious Games are becoming popular tools to overcome the limitations of conventional science communication (Galeote *et al.*, 2021a; Connolly *et al.*, 2012). Unlike traditional games focused solely on entertainment, Serious Games aim to educate and raise awareness about various topics. Numerous studies have concluded that Serious Games are more effective than conventional methods for science education (Vogel *et al.* 2006; Sitzmann and Ely, 2011; Wouters *et al.*, 2013; Clark *et al.*, 2015; Riopel *et al.*, 2020). Within the Serious Games arena, videogames have become particularly popular due to their ability to create immersive virtual environments that allow users to experiment and engage deeply with the educational process (Foltz *et al.*, 2019; Galeote *et al.*, 2021a). This interactive nature enables players to gain firsthand experiences and practice scenarios they would not encounter in their daily lives. Videogames hold great potential to educate the current and upcoming generations, since young people heavily rely on technology and do not acquire knowledge as effectively employing conventional methods (Riopel *et al.*, 2020). Experimentation and immersion make Serious Games ideal tools to address the cognitive, affective, and behavioral components of climate change engagement (Galeote *et al.*, 2021a). In this sense, Ouriarchi *et al.* (2017) stressed the importance of involving scientists in the development of climate change Serious Games, especially those focused on adaptation. This helps to ensure that the most important messages to adapt are effectively communicated.

Recent reviews highlighted that Serious Games have great potential as climate change communication tools (Douglas and Brauer, 2021; Galeote, 2021b; Riopel *et al.*, 2020; Rajanen and Rajanen, 2019; Flood *et al.*, 2018). There are numerous examples of successful Serious Games, both digital and analog, developed to raise awareness about specific climate change issues. For instance, some recent games focus on educating about risk and hazard management with stakeholders (Fleming *et al.*, 2020), pandemics and diseases spreading (Galeote *et al.*, 2022), flood management and adaptation (Hügel and Davies, 2022), urban planning (Neset *et al.*, 2020), and climate tipping points (van Beek *et al.*, 2022). Among the analog examples, Undorf *et al.* (2020) co-designed the Serious Game *Cascade* with stakeholders, a multiplayer board game that illustrates future hazards to infrastructure services. The developers extracted a decade of real weather data from climate projections to design plausible scenarios for the game. Each game round involves a hazard occurrence, and players, each managing an infrastructure type, must discuss and agree on socioeconomic impacts and potential recovery strategies. Regarding digital examples, Hügel *et al.* (2022) recently developed *iAdapt*, a turn-based role-playing game that illustrates the complexities of decision-making under climate change uncertainty. Notably, *iAdapt* includes a feature to collect anonymized gameplay data, a novel approach to gather in-game information not previously utilized in climate change Serious Games. This data collection enhances the potential for studying users' decision-making processes in the context of climate change adaptation.

Our goal is to conceptualize and build a prototype of *BALANCE*, a Serious Game that features climate change adaptation in the Pyrenees and that also has the capability to collect data on players' *in-game* decisions. Targeting adaptation is particularly important in areas such as the Mediterranean, where adaptation measures will be key to reduce the negative consequences of expected phenomena such as desertification (Carvalho *et al.*, 2022). The game aims to illustrate and combine the findings of two studies carried out in a Pyrenean region, corresponding to Chapters two and three of this thesis. **Chapter two** addresses how different development pathways conflict or align with the local mental frameworks of the region in the context of climate change adaptation. **Chapter three** analyzes and quantifies the relationships between different components of the Pyrenean social-ecological system. By combining the insights from these two studies, *BALANCE* aims to illustrate how different elements of the local socio-ecological system (SES) interact with each other and affect different stakeholders' interests. These SES variables will be impacted by climate change, and depending on the development pathway chosen by the user, different social and developmental objectives must be reached and maintained throughout the game.

The next part of this Chapter is divided into three main sections. In *Game conceptualization*, we first identify the key features necessary for building a successful Serious Game for climate change engagement, based on the current state of the art on the topic. Following, we establish the learning goals of *BALANCE*. The identified key features and the learning goals then serve as a foundation for deriving a list of the primary components that the game should incorporate. Next, in the *Game description* section we present and describe the prototype of *BALANCE*. Finally, in *Future development steps*, we discuss future improvements of the prototype.

4.2 Game conceptualization

4.2.1 What do successful Serious Game have in common?

Several studies highlight that Serious Games present a more effective way of communicating science topics than conventional methods, improving knowledge acquisition, problem-solving skills, and information retention (Vogel *et al.*, 2006; Sitzmann and Ely, 2011; Wouters *et al.*, 2013; Clark *et al.*, 2016; Riopel *et al.*, 2020). Within Serious Games, however, there are features which make some games more successful in conveying scientific information than others. For example, the assimilation of concepts and the generation of emotional and behavioral responses are better achieved when the learning process is intrinsic to the game mechanics, story, and context (Supriana *et al.*, 2017). In other words, the game should not adopt a "chocolate-covered-broccoli" approach, where gameplay is periodically interrupted by educational content presented through quizzes, questionnaires, or similar (Hopkins and Roberts 2015; Camps-Ortueta *et al.*, 2019). Such an approach disassociates enjoyment from learning. Instead, games should be designed in a way that understanding and applying learning objectives become intrinsic to the gaming experience and enjoyment.

Active participation, rather than passive engagement, has also been found to enhance learning in simulations for adult training (Sitzmann and Ely, 2011). Similarly, Riopel *et al.* (2020) found that games with higher levels of user control yielded more effective learning outcomes than those which constrained the pace and the interactivity. Providing users with control over accessing information helps prevent information overload and promotes a more engaged learning experience (Riopel *et al.*, 2020). In any case, it is essential that games are tailored to the users' level of knowledge and expertise

(Baaden *et al.*, 2018; Ouariachi *et al.*, 2019). By considering the users' existing knowledge, games can be more effectively designed to match their specific learning needs. Moreover, visual input plays a critical role in allowing players to visualize the consequences of their actions and conveying memorable messages (Ouriarchi *et al.*, 2017). However, the type of visuals notably matters. Schematic and simplified visual representations of scientific concepts tend to be more effective than photo-realistic features (Vogel *et al.*, 2006; Wouters *et al.*, 2013; Clark *et al.*, 2015; Riopel *et al.*, 2020). Riopel and collaborators (2020) argued that the complexity of a photorealistic game can be overwhelming and induce cognitive overload, diverting the user's attention from the scientific message the game aims to convey.

With regard to the effectiveness of single player versus multiplayer games, the evidence is mixed. Some authors have found that individual navigation through the game is more beneficial than group or collaborative navigation (Vogel *et al.*, 2006; Clark *et al.*, 2015), while some others found that playing in a group yields better learning outcomes than playing alone (Wouters *et al.*, 2013; Ouariachi *et al.*, 2017). Similarly, the support for the effectiveness of a strong narrative component in yielding greater learning outcomes varies. Some authors have found that the absence of a narrative or storyline can be more effective than a strong use of narrative (Wouters *et al.*, 2013; Clark *et al.*, 2015). However, others argue that an immersive narrative is key in conveying meaningful messages (Ouariachi *et al.*, 2017).

Concerning specific climate change communication, studies show that alarmist or fatalist climate change messages often lead to apathy or a sense of helplessness, rather than motivating a change in behavior (Moser, 2010). Additionally, games that do not focus on local problems can induce psychological distance and be less effective than those addressing local issues (Ouariachi et al, 2017). Problems at the planetary scale are often perceived as distant threats, while local issues are deemed meaningful and contribute to raising awareness (Arikan and Günay, 2021). As a result, recent climate change Serious Games tend to focus on the local scale (Flood, 2018).

Ouariachi *et al.* (2019) identified a set of recommended features to include in Serious Games specifically intended for Climate Change communication. Among other aspects, they found that a successful Serious Game must be easy to understand while maintaining scientific accuracy. Scientific accuracy and credibility, despite being crucial aspects of Serious Game development, are often overlooked (Galeote and Hamari, 2021a). If users do not find the information believable, engagement and learning may decrease (Ouariachi *et al.*, 2019; Flood *et al.*, 2018). Therefore, games that are based on real data and allow players to experiment with it are ideal (e.g., Gao *et al.*, 2021; Hügel *et al.*, 2022; Neset *et al.*, 2020). However, finding a balance between complexity and accuracy is essential because players must be able to associate in-game actions with their consequences, giving them a sense of control and the possibility to experiment. Moreover, it is crucial for the game to be relatable and meaningful to the user to overcome engagement barriers linked to emotions and attitudes. In this sense, Hügel *et al.* (2022) discussed the relevance of designing Serious Games that are easy to replicate in different settings. This approach is interesting because it allows to tailor the game to feature different contexts, making it meaningful to different groups of people. As most Serious Games are developed in Europe and America (Riopel *et al.*, 2020), designing a game that can easily feature other parts of the world is highly desirable. Furthermore, to reach various groups, the ability to translate the game into multiple languages is equally important (Mangiron *et al.*, 2014).

Finally, Serious Games can serve as excellent methods to generate data (Moreno-Ger *et al.*, 2014; Kato and Klerk, 2017). However, most Serious Games lack an intrinsic system to generate data beyond player’s motivation or engagement during gameplay (Baaden *et al.*, 2018). Typically, the preferred method for data collection in most Serious Game testing is through surveys conducted after gameplay (Smith *et al.*, 2014; Kara, 2021). While a few Serious Games take advantage of gameplay itself to produce other types of data (Cooper *et al.*, 2010), such examples are relatively rare (Baaden *et al.*, 2018). One of the best examples is the Serious Game *Foldit*, which benefited from the users’ puzzle solving abilities to find potential configurations of unknown protein structures. In several cases, players’ solutions outperformed algorithmically computed solutions, demonstrating the exciting potential of collecting gameplay data (Cooper *et al.*, 2010). Despite this potential, the practice of collecting gameplay data in the context of climate change Serious Games remains relatively unexplored. To our knowledge, the only climate change game that has taken advantage of the users’ gameplay to produce data is *iAdapt* (Hügel *et al.*, 2022). Incorporating a backstage data collection method in a game featuring climate change adaptation could bring valuable insight regarding the decision-making process, as well as the player’s interests and priorities (Douglas *et al.*, 2021). Further, the data collected could be made available to the users to explore their own progress, allowing them to analyze how their decisions impact sustainability.

4.2.2 Learning goals of BALANCE

BALANCE aims to feature the difficulties and compromises linked to climate change adaptation in the Pyrenees. The primary learning goal is to illustrate the intricate relationships between socioeconomic and ecological variables and how they influence development objectives and the interests of the local population. To achieve this, the game depicts a complex network of interacting social-ecological elements that are directly or indirectly affected by climate change (based on Chapter three). In the game, the player assumes the role of decision-maker who has to take actions to reach certain development goals while also satisfying the local population's needs (based on Chapter two). Simultaneously, the player must counteract the impacts of a changing climate. To be successful, the player needs to understand the interplay between socioeconomic and ecological variables and modify these elements strategically to optimize the game's objectives.

4.2.3 Keys to make BALANCE a successful Serious Game for science communication

A series of features regarding theme, graphics, narrative, gameplay, and development have been identified as key elements to make BALANCE a successful Serious Game to communicate scientific information (Table 1).

Table 1. Main key features to incorporate to *BALANCE* based on observations from the literature regarding theme and scope, graphics, narrative, gameplay, and development. References to each observation are provided.

	Observations from the literature	Application to BALANCE	References
Theme and scope	Targeting adaptation is key in regions like the Mediterranean	Focus on adaptation	Ouariachi *et al.*, 2017
	Information should be relatable (meaningful to the user) and accurate (based on real data)	Featurization of a local area and information based on real data from two concurring studies in the region	Lesnikowski *et al.*, 2015; Clayton *et al.*, 2015; Ouariachi *et al.*, 2019; Baaden *et al.*, 2018
Graphics	Natural sciences are better communicated through non-realistic interfaces	Schematic representation of relationships between SES elements using a network	Vogel *et al.*, 2006; Wouters *et al.*, 2013; Clark *et al.*, 2015; Riopel *et al.*, 2020
	Photorealistic scenarios can induce information overload	Simplified version of the local landscape	Riopel *et al.*, 2020

Narrative	Mixed evidence regarding the relevance of a strong narrative to effectively communicate	Low narrative component to prototype; Use play-testers to determine if story-telling features must be included	Wouters *et al.*, 2013; Clark *et al.*, 2015; Ouariachi *et al.*, 2019
Gameplay	Game goals need to be clear and increasingly challenging throughout the game	Initial scene clearly explaining the three game goals and how they can be achieved. The goals become increasingly difficult as the game advances	Ouariachi *et al.*, 2017; Baaden *et al.*, 2018
	Too much information at once can induce cognitive overload	Information of each SES element only shown when accessed by the player	Riopel *et al.*, 2020; Sitzmann and Ely, 2011
	Visual feedback necessary to convey memorable messages	Responsive goal charts and landscape visualization, changing with player's decisions	Ouariachi *et al.*, 2017
Development features	Games available in multiple languages broaden the potential audience	Localisation system: all game text loaded through a .csv file containing translations to all available languages	Mangiron *et al.*, 2014
	Serious games are useful tools to collect data, but are seldomly used to do so	Backstage data collection system included in the game	Moreno -Ger *et al.*, 2014; Kato and Klerk, 2017; Cooper *et al.*, 2010
	Game complexity should adapt to the audience's expertise on the topic	The game needs to be easy to escalate or deescalate (include a higher or lesser number of variables) to adjust complexity	Baaden *et al.*, 2018; Ouariachi *et al.*, 2019; Weitze, 2014
	Most games feature North America or Europe	The game base should be easily modifiable to feature different social-ecological systems from other regions	Riopel *et al.*, 2020; Hügel *et al.*, 2022

4.3 Game description

4.3.1 General description

The prototype of BALANCE was developed using Unity Engine version 2020.2.01, with all scripts written in the C# programming language within the Visual Studio 2019 Integrated Development Environment. The game is designed for Windows and requires a keyboard and a mouse to play. All game assets, including music, sound effects, sprites, 3D models, textures, and materials, were developed by third parties.

BALANCE focuses on climate change adaptation in the Pyrenees. The name of the game refers to its main goal, which is finding the balance between different actors' interests and development goals under a sustainability premise. It is a single player, offline game where the player takes the role of a local manager who must decide where to allocate actions to maintain development goals and the level of satisfaction of the local population. To do so, the player needs to understand how the different social-ecological elements of the Pyrenean system interact with each other and how they affect the local actors (Figure 1). At the beginning of the game, the player must choose a specific climatic scenario and a development pathway. The selected climatic scenario determines the rate at which the temperature increases, while the chosen development pathway sets the game goals.

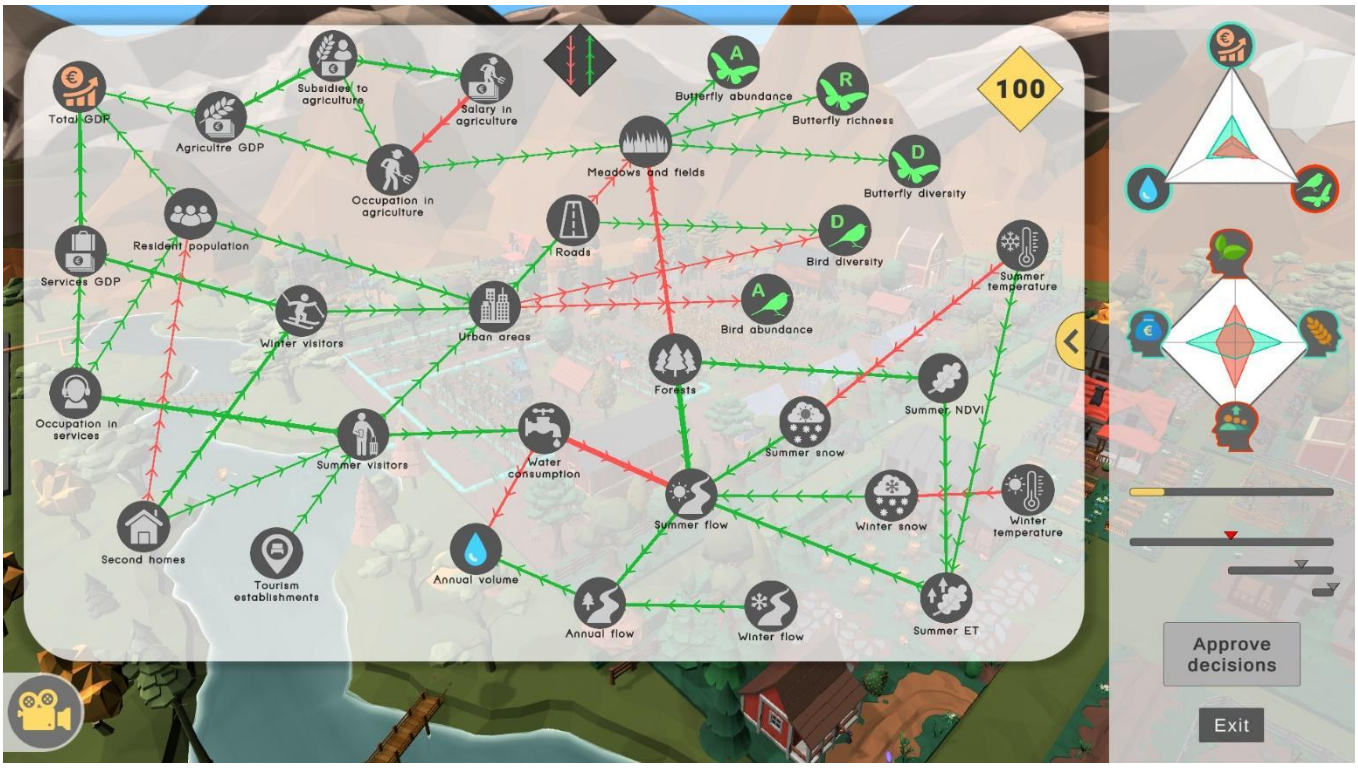


Figure 1. Screenshot of the game scene of BALANCE. The main panel occupies most of the screen and illustrates the relationships between the different Social-Ecological System (SES) elements. The player can hide this panel to see the scenario behind it. To the right, there is a fixed panel illustrating the game goals, slider bars representing the time and achievement of goals, and buttons to approve decisions or exit the game. At the bottom left there is a button to show the different cameras available to visualize the scenario.

4.3.2 Game goals and gameplay

In BALANCE, the objective is not to reach a specific point in development or actor satisfaction at a given time. Instead, the challenge lies in consistently maintaining them above a certain threshold under the pressure of climate change (Figure 2). To win, three conditions must be met:

1- Actors' satisfaction and development indicators must be above their thresholds for at least half of the total game time (first goal bar in Figure 2).
2- Actors' satisfaction and development indicators must be above their thresholds for at least 70% of the second half of the game (second goal bar in Figure 2).
3- Actors' satisfaction and development indicators must be above their thresholds during the final 10% of the game (third goal bar in Figure 2).

The goals are increasingly difficult to make the game increasingly challenging for the player (Denisova *et al*., 2020). While the length of the game can be adjusted, the current prototype is designed to last 10 minutes. At the beginning of the game, the player receives 70 action points (in Figure 1, the player has 100 action points, displayed in the yellow diamond). Action points are received periodically during the game at fixed intervals decided by the developer, and more points are received if the player is above all actors and development thresholds. The player must strategically allocate these points to increase or decrease the social-ecological system (SES) elements that are modifiable.

Development status depends on three indicators: economic wealth (represented by global GDP), biodiversity (represented by an average between all biodiversity variables) and water (represented by the water volume). All three indicators must be above the visual threshold simultaneously to achieve development goals at a given time (Figure 2a). The overall actor satisfaction depends on four indicators, one for each actor type: conservationist, farmer, cooperativist, and entrepreneur. The satisfaction of each individual actor depends on the values of the SES elements that please or displease them. Similar to the development goal, an actor is satisfied when their current satisfaction level is above a threshold value, and all actors must meet their respective thresholds to reach overall actor satisfaction (Figure 2b). The portrayal of actors, the elements affecting them, and how their interests align with different Development Pathways are based on the work developed in Chapter 2 of this thesis. The game provides feedback to the player through both audio and visual cues. If any indicator falls below its respective threshold, an alarm sound and a visual display are triggered as a warning (Figure 2b). Alternatively, if all indicators go above their thresholds, a visual display highlighting the goal bar appears (Figure 2c)

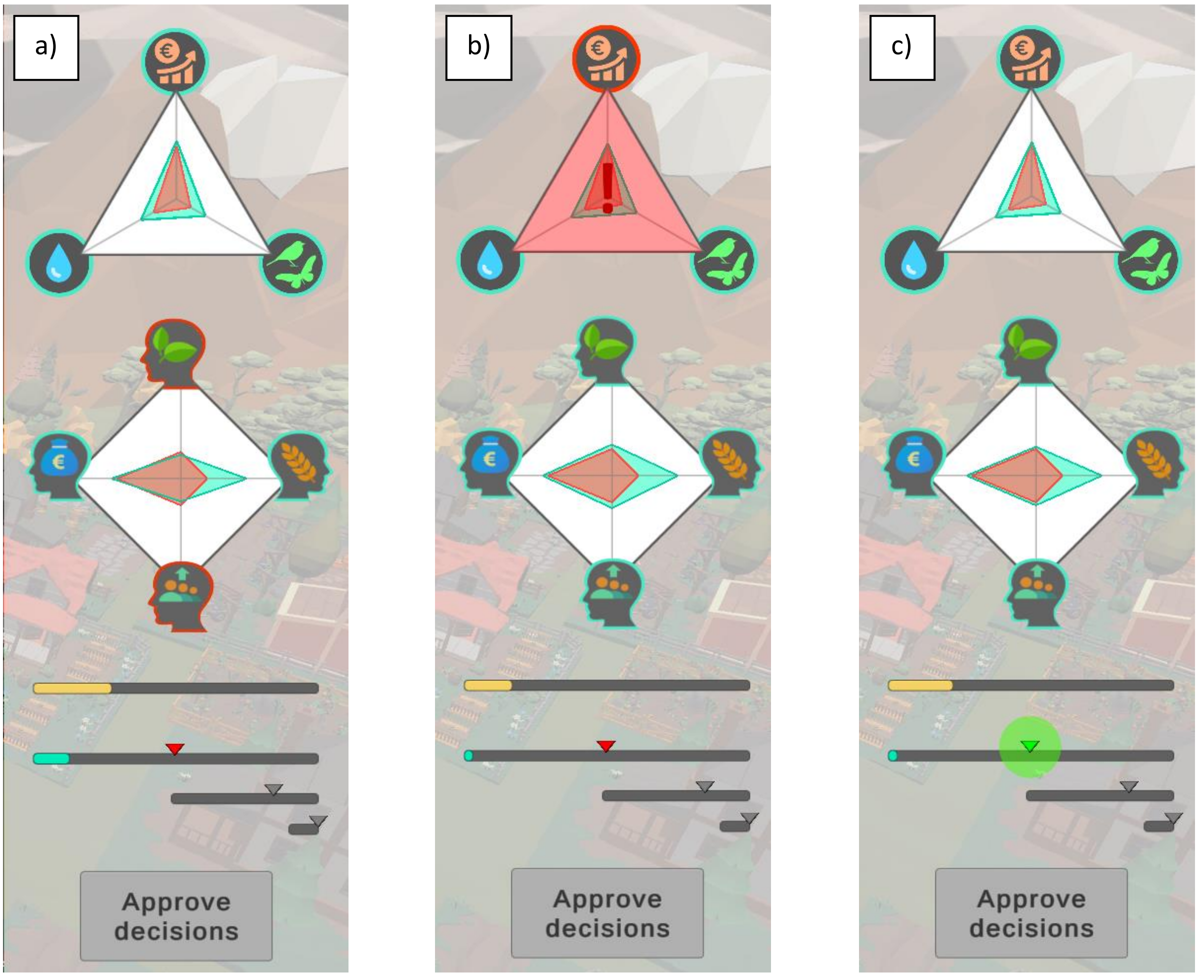


Figure 2. In-game visualizations of the fixed panel representing the goals to achieve and maintain in the game. From top to bottom, for all three figures: triangle with axes illustrating development goals (GDP, biodiversity, water); square with axes illustrating actors' satisfaction goals (Conservationist, Agriculturalist, Cooperativist, Entrepreneur); slider illustrating the pass of time; three sliders representing the three winning conditions (the whole game, the last half, and the last 10% of the time); and a button to approve the current decisions. The player must try to reach above the red thresholds for all the axes of the development goals and actors' satisfaction goals. These thresholds depend on the development scenario chosen. Note that if the player is above the threshold for an element or actor, its outline is green; otherwise, the outline is red. a) Normal visualization of the goals with no highlights; b) Alarm sign in the development goals' axes. The alarm appears when an axis that was above the threshold goes below it. The alarm exists for the actors' satisfaction goals as well. c) green highlight in the first goal slider bar. The highlight appears when all development and actors' satisfaction goals are above their respective threshold. It indicates that the goal bar starts filling in. Note that when this occurs, the triangle above the goal bar turns green; otherwise, it is red. A grey triangle above a goal bar indicates that this goal is not yet achievable.

To reach both the development goals and the actors' satisfaction, the player needs to identify which SES-elements influence these objectives. To do so, the player must pay attention to the main panel (Figure 1), which displays the SES elements and the interactions between them. The relationship between the SES-elements is based on the relationships found in the work developed in Chapter 3 of this thesis. To avoid overwhelming the player with information (Riopel *et al.*, 2020), not all interactions between elements are shown by default. Instead, when the player hovers the mouse over a specific element, all its interactions are revealed as arrows, with the thickness indicating the magnitude of the effect (Figure 3). To increase or decrease a modifiable SES-element, the player must click on it to open its panel. Each SES-element panel (Figure 4) contains a short description of the element, the main elements that it affects, and a graph displaying the values of the selected element across time during the session If an element is modifiable, buttons to increase or decrease it are also provided. The player can approve decisions individually for the selected SES-element in this panel, or approve all pending decisions at once by using a button on the right panel. The information regarding each element and the interactions between them is uploaded through a "Json" file, making it modifiable by the developer (see section *Data input and language*, below).

Figure 3. Screenshot of the game scene of BALANCE with only the interactions pertinent to Urban areas shown.

Both the thresholds for the development indicators and the actors' satisfaction vary depending on the chosen Development Pathway in the "Game Choices" scene (compare thresholds in Figure 3, which are set to *Degrowth* goals, with those in Figure 4, which are set to *Business-As-Usual* goals). For instance, under a *Business-As-Usual* development pathway, the player's objective is to maximize GDP and prioritize the interests of the entrepreneur actor. Similarly, the effect of climate change on the system is simulated through three climatic scenarios. Depending on the scenario chosen in the scene "Game Choices", the temperature increase will be more or less pronounced throughout the game session. If the worst climatic scenario is chosen, the climate change impacts on the SES-elements will be more pronounced, making it more challenging to achieve the game goals.

Figure 4. Screenshot of the game scene of BALANCE with the panel corresponding to Second homes open. The panel contains several elements: an icon representing the social-ecological system element selected; a title and short description; a bar indicating the current value of the element and buttons to increase or decrease it; bars showing the value of elements affected by the current selected element; a graph showing the values the element has taken during the time played; and a button to close the panel.

4.3.3 Game scenes

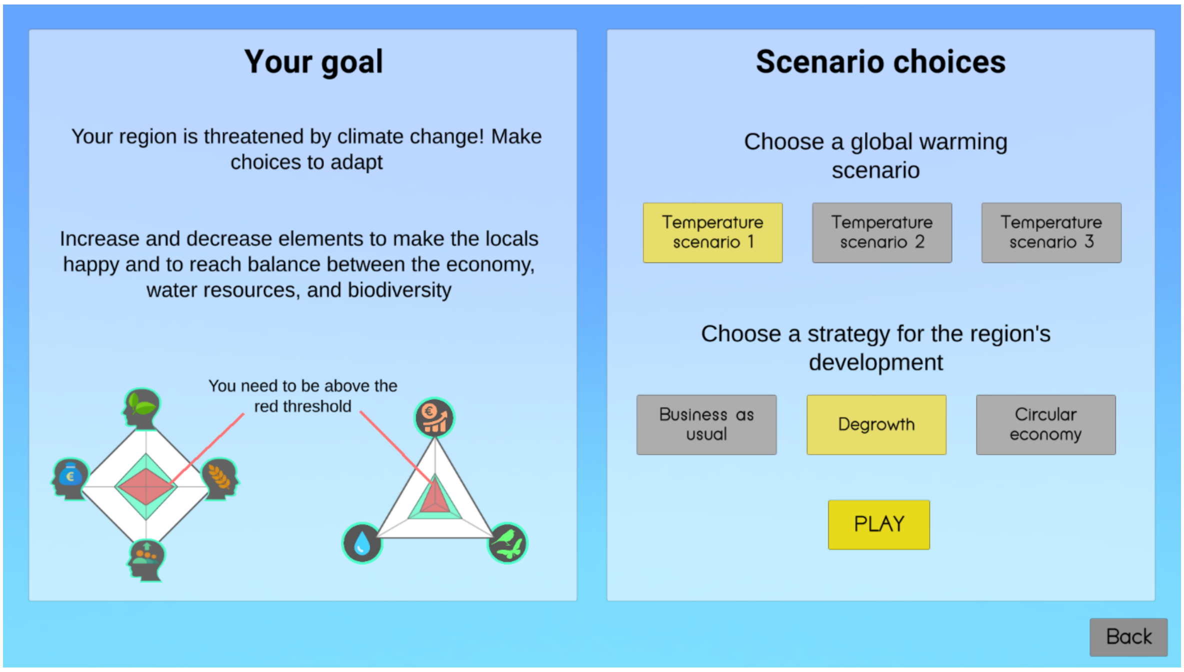
Main Menu

An introductory scene to welcome the player into the game. From here, the player can either start playing, exit the game or see the credits. References to the authors of the game and the usage of third-party assets can be found clicking on the button Credits, which opens a pop-up window with the information. Game language can be chosen here as well. If the author clicks on Play, the user is sent to the *Scenarios* scene.

Figure 5. Screenshot showing the game Main Menu. Different languages can be selected by clicking on the bottom left buttons. From here, the player can start playing, see the game credits, or exit the game.

Scenarios

This scene contains a short explanation of the goals to achieve in the game (Figure 6). Moreover, the player must choose (a) one of the three Climatic Scenarios, each determining the rate at which the temperature will increase throughout the game; and (b) one of the three Development Pathways, each setting different thresholds for each development indicator and each actor's satisfaction.


Your goal

Your region is threatened by climate change! Make choices to adapt

Increase and decrease elements to make the locals happy and to reach balance between the economy, water resources, and biodiversity

You need to be above the red threshold

Scenario choices

Choose a global warming scenario

Choose a strategy for the region's development

Figure 6. Screenshot showing the Game Choice scene. The left panel briefly explains the game goals. The right panel allows the player to choose the climate and development settings to play with. The button PLAY does not activate until the player has chosen both a climate scenario and a development pathway.

Game Scene

This is the main scene of the game. It contains both the panel where player decisions are made (Figure 7) and a scenario to visually represent the landscape (Figure 8). The decision panel is composed of two sub-panels (Figure 7). The first one is a fixed panel on the right illustrating global game stats: the development indicators, the actors' satisfaction indicators, the timeline, the current status of game goals, and buttons to approve all pending decisions or exit the game. The second panel occupies most of the screen and contains a schematic representation of the relationships between SES-elements, as well as the action points available (Figure 8). This second panel is moveable, and the player can hide to better visualize the scenario.

Figure 7. Screenshot showing the main panel of the Game Scene.

Behind these panels there is a scenario representing a simplified version of the landscape (Figure 7). Some elements of the scenario change depending on the value of the SES element they are connected to (e.g., the density of trees varies based on the value of the "Forest" SES-element). This enables the player to visualize how landscape elements change in response to their decisions regarding certain SES elements. The player can access different perspectives of the scenario by pressing the camera buttons located at the bottom left of the scene, providing various movable bird's-eye-view cameras.

Figure 8. Screenshot showing the scenario representing the landscape. Different views of the scenario can be selected by clicking on the bottom left buttons.

When the game concludes, a pop-up panel appears indicating whether the player has won or lost, and displaying the achievements accomplished during the game. From here, the player has the option to either play again or return to the Main Menu scene. If the player chooses to play again, the scene is loaded with the same settings for the development pathway and climatic scenario.

4.3.4 Data input and language

One of the main design objectives was to make a game easily to modify and flexible. In order to achieve this, a JSON file (JavaScript Object Notation, a file that allows storing simple data structures in JavaScript) is used to configure the values of the socio-ecological game variables. The JSON file contains essential information for each social-ecological variable, including: a unique code identifier, variable index, name, description, initial value, minimum and maximum values, whether the variable is interactable (true or false), and its effect on the other social-ecological elements. Using the data from this file, the game establishes the relationships between SES elements and populates the information for each element, such as its name, description, and initial value.

By utilizing an external file to configure the social-ecological variables, the game can easily be adapted to feature a different set of elements (or relationship magnitudes) simply by modifying the JSON file and making minimal code adjustments. This accomplishes two design objectives. Firstly, it allows for tailoring the game's complexity to suit audiences of different ages or varying background knowledge on the topic. This can be achieved by increasing or decreasing the total number of variables in the game as well as by changing the terminology used. Secondly, it enables the creation of multiple versions of the game, each featuring different social-ecological systems (SES). For instance, with available data on other SESs, the game could be adapted to depict a coastal SES in South Africa or an agricultural environment in the Andes by modifying game actors, goals, variables, and their relationships in the JSON file. This empowers future developers to use the game's foundation as a base to create relatable and meaningful games for diverse audiences without starting from scratch.

Furthermore, a .csv file is employed for the localization system, facilitating the translation of all game texts into various languages. The file contains a unique key for each language, a unique identifier for each game text to be translated, and the corresponding translations in all available languages. Although the current prototype version is only available in English, the system to modify all game texts to other languages is already established and ready for implementation.

4.3.5 Data collection

One of the goals of *BALANCE* was to exploit the possibility of collecting gameplay data to study decision-making in climate change adaptation. To achieve this, a system to collect crucial gameplay data was developed. Upon the completion of each game session, two *.csv* files are generated. The first one stores the values of each social-ecological variable throughout the entire game session (recorded at regular intervals determined by the developer). The second one stores the decisions that the player made in the game session, including: game setting (the climate and development scenario chosen); adaptation decisions taken during the game (social-ecological elements modified and in-game time of the change); and final status (i.e., if the player succeeded or lost). The data from different game sessions and players can be pooled together and analyzed to answer multiple questions. For instance, one can explore which decisions players tend to make under different conditions, identify adaptation actions that lead to success in specific circumstances, or determine which actor groups are more challenging to accommodate.

The current prototype version does not collect any data regarding the user's characteristics, such as age, gender, or number of rounds played. Additionally, the data storage is currently saved locally in the machine that the player is using to play.

4.4 Future development steps

The current prototype of the Serious Game BALANCE incorporates most of the desired features discussed earlier. The next features of the development process are:

- **Playtesting**. Testing is one of the most important steps of game development, as it allows to evaluate player engagement as well as to identify potential issues such as bugs. In the case of Serious Games, testing is also key to assess if a good balance between complexity and accuracy was reached, and if the learning goals are effectively achieved (Hügel and Davies, 2022; Galeote *et al.*, 2022; Neset *et al.*, 2020). Moreover, testing can also contribute to generating new mechanics and ideas. Since the goal of this part of the thesis was to develop a prototype, the current version has only undergone basic alpha testing, which consists of tests within the group of developers to identify potential major bugs. The game has yet to undergo beta-testing, that is, testing the game with a selected group of real users. To carry out beta-testing, we have started to contact teachers from secondary schools in Catalonia to perform testing sessions with students throughout the next academic year.
- **Translate the game texts to other languages**. While the system to change texts based on language is implemented, actual translations are yet to be done to make the game accessible to a broader audience.
- **Store gameplay data remotely**. The game generates and stores information at the end of each game loop, but this data is currently saved locally. To facilitate access and analysis, a system to store and collect gameplay data remotely needs to be developed, benefiting players, teachers, researchers, and developers.
- **Collect more user data**. The game currently lacks a way to identify users and to gather key user information, such as age, gender, or number of completed game loops. A login system to collect this data could be very useful to relate the in-game decision making process with specific user profiles. Moreover, it would allow the players to evaluate their own progress across game sessions. Thus, we aim to incorporate a login system which allows to collect and send information to the remote database described above.

- **Create specific adaptation measures**. In the current prototype, the player can modify a variable by directly increasing its value. Although the effects between variables are a necessary step to the game logic, enabling a direct modification of the variable by the player is not realistic; managers cannot directly increase, for instance, the forest cover. Instead, they would promote a reforestation project, which would increase the forest cover in the long run. Following the strategy used in other games, such as the French game Espéride (ONF, 2023), a more realistic approach would be to create a set of adaptation measures the player could take at a given time. If an adaptation measure is chosen, this measure would modify the social-ecological system variables across time. To create such a system, the adaptation actions discussed in Chapter two could be used.
- **Incorporate extreme events**. The game would be more dynamic and challenging if it had a way to incorporate extreme events linked to climate change, such as forest fires or drought. Moreover, such a system would pose a great opportunity to start discussions related to climate uncertainty. We intend to develop a system to feature extreme events based on probabilities that would depend on system variables. For instance, the probability of occurrence of a forest fire could increase with the maximum summer temperature and the extension of urban areas in contact with forested area.
- **Develop a multiplayer option**. A multiplayer option could enable the players to take the role of different stakeholders with opposing interests, creating the perfect setting to discuss conflicts and compromises in climate change adaptation (Ouariachi *et al*., 2017; van Beek *et al*., 2022). For this, a future development step aims at including a multiplayer option. In the multiplayer setting, each player would take the role of a stakeholder who can act upon some modifiable variables, but not all. The players would then need to coordinate and compromise with each other to reach development goals. In this setting, the players would have individual goals as well as common group goals. The different actor roles would be based on the mental models described in Chapter two.
- **Create a simplified and responsive scenario**. The current game scenario was built using free 3D models. Although these are helpful to visualize the scenario, they are not optimized and consume a lot of computing power for their display. Moreover, not all social-ecological system variables are linked to scenario elements, and the modification of some variables currently triggers no visual response. A future development step consists of developing a simpler but optimized version of the current scenario, and linking all scenario elements to social-ecological system variables.

4.5 Conclusions

The Serious Game BALANCE represents a significant step towards effective climate change communication and education, particularly focused on adaptation in the rural Pyrenees. Drawing on existing research on Serious Games, BALANCE incorporates key features that aim at overcoming the cognitive, affective, and behavioral barriers to climate change engagement. The game's learning goals center around illustrating the complex relationships between socioeconomic and ecological variables in the Pyrenean region and their impacts on development goals and local interests. By simulating different development pathways and climatic scenarios, BALANCE challenges players to find a balance between stakeholders' interests and development goals under climate change pressures. BALANCE has been designed to be easy to modify and flexible. This enables to adjust complexity and terminology to suit diverse audiences. Moreover, its flexibility also allows to create different versions of the game to feature various social-ecological systems, making it meaningful and relatable to different groups of users. Future development steps include playtesting with students to gain feedback, remote data storage, featurization of extreme events, and a multiplayer option. In conclusion, BALANCE represents a promising tool for climate change communication, and it hopefully encourages researchers to explore Serious Games as a novel approach to communicate their scientific findings to non-experts in an engaging manner.

General discussion

Mountain regions are complex social-ecological systems (SES) influenced by social, economic, and ecological drivers (Klein *et al.* 2019a) To fully understand the functioning of such complex systems, it is crucial to examine both their natural and human dimensions. SES approaches have proven particularly useful in analyzing these interconnected human-nature systems (Folke, 2006, Ostrom, 2007, 2009; Alessa *et al.*, 2015). However, there is no consensus on how to approach the study of mountains from a SES perspective. Scholars have employed different frameworks, scales, and methods, and have included different variables to study mountain SES. Therefore, one of the objectives of this thesis was to investigate the existing approaches to studying mountain SES as addressed in **Chapter 1**. The first study identified several unaddressed aspects in the literature on mountain SES. Consequently, **Chapter 2** and **Chapter 3** focused on addressing some of these gaps. Finally, **Chapter 4** delved into the development of a science communication tool designed to illustrate the scientific findings of this thesis to non-expert audiences.

In **Chapter 1**, we found that many works carried out in mountains used a social-ecological approach to study their mountain systems, in line with the increasing amount of SES studies in other regions (Colding and Barthel, 2019). However, similar to non-mountain studies (Herrero-Jáuregui *et al.*, 2018; Rissman and Gillon, 2017), less than half of these studies included both social and ecological data, and quantitative environmental data was seldom used. Surprisingly, few studies applied any framework to analyze their mountain social-ecological system(s) as well. This may explain the limited number of elements included per study (on average 2.5), as it has been argued that working without a framework can lead to unintentional omissions of potentially relevant system elements (Colding and Barthel, 2019; Ostrom, 2007, 2009). Furthermore, our findings reveal a bias towards the inclusion of socioeconomic variables over ecological ones, similar to non-mountain SES studies (Refulio-Coronado, 2021, Herrero-Jáuregui *et al.,* 2018). However, despite the inclusion of local socioeconomic variables, global socioeconomic and political drivers were seldom addressed. Nearly two decades ago, Young *et al.* (2006) showed how socioeconomic drivers associated with globalization can significantly influence the interconnectedness, intensity, and speed of interactions within social-ecological system elements. Consequently, disregarding the socioeconomic and political contexts would result in an incomplete understanding of the drivers of change in any given region. Over the past few decades, many European mountain regions have integrated into global markets, prompting a series of socioeconomic changes affecting mountain societies, ecosystems, natural resources, and landscapes (Mitchley *et al.*, 2006;

MacDonald *et al.*, 2000; Vaccaro and Beltran, 2007). Considering the influence of socioeconomic drivers is therefore crucial in such systems.

Accounting for the impact of socioeconomic drivers on system functioning can be complex. One of the few approaches attempting to quantitatively measure the effects of socioeconomic drivers is the socioeconomic metabolism approach (Haberl *et al.*, 2006). This method seeks to estimate the stock and flow of resources (including energy and materials) used by human societies from the environment (Haberl *et al.*, 2006, 2009; Baynes and Müller, 2016). Nonetheless, applying this approach to small-scale systems poses challenges (Haberl *et al.*, 2009). Establishing direct links between the pressures exerted by global socioeconomic drivers and the changes occurring in specific elements of a SES is difficult. Consequently, there is limited available data quantifying the impacts of socioeconomic drivers on small-scale systems. In fact, during our social-ecological study in the Pyrenees from **Chapter 2**, we encountered difficulties in gathering information on the region's socioeconomic and political drivers, including globalization. Nevertheless, the study in **Chapter 2** identified signs of globalization impacting the Pyrenees, notably the loss of local traditional knowledge and the decline of communal management. A decline of diversity – in terms of knowledge, biodiversity, cultural, institutional – is associated with globalization due to mixing and homogenization of systems (Young, 2006). Consequently, globalization can lead to a loss of local traditional knowledge. Moreover, global capitalist markets often encourage individualism and competition, diminishing communal practices and values (Casciarri, 2009; Nafstad *et al.*, 2013). Therefore, while the consequences of globalization are evident descriptively, capturing the precise linkages between these drivers and their impacts proves challenging.

Chapter 2 of this thesis introduces a set of guidelines to help address the challenge of incorporating socioeconomic drivers into decision-making. These guidelines serve the purpose of integrating the interests of local actors and global development pathways into the decision-making process. By considering these development pathways as socioeconomic drivers, we aimed to examine their alignment or conflict with the interests of local actors and the necessary adaptive actions to be implemented in the region. Applying these guidelines to the Pyrenees study region helped unravel potential sources of conflict between different actors, as well as between these actors and the development pathways. Thus, these assessments identified actions that could prove maladaptive. By assessing conflicts among local actors, the guidelines were helpful to identify which actions could shift vulnerability between groups of actors (Barnett and O'Neil, 2010), as well as to identify actions with high opportunity cost, i.e., with a high risk of failure (Juhola *et al.*, 2016). Evaluating conflicts between actors and development pathways revealed that the *Business-As-Usual* pathway was the least compatible. This development pathway promoted actions that displeased the locals, while it hindered those that would be welcomed. On the other hand, *Degrowth* was shown to have the best fit with the locals and the potential adaptive actions carried out in the region. A *Degrowth* approach aims at a radical reorganization of societies and economies to reduce energy consumption and resource use, challenging the paradigm of constant economic growth (Weiss and Cattaneo, 2017). Interest in *Degrowth* has increased alongside studies showing the difficulty of decoupling global economic growth from carbon emissions and resource consumption (Haberl *et al.*, 2020; Burke *et al.*, 2015; Steinberger *et al.*, 2013). Moreover, unlimited economic growth is the prime cause of global biodiversity loss, mainly driven by land use changes, increased resource consumption and higher emissions (Moranta *et al.*, 2022, Otero *et al.*, 2020; Marques *et al.*, 2019). The relationships between economic development and natural resources can also be observed at smaller scales. Chaudhry and Barbier (2013), for instance, showed a strong correlation between per-capita agricultural yield in Wyoming, USA, and increased water consumption, highlighting that regulations in water use would have implications for agricultural development in the long run. As for biodiversity, Sandker *et al.* (2012) found that the best path to regional economic development in multiple forest regions across Asia and Africa was *Business-As-Usual*, but this approach came at the expense of preserving biodiversity. Our analysis of the Pyrenean social-ecological system (**Chapter 3**) also revealed the trade-offs associated with economic growth. Variables linked to it had impacts on biodiversity and water resources. In addition to the environmental implications highlighted in Chapter 3, the results of **Chapter 2** revealed that the *Business-As-Usual* scenario, which prioritizes economic growth above all, did not align with the interests of the Pyrenean locals. Therefore, continuing on the path of economic growth in the Pyrenees would not only negatively impact natural resources, but also the well-being of the region's inhabitants.

Kubiszewski and collaborators (2013) showed that prosperity, measured through an indicator considering environmental and social aspects, reached its peak in 1978. From then on, economic growth continued, but the expected increase in prosperity did not. Presently, no country successfully meets social needs while simultaneously ensuring sustainable resource use (O'Neill *et al.*, 2018). Thus, reevaluating the paradigm of endless economic growth becomes imperative (Costanza *et al.*, 2014; Van den Bergh, 2009). *Degrowth* has been proposed as a good development path for rural and marginal areas, local economies embedded in global capitalist economies (Rooney and Vallianatos, 2021). Drawing from the case of the Pyrenean social-ecological system, *Degrowth* appears to be a fitting development pathway for certain rural mountain areas as well. On one hand, *Degrowth* aligns better with the potential adaptation actions that local communities would welcome (**Chapter 2**); On the other hand, paths associated with increasing GDP, such as *Business-As-Usual*, result in a loss of water resources and biodiversity (**Chapter 3**). However, the absence of a comprehensive and actionable framework for *Degrowth* and its implications in the SES dynamics and actors' interests needs further examination. Future research should prioritize the development of analytical tools to accurately account for socioeconomic drivers and their impacts at local scale. Conducting more in-depth investigations into the effects of global market interests at the local level would enable to foster an inclusive approach to local development that aligns with global agendas. Ultimately, this will allow to design strategies that promote *Degrowth* while also considering the interests of rural actors.

It should be noted that the proposed guidelines in **Chapter 2** do not consider the percentage of population within each mental model. If, for example, the majority of the population falls into the agriculturalist group, this mental model could be given greater weight than others. Similarly, some adaptation actions may hold more social, cultural, or economic significance than others and warrant further discussion. For instance, ski resorts have environmental impacts related to water and energy consumption for snowmaking and may not be economically viable *per se* (Moreno-Gené *et al.*, 2020; Spandre *et al.*, 2019; Lasanta *et al.*, 2013). However, they serve as a tourism attraction in winter and significantly contribute to the locals' income (Campillo Besses and Font Ferrer, 2004; Lasanta *et al.*, 2013). Therefore, while it is necessary to reduce dependence on snow-related activities due to climate change (Steiger *et al.*, 2019; Sánchez Pulido *et al.*, 2016; Moreno-Gené *et al.*, 2020), adaptation strategies should be carefully planned to ensure alternative ways to boost the local economy. Conversely, there are practices that are diminished but could potentially become feasible sources of income for locals in the long run. Dairy products and organic meat, for instance, could be transformed into commodities with added market value (Tulla, 2019). Another example is transhumance, a traditional form of seasonal herd mobility over long distances practiced in the Pyrenees since the Neolithic period, which significantly declined during the 20th century (Geddes, 1982). A recent study in the Central Pyrenees found that transhumance is estimated to be more profitable than current semi-extensive production in 64-78% of cases (Fernández-Giménez, 2020), while also contributing to the preservation of cultural heritage and biodiversity (Oteros-Rozas, 2014; Garzón-Heydt, 2004). Therefore, despite a weighting system based on current economic relevance could be considered, it is crucial to assess the long-term potential of adaptation actions. Otherwise, adaptation actions with great potential for success could be hindered, slowing down adaptation.

In addition to the omission of socioeconomic drivers, an important caveat detected in the review of mountain SES studies from **Chapter 1** was the inclusion of only a few elements per study. This finding likely explains why the majority of the reviewed studies did not integrate information from both the social and ecological dimensions. To address this issue, Ostrom's social-ecological system (SES) framework can be applied to structure and organize the information, as it is arguably one of the most comprehensive frameworks available (Delgado-Serrano and Ramos, 2015; Colding and Barthel, 2019; Partelow 2018). Applying Ostrom's SES framework in the Pyrenees region helped identify a large number of potentially relevant elements to describe this social-ecological system in **Chapter 3**. However, due to missing data in the study region, some variables could not be included. For example, socioeconomic and political drivers, as previously mentioned, posed challenges. Similar issues were encountered with other data, such as salary and occupation per sector, which were only available at larger scales than the two counties within the study region. Additionally, crucial data, such as water usage for snowmaking by ski resorts, or the range of norms and strategies applied to reduce water consumption, were unavailable at any scale. In the Pyrenees, missing data proved particularly problematic for socioeconomic variables (**Chapter 3**), which contrasts with the bias towards the inclusion of socioeconomic variables over ecological ones in the mountain SES literature (**Chapter 1**). As it occurs in other regions, most social-ecological studies in the Pyrenees mainly rely on socioeconomic survey data and seldom include environmental data (e.g., Muñoz-Ulecia, 2021; Fernández-Giménez *et al.*, 2022). Although these studies bring valuable information regarding the locals' perception of the causes and consequences of vulnerability, they provide little information regarding holistic social-ecological system functioning. The Pyrenean social-ecological study in **Chapter 3** complements previous research by adopting a holistic perspective on the sustainable development of this SES. By doing so, it enables the planning of strategies that target multiple aspects of the system simultaneously through direct and indirect pathways. For instance, promoting extensive agricultural and livestock practices reduces dependence on tourism while contributing to the preservation of favorable habitats for butterflies. Overall, the study from **Chapter 3** emphasizes the importance of combining information from both the social and environmental dimensions to understand how a system functions, and how it may respond to global change.

Modularity analyses from **Chapter 3** highlight the importance of measuring the relationships between variables quantitively rather than qualitatively. Neglecting the magnitudes of these relationships often led to under- or overestimations. Likewise, the role of each variable in connecting other variables and modules (betweenness and participation) cannot be properly measured using qualitative methods. Structural Equation Modeling (SEM) was useful to quantify the relationships between variables, as well as to capture both direct and indirect impacts. However, SEM has some limitations. First and foremost, feedback loops cannot be implemented in SEM, which limits the representation of some relationships. For example, occupation in the services sector and in agriculture are inherently connected through a feedback loop: the more people employed in one sector, the fewer there are in the other. A partial workaround for this issue is to identify the strongest direction of the relationship and represent it as unidirectional. Nevertheless, this may not always be feasible. In such cases, the relationships had to be omitted. Furthermore, SEM cannot handle missing values, requiring the use of various imputation methods to estimate the gaps in the dataset. Thus, complementary statistical tools need to be developed to address the computation of feedback loops in network analyses (Herrero-Jáuregui *et al.*, 2018), as well as to deal with missing values.

Although it would have been intriguing to apply the guidelines outlined in **Chapter 2** to the analysis of the social-ecological system in **Chapter 3**, both studies were conducted in parallel, preventing their direct integration. Nonetheless, combining these approaches could yield valuable insights. On the one hand, **Chapter 2** provides information regarding the interests of the local community and how various development pathways may intersect with them. On the other hand, **Chapter 3** offers a quantitative understanding of the interactions among different social-ecological elements within the same region. The development pathways discussed in **Chapter 2** represent potential macroeconomic trajectories that the region may (or may be compelled to) pursue, each aiming to maximize specific variables within the social-ecological system from **Chapter 3**. For instance, *Business-As-Usual* seeks to maximize the region's total GDP. In the Pyrenees, this approach would entail prioritizing the dominant economic asset of the area: tourism (Offenhenden and Soronellas-Masdeu, 2021; del Marmol and Vaccaro, 2015). Conversely, a *Degrowth* approach involves decelerating economic growth while emphasizing biodiversity and natural resources such as water (Weiss, 2017). Likewise, the distinct mental frameworks discussed in **Chapter two** prioritize the maximization of different SES variables within the system. For instance, the *Endogenous Development* mental framework focuses on increasing the resident population and reducing the region's reliance on tourism (López-i-Gelats *et al.*, 2009). Conversely, the *Entrepreneurial* framework promotes development through tourism, including the maintenance of ski resorts. Thus, it would be insightful to explore which variables would change as a response to following each development pathway, as well as how these changes would subsequently impact other variables and satisfy the various mental frameworks. Such an analysis could offer valuable insights into the potential trade-offs and synergies between different actors and pathways, shedding light on the complex dynamics of the social-ecological system.

The science communication tool developed in **Chapter 4** partially addresses the exploration of interactions between development pathways, actors, and the quantitative network. *BALANCE*, the Serious Game prototype, enables players to select a development pathway, which determines the game's development goals; and, in parallel, each actor is influenced positively or negatively by system variables related to their interests. By adjusting the values of social-ecological system variables, players aim to achieve the development goals while indirectly impacting other variables (as per **Chapter 3**) and the satisfaction of the actors (as per **Chapter 2**). These game mechanics enable players to directly experiment with the trade-offs between following a development pathway, accommodating the interests of local actors, and preserving natural resources. Therefore, the game serves as an interactive tool to visualize the compromises linked to sustainable development in the Pyrenees, as explored in the studies of this thesis. Since the thesis primarily focused on developing the tool, the current prototype version has not undergone beta-testing yet (i.e., testing the game with a selected group of real users with the goal of identifying potential issues). Testing is, however, an indispensable aspect of Serious Game development. It not only helps identify potential errors but also evaluates players' learning and engagement, helps assess and balance mechanics, and generates innovative ideas to integrate into the game (Hügen and Davies, 2022; Galeote *et al.*, 2022; Neset *et al.*, 2020). Thus, we plan on carrying out beta-testing sessions with students as the next step of the development process.

We have a series of new features planned that we intend to incorporate into a near-future version of *BALANCE* to enhance its overall experience. For instance, directly modifying certain system variables, such as forest cover or the percentage of people working in a specific sector, is somewhat unrealistic. Other Serious Games have tackled this challenge by incorporating cards featuring adaptation measures (such as the French game Espéride, ONF, 2023). Instead of directly modifying variables, players can employ these cards to implement specific measures, which subsequently affect system variables and actors. In a future version of *BALANCE*, the adaptive actions discussed in Chapter 2 would be good candidates to use to explore this approach. Moreover, to make the game more realistic and engaging, we plan to incorporate additional features in the future. For instance, the game could incorporate a system to simulate extreme events linked to climate change, such as forest fires or droughts (Ruffault *et al.*, 2018). Additionally, implementing a multiplayer option would enable the players to take the role of different managers with potentially opposing interests, creating an excellent scenario to discuss conflicts and compromises linked to climate change adaptation (Ouriarchi, 2017).

Aside from the science communication tool, there is value in building a similar instrument to simulate potential trajectories that the system could follow to achieve the goals of the development pathways. In this regard, dynamical networks offer an interesting approach. Dynamical networks provide the ability to make future projections and simulate how a system may change under different scenarios. These networks have been successfully applied to various social-ecological systems, including agricultural and coral reef systems (Paz *et al.*, 2020, Hafezi *et al.*, 2021). By employing this methodology, valuable insights can be gained regarding the system's adaptive capacity and its potential responses to different development pathways.

The elements and methodologies presented in the last three chapters of this thesis—the guidelines for preventing maladaptation, the quantitative network analysis, and the Serious Game—have the potential to be applied to various social-ecological systems. Firstly, the guidelines (**Chapter 2**) have been intentionally designed to be flexible and adaptable to different settings. Thus, they can be applied to any social-ecological system, regardless of the method used to classify mental models or the development pathways employed. Secondly, although we did not develop the Structural Equation Modeling methodology itself, its application to quantitatively analyze the relationships between social-ecological elements (**Chapter 3**) was unprecedented. Despite the aforementioned limitations, structural equation modeling enables the quantitative measurement of the magnitude of effects between variables (Malaeb *et al*., 2000). Adopting a quantitative approach allows for modularity analyses, which are valuable for identifying tightly interconnected variables and those that act as connecting points between different parts of a network. This methodology can be applied to quantitatively characterize other social-ecological systems, enabling meaningful comparisons beyond qualitative descriptions. Finally, the Serious Game *BALANCE* (**Chapter 4**) has been designed to be flexible and adaptable to any social-ecological system for which the relationships among variables are known. This flexibility is achieved by introducing game settings, such as variable names, interactions, and magnitudes, through an external file that can be easily modified. By leveraging this feature, the Serious Game can be tailored to simulate the dynamics of virtually any social-ecological system.

In conclusion, this thesis presents an integrated approach to understanding and managing social-ecological systems in the context of climate change adaptation. By combining qualitative and quantitative methods, and developing a Serious Game as a science communication tool, we have developed a comprehensive framework that is flexible and adaptable to diverse social-ecological systems. The guidelines outlined in Chapter 2 provide a robust foundation for preventing maladaptation, while the Structural Equation Modeling methodology described in Chapter 3 offers a quantitative approach to analyze the intricate relationships among system elements. Finally, the *BALANCE* Serious Game introduced in Chapter 4 serves as an interactive platform to explore different development pathways and their consequences on the system and its actors. This integrated approach holds great potential to enhance our understanding of social-ecological systems and guide the development of more effective climate change adaptation strategies. Furthermore, the methodologies and tools developed in this thesis are not limited to a specific context but can be applied to a wide range of social-ecological systems. As a result, they are valuable resources for researchers, policymakers, and practitioners working in various settings. Ultimately, this work contributes to the advancement of knowledge in the field and supports efforts to build resilient and sustainable social-ecological systems.

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Appendix 1: Supplementary material Chapter one

A1.1 Supplementary Material A – Ostrom's social-ecological variables

First and second level tiers of Ostrom SES framework (see Epstein *et al*., 2013 and Vogt *et al*., 2015 for information about each tier)

First level tiers	Second level tiers	
Resource Systems	RS1	Sector
	RS2	Clarity of system boundaries
	RS3	Size of resource system
	RS4	Human-constructed facilities
	RS5	Productivity of the system
	RS6	Equilibrium properties
	RS7	Predictability of system dynamics
	RS8	Storage characteristics
	RS9	Location
	RS10	Ecosystem history
Resource Units	RU1	Resource unit mobility
	RU2	Growth or replacement rate
	RU3	Interaction among resource units
	RU4	Economic value
	RU5	Number of units
	RU6	Distinctive characteristics
	RU7	Spatial and temporal distribution
Governance System	GS1	Policy area
	GS2	Geographic scale of governance system

First level tiers	Second level tiers	
Actors	A1	Number of relevant actors
	A2	Socioeconomic attributes
	A3	History of past experiences
	A4	Location
	A5	Leadership/entrepreneurship
	A6	Norms (trust-reciprocity)/social capital
	A7	Knowledge of SES/mental models
	A8	Importance of resource (dependence)
	A9	Technologies available
Ecological Rules	ER1	Physical rules
	ER2	Chemical rules
	ER3	Biological rules
Related Ecosystems	ECO1	Climatic patterns
	ECO2	Pollution patterns
	ECO3	Flows into and out of focal SES
Socio-economic and political drivers	S1	Economic development
	S2	Demographic trends
	S3	Political stability
	S4	Other governance systems

	GS3	Population
	GS4	Regime type
	GS5	Rule-making organizations
	GS6	Rules-in-use
	GS7	Property-rights system
	GS8	Repertoire of norms and strategies
	GS9	Network structure
	GS10	Historical continuity

	S5	Markets
	S6	Media organizations
	S7	Technology

A1.2 Supplementary Material B – List of reviewed works

1. Fontefrancesco MF, Pieroni A (2020) Renegotiating situativity: transformations of local herbal knowledge in a Western Alpine valley during the past 40 years. Journal of Ethnobotany and Ethnomedicine (16) doi: 10.1186/s13002-020-

2. Sun X, Shan R, Liu F (2020) Spatio-temporal quantification of patterns, trade-offs and synergies among multiple hydrological ecosystem services in different topographic basins. Journal of cleaner production (268) doi: 10.1016/j.jclepro.2020.122338

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14. Berges L, Dupouey JL (2020) Historical ecology and ancient forests: Progress, conservation issues and scientific prospects, with some examples from the French case. Journal of Vegetation Science doi: DI 10.1111/jvs.12846

15. Thakur S., Negi VS, Pathak R, Dhyani R, Durgapal K, Rawal RS (2020) Indicator based integrated vulnerability assessment of community forests in Indian west Himalaya. Forest Ecology and Management 457, doi: 10.1016/j.foreco.2019.117674

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A1.3 Supplementary Material C – Figures and tables

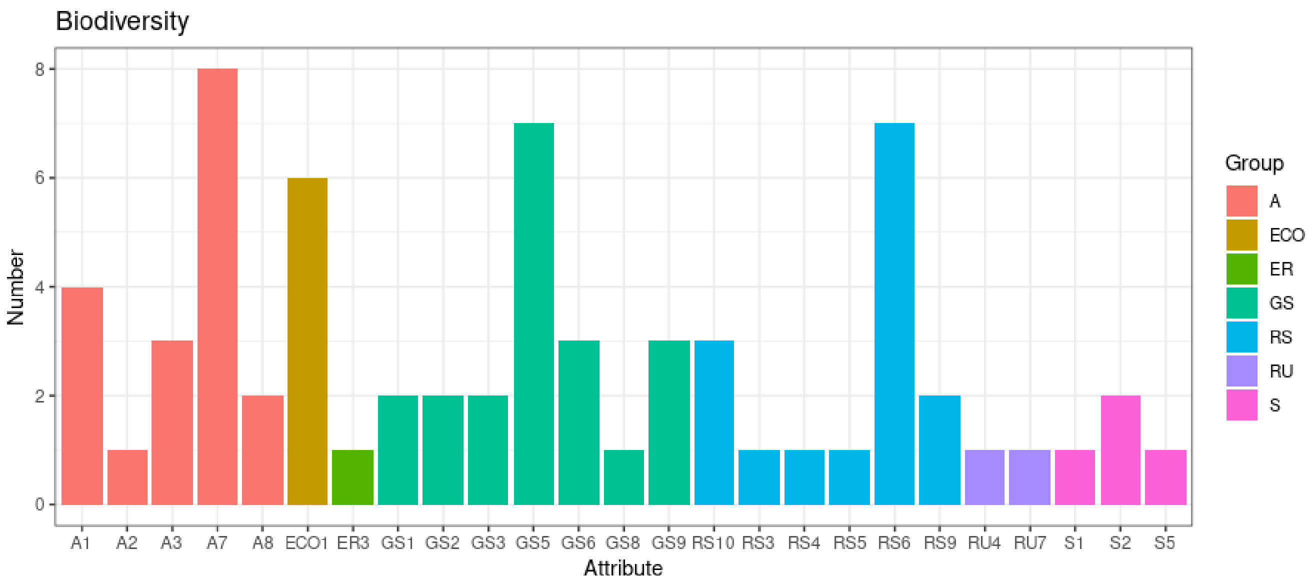
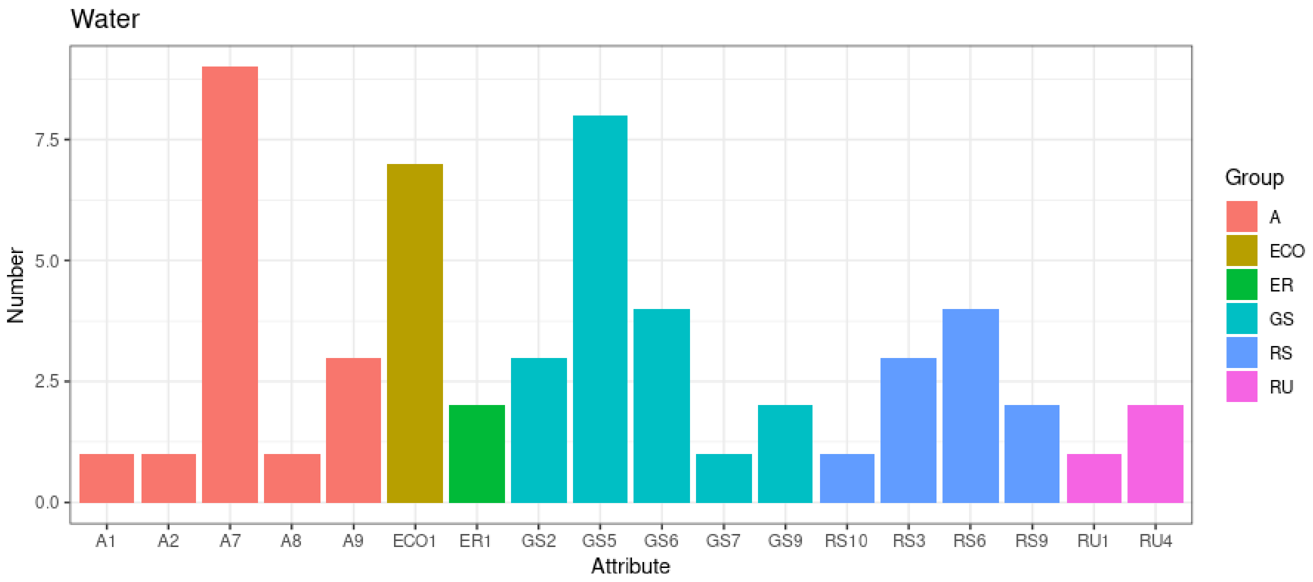


Figure C1. Number of times an attribute has been included in manuscripts where "Biodiversity" was the Sector (RS1)



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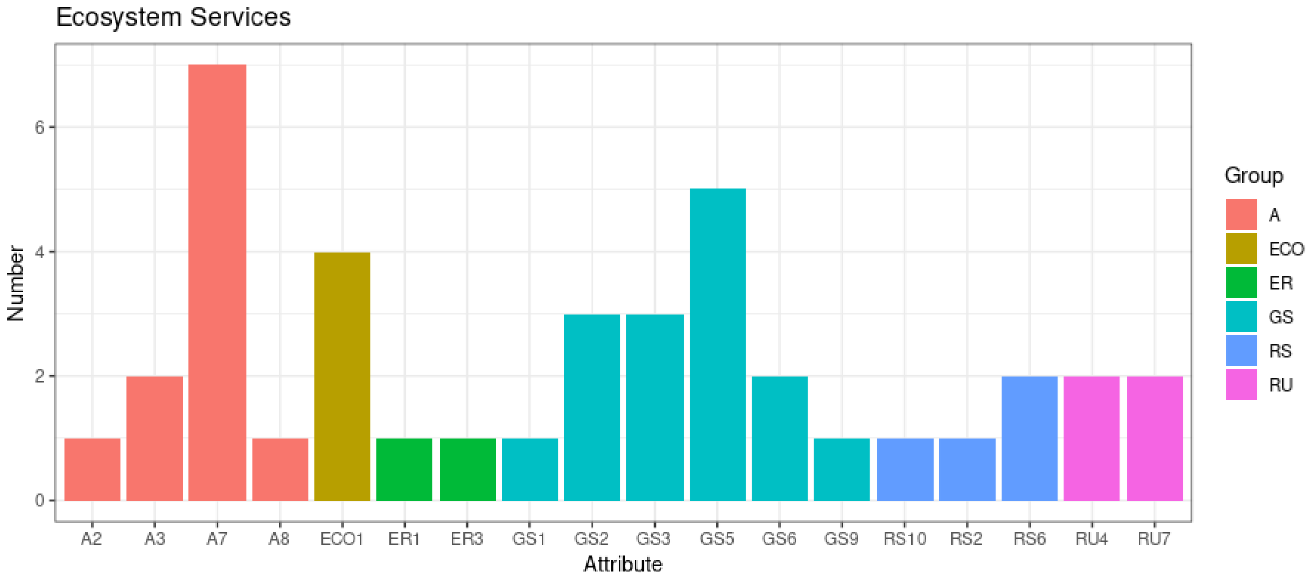

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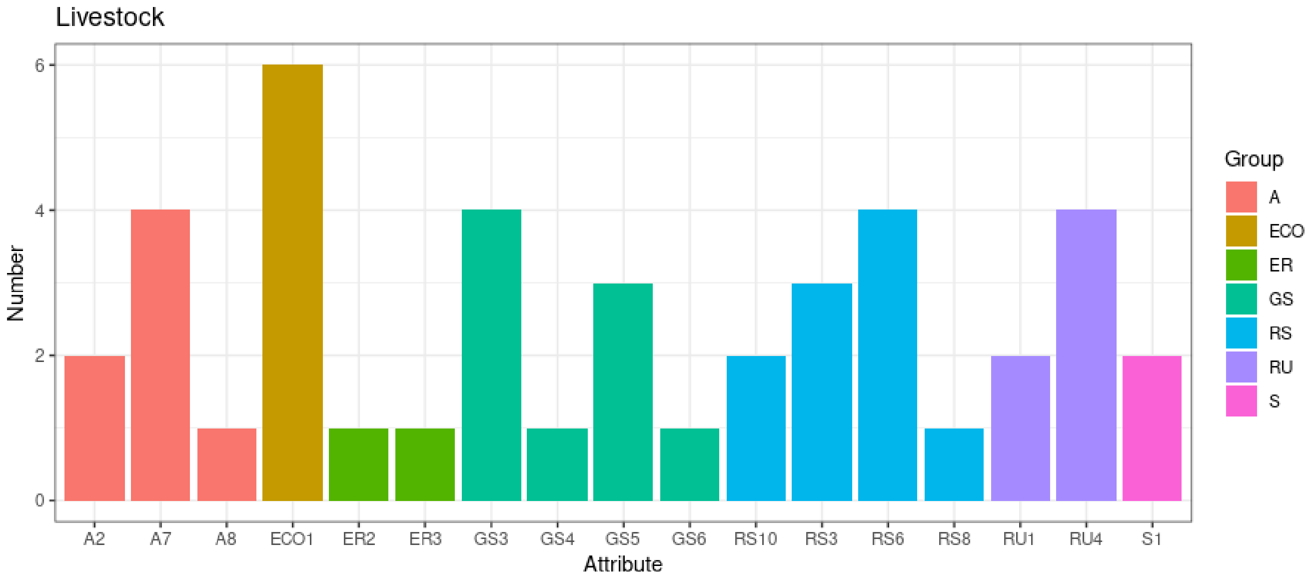

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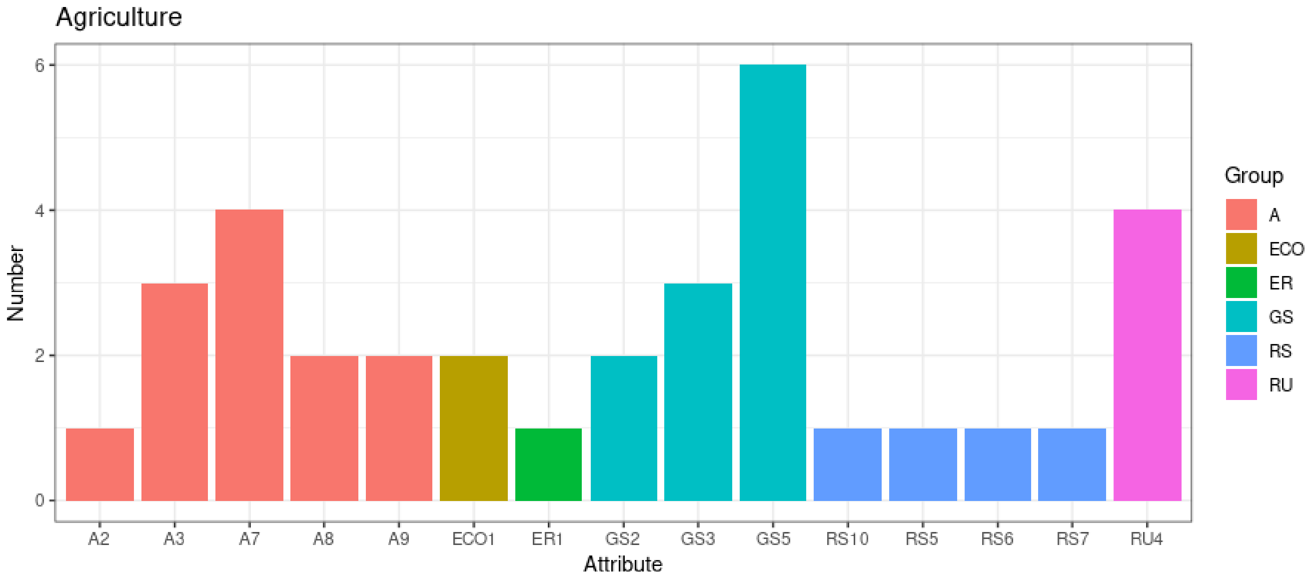

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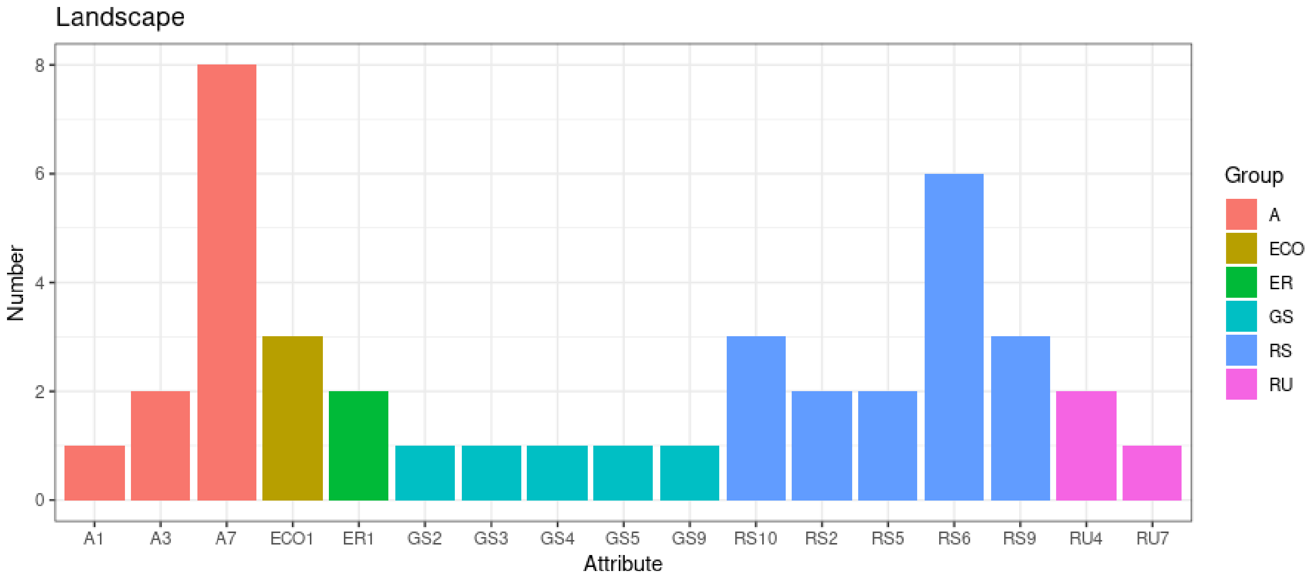

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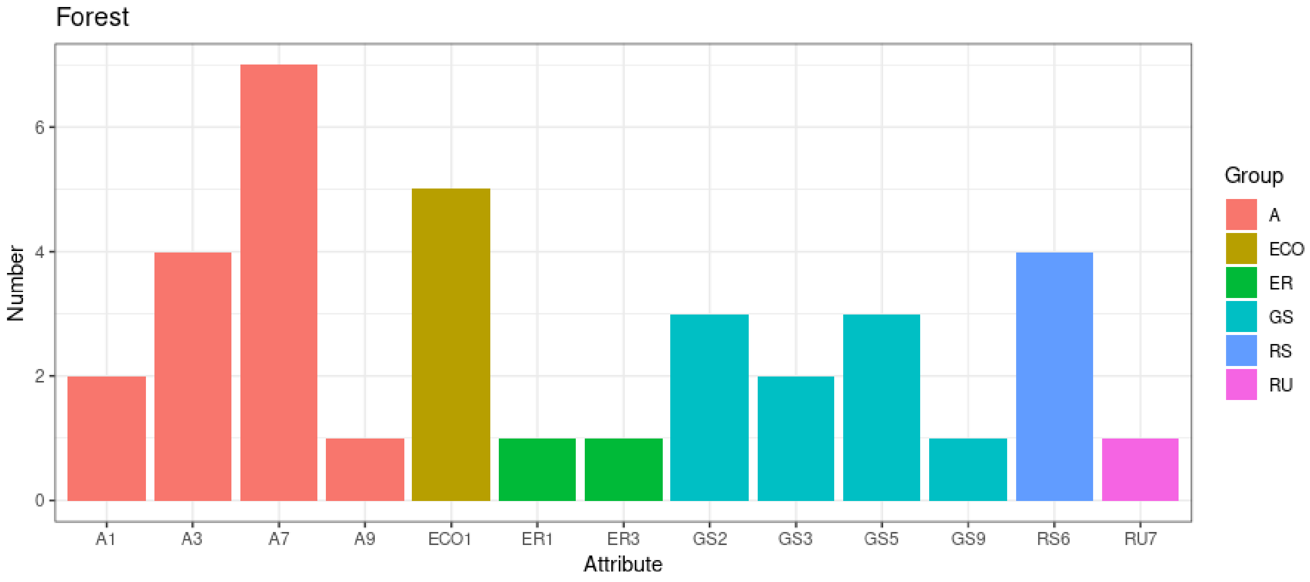

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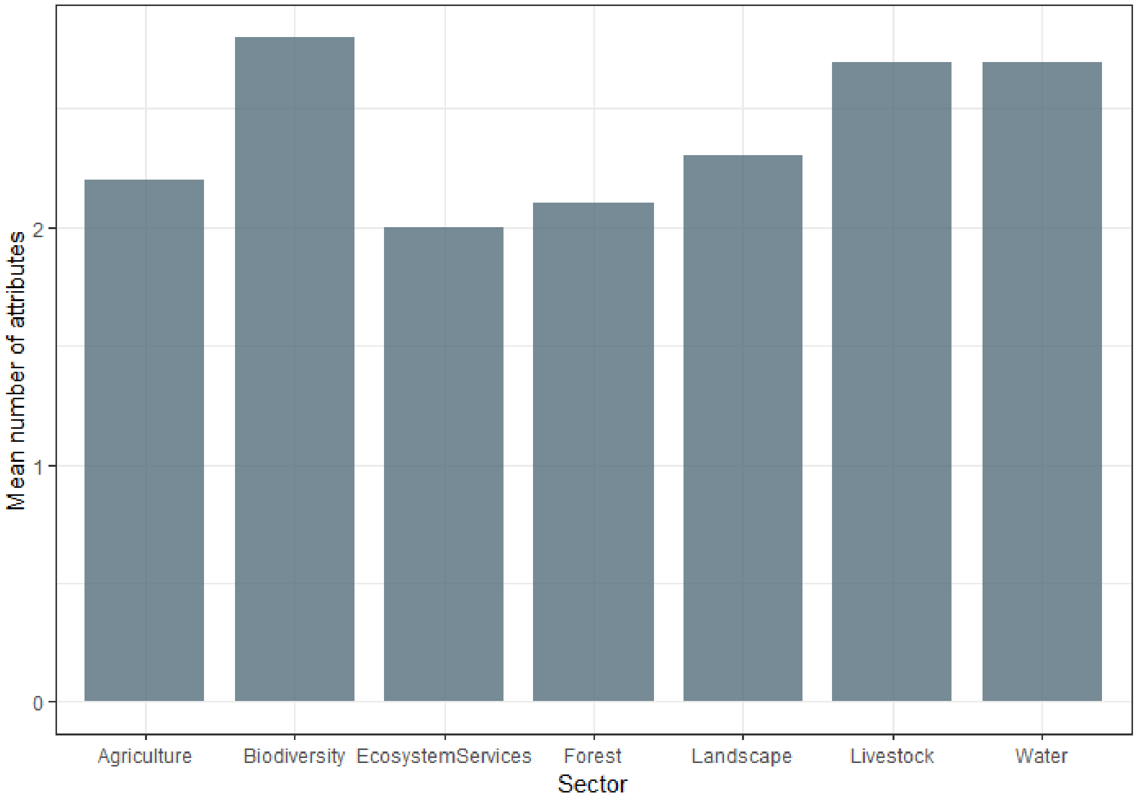
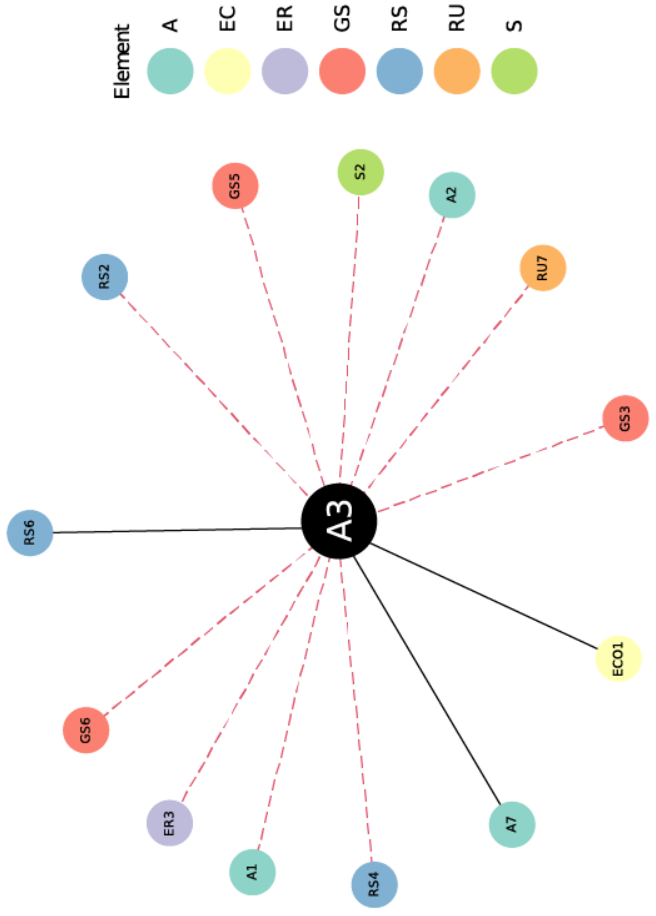


Figure C8. Mean number of addressed attributes per sector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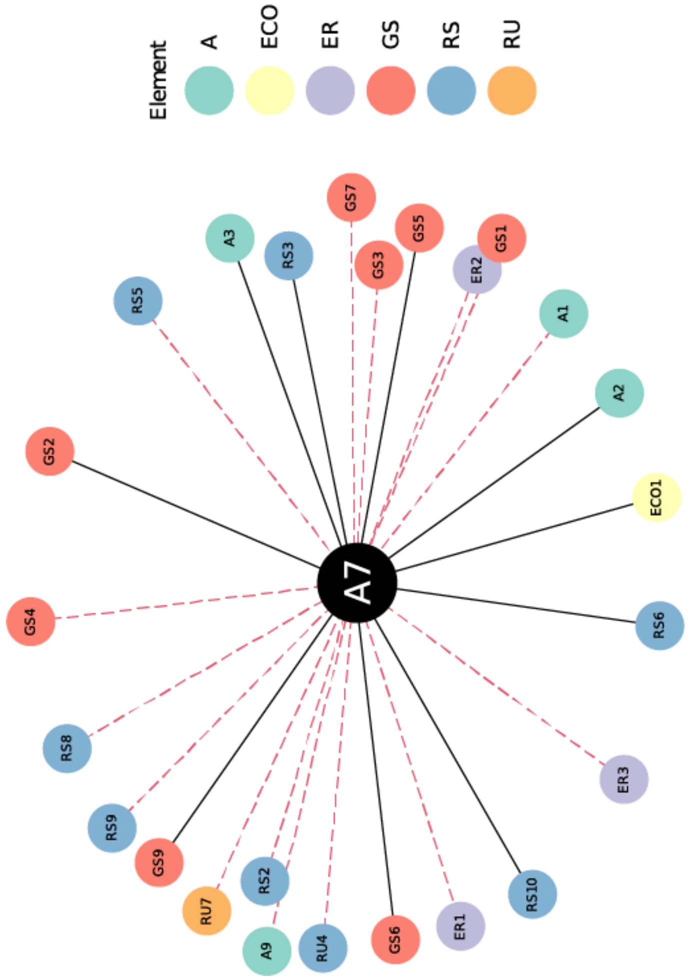
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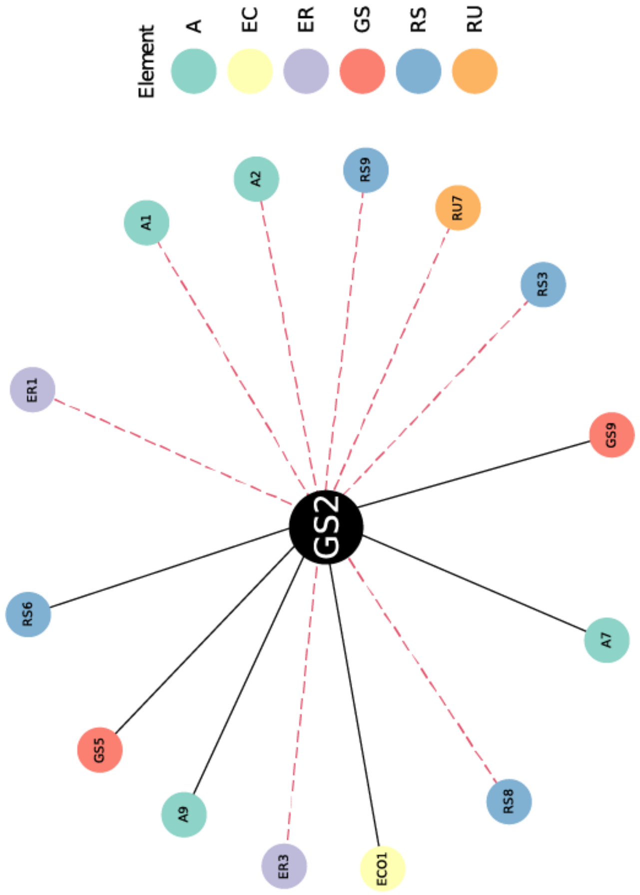
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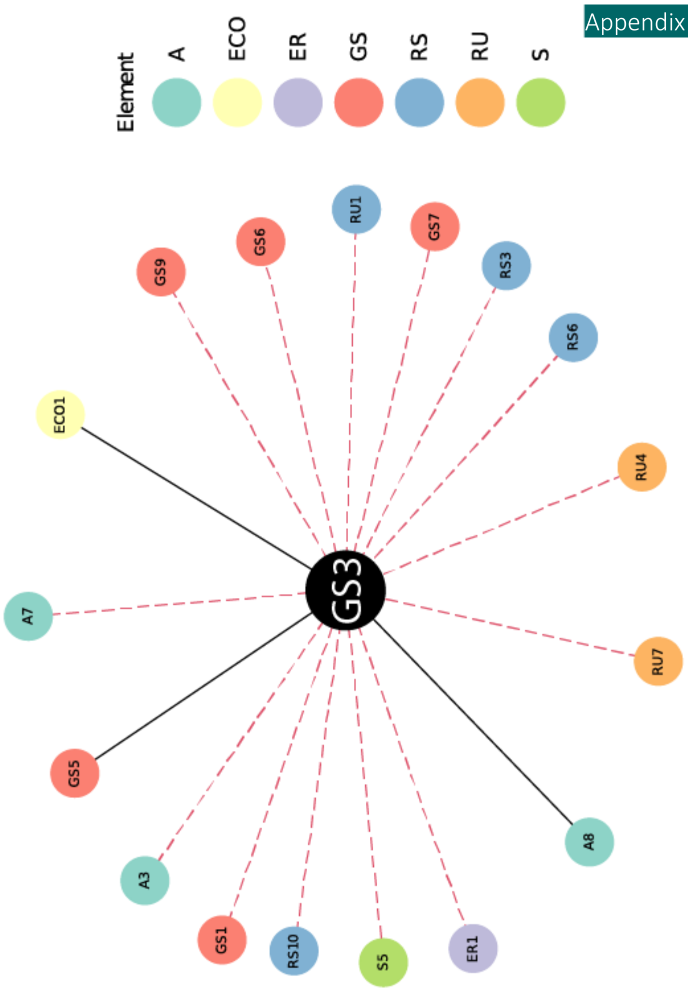
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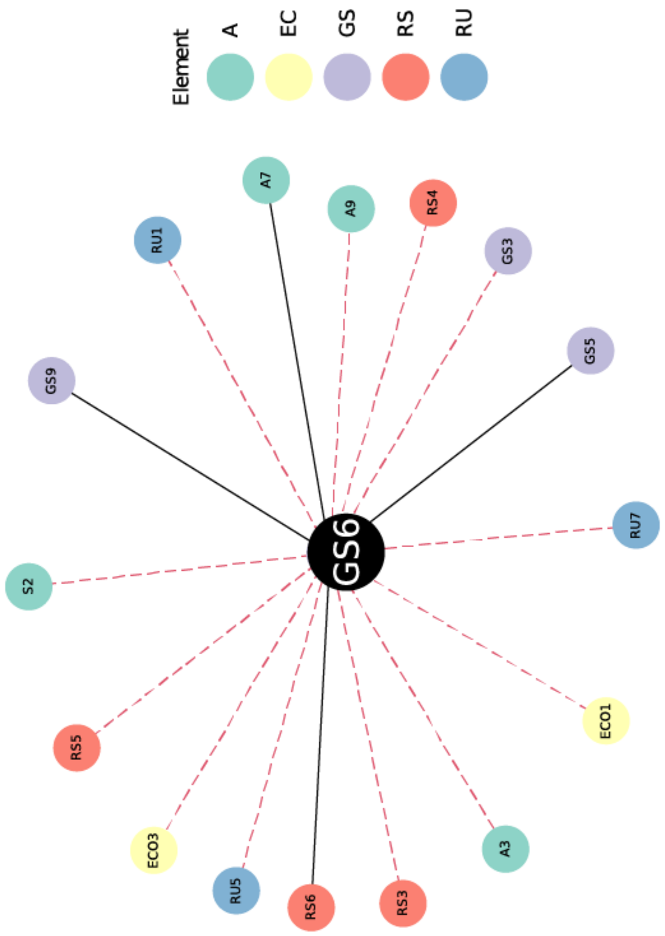
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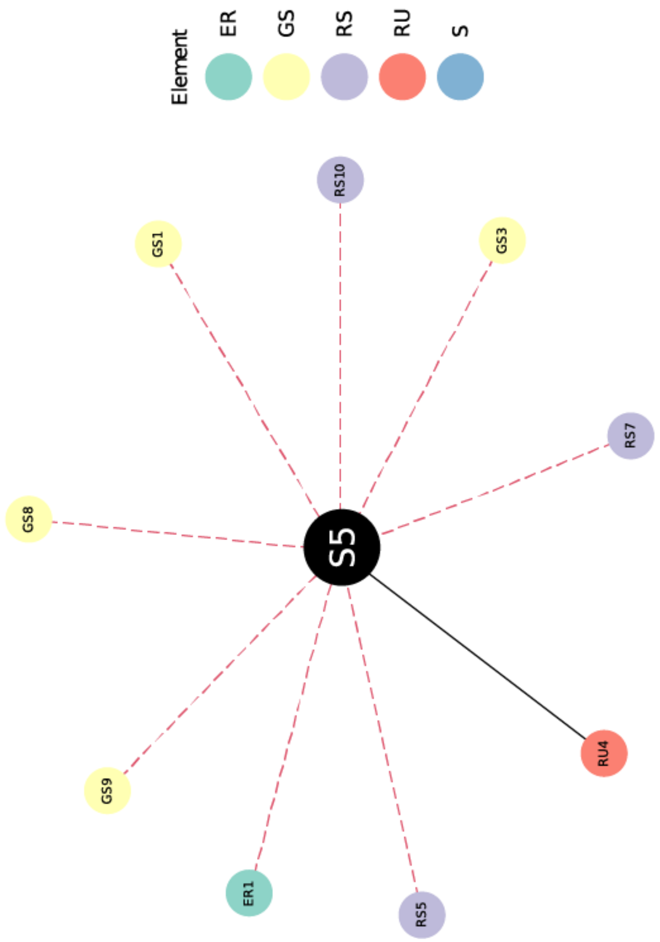
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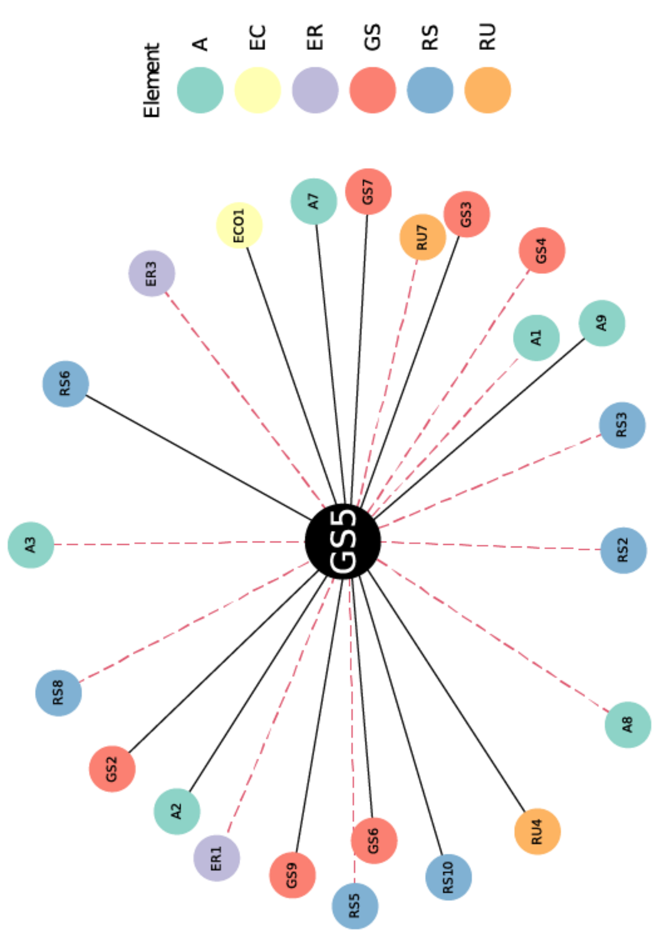
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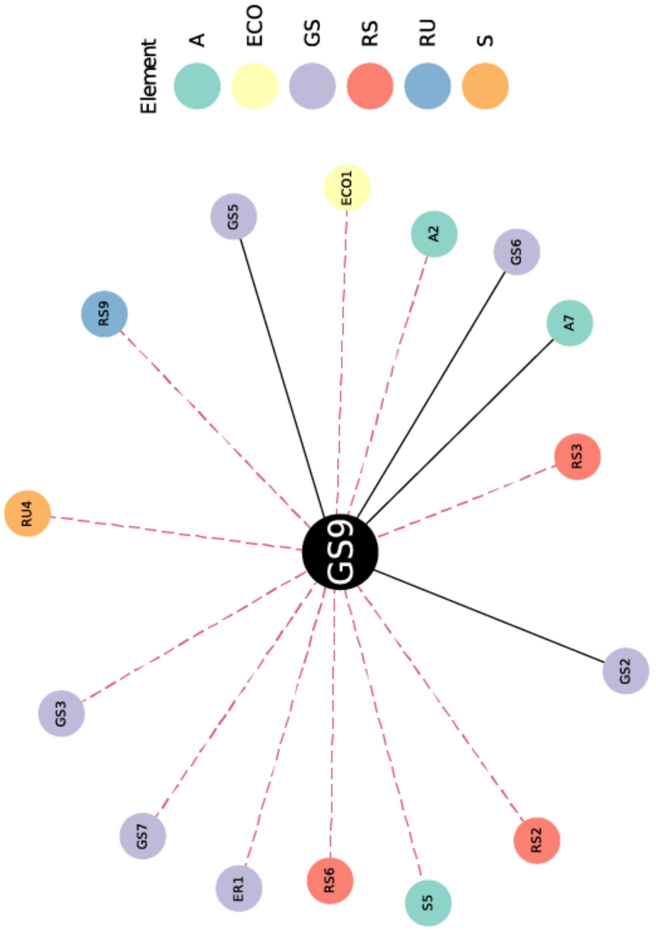
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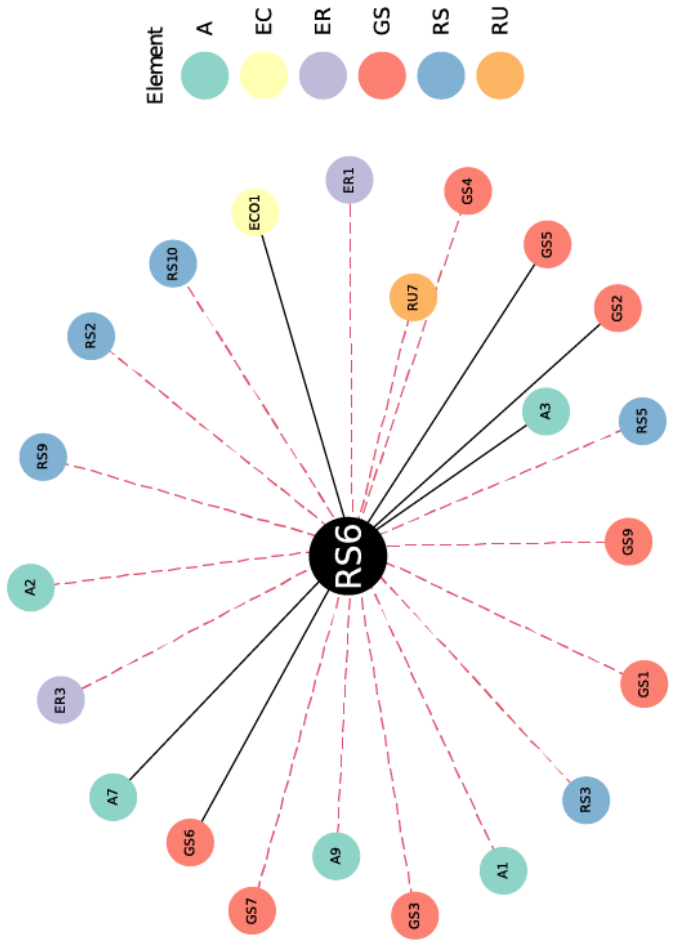
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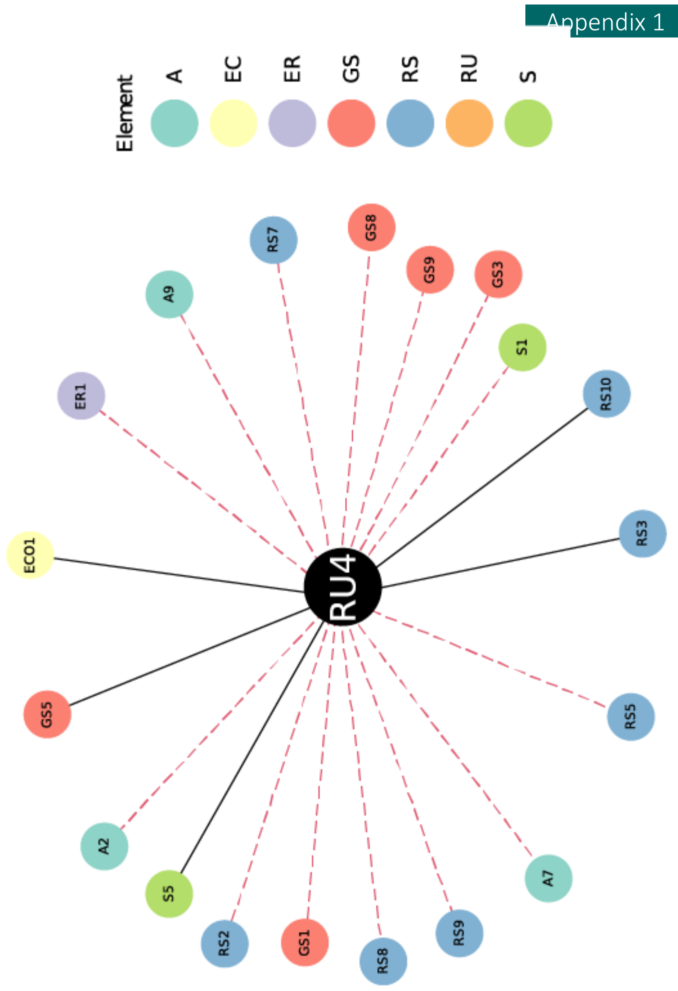
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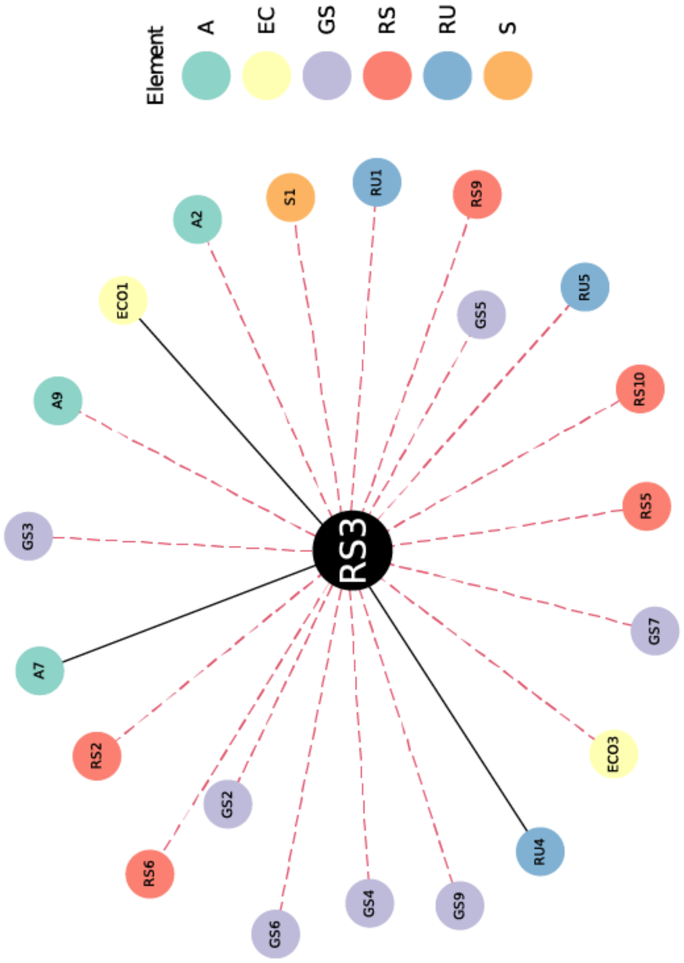
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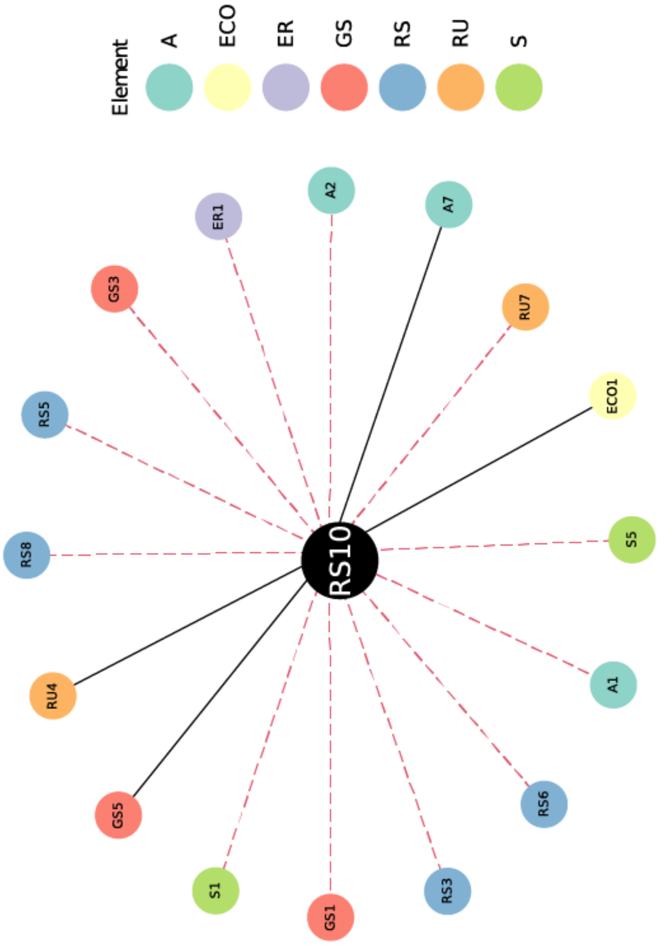
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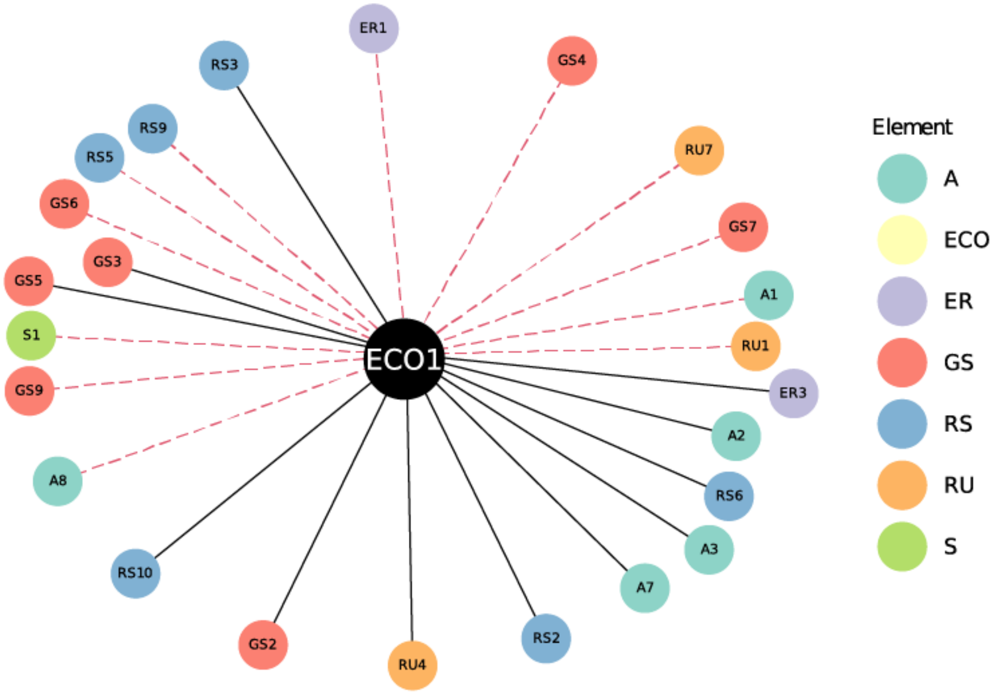

Figure C9. Single networks showing the links between the most addressed attributes and the rest. Solid lines indicate that these links appear in three or more papers and dashed red lines indicate the links that appear in less than three manuscripts (A: Actors, ECO: Related Ecosystems, ER: Ecological Rules, GS: Governance System, RS: Resource System, RU: Resource Unit, S: Socio-economic and Political Drivers).

Table C1. Number and percentage of papers not employing a framework and employing one, as well as the mean number and standard deviation of attributes addressed per study within each category. The category *Globally* includes all works addressed in this study. Percentages per framework type were calculated over the total of papers using a framework.

Framework	Number of papers	%	Attributes per study	SD
Globally	172	100	2.5	1.23
No framework used	128	74.4	2.5	1.16
Framework used	44	25.6	2.7	1.42
Ad-hoc unique framework	14	31.8	3.1	1.35
Resilience (1)	6	13.6	2	1.26
Ostrom SES Framework (2)	5	11.4	3.6	1.95
Vulnerability (3)	4	9.1	2	1.41
Q-methodology (4)	3	6.8	2.3	1.53
Driving force, Pressure, State, Impact, Response (DPSIR) (5)	2	4.5	1.5	0.71
Social Values for Ecosystem Services (6)	2	4.5	1.5	0.71
Adaptive Capacity in SES (7)	1	2.3	-	-
Ecoagriculture approach (8)	1	2.3	-	-
Ecosystem Services framework (9)	1	2.3	-	-
Pahl-Wostl (10)	1	2.3	-	-
Social-ecohydrological thresholds (SEHT) (11)	1	2.3	-	-
Socio-ecological systems water metabolism framework (12)	1	2.3	-	-
Socio-environmental coevolutionary perspective (13)	1	2.3	-	-
STEEP (Social, Technological, Environmental, Economic, Political) (14)	1	2.3	-	-

Table C2. Number and percentage of papers addressing only social elements, only ecological elements and both social and ecological elements together. Results are presented globally for all papers, as well as per the use of a framework.

	Attributes addressed	Nº of papers	%
Globally	Only social elements	66	38.37
	Only ecological elements	23	13.37
	Both social and ecological elements	83	48.26
Works using a framework	Only social elements	17	38.64
	Only ecological elements	6	13.64
	Both social and ecological elements	21	47.73
Works not using a framework	Only social elements	49	38.28
	Only ecological elements	17	13.28
	Both social and ecological elements	62	48.44

Table C3. List of attributes that have not been detected in the analyzed bibliography and one example of the attribute addressed in a paper that did not mention mountains as social-ecological systems.

SES element		Short description	Reference	
Resource system	RS2	Clarity of system boundaries	Dangi and Gribb, 2008	Sustainable ecotourism management and visitor experiences: managing conflicting perspectives in Rocky Mountain National Park, USA. **Journal of Ecotourism**
	RS4	Human constructed facilities	Locatelli *et al.*, 2011	Ecosystem services and hydroelectricity in Central America: modelling service flows with fuzzy logic and expert knowledge. **Regional Environmental Change 11:393–404**
	RS7	Predictability of the ecosystem dynamics	Seidl *et al.*, 2011	What drives the future supply of regulating ecosystem services in a mountain forest landscape? **Forest, Ecology and Management** 445, 37-47
	RS8	Storage characteristics	Phillips *et al.*, 2019	Differences in carbon stocks along an elevational gradient in tropical mountain forests of Colombia. **Biotropica** 51(4): 490-499

Resource Units	RU2	Growth or replacement rate of the RU	Rieman and Isaak, 2010	Climate change, aquatic ecosystems, and fishes in the Rocky Mountain West: implications and alternatives for management. **Gen. Tech. Rep. RMRS-GTR-250. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 46 p**
	RU3	Interaction among RU	McNaught *et al.*, 1999	Restoration of the food web of an alpine lake following fish stocking. **Limnology and Oceanography 44(1):127-136**
	RU5	Number of units	Post vam der Burg and Tyre 2011	Integrating info-gap decision theory with robust population management: a case study using the Mountain Plover. **Ecological Applications 21(1): 303-312**
	RU6	Distinctive Characteristics	Sollman *et al.*, 2013	Combining camera-trapping and noninvasive genetic data in a spatial capture–recapture framework improves density estimates for the jaguar. **Biological Conservation 167:242-247**
Actors	A4	Location	Rodriguez-Ponce and Crescenci 2008	Mountains in a flat world: why proximity still matters for the location of economic activity. Cambridge Journal of Regions, **Economy and Society 1(3):371–388, https://doi.org/10.1093/cjres/rsn011**
	A5	Leadership/entrepreneurship	Taylor *et al.*, 2019	Exploring how entrepreneurial actors shape tourism development: the case of mountain bike tourism at Rotorua. **Tourism Recreation Research 44(4):479-491**
	A6	Norms (trust/reciprocity) or social capital	Thapa *et al.*, 2012	Building collective capabilities through ICT in a mountain region of Nepal: where social capital leads to collective action. **Information Technology for Development 18(1):5-22**
	A8	Importance of the resource (dependence)	Balla *et al.*, 2014	Farmers' dependency on forests for nutrients transfer to farmlands in mid-hills and high mountain regions in Nepal (case studies in Hemja, Kaski, Lete and Kunjo, Mustang district). **International Journal of Biodiversity and Conservation 6(3):222-229**
	A9	Technologies available	Knapp 2017	Mountain Agriculture for Global Markets: The Case of Greenhouse Floriculture in Ecuador. **Annals of the American Association of Geographers 107(2):511-519**

Appendix 2: Supplementary material Chapter two

Table A1. Definitions of the development pathways used, with their respective references.

Term	Definition	Reference
Degrowth	Strategy which "challenges the hegemony of growth and calls for a democratically led redistributive downscaling of production and consumption in industrialized countries as a means to achieve environmental sustainability, social justice and well-being. (…) On one side, degrowth is the reduction of energy and material throughput, needed in order to face the existing biophysical constraints (in terms of natural resources and ecosystem's assimilative capacity). On the other side, degrowth is an attempt to challenge the omnipresence of market-based relations in society and the growth-based roots of the social imaginary replacing them by the idea of frugal abundance. (…) Finally, degrowth implies an equitable redistribution of wealth within and across the Global North and South, as well as between present and future generations."	Demaria, F., Schneider, F., Sekulova, F., and Martinez-Alier, J. (2013). What is degrowth? From an activist slogan to a social movement. Environmental Values, 22(2), 191-215
Circular economy	"to shift from a linear model of resource consumption that follows a 'take- make- dispose' pattern, to an industrial economy that is 'restorative by intention'; i.e. that replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models"	Ellen MacArthur Foundation. (2013). Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition.
Business-As-Usual	Strategy "based on a purely economic view of the firm and business processes. The underlying assumption is that typical economic concerns (e.g., access to cheap resources, efficient processes, striving for a strong market position) are pursued to produce economic value in the form of profit, market value or, more generally, shareholder value. Such an approach typically results in significant externalized costs that are not understood, measured, or declared. The perspective is inside-out, with the business and its objectives as the starting point and main reference for all planning and action. The main beneficiaries of the economic values created are shareholders, complemented by management and customers."	Dyllick, T., and Muff, K. (2016). Clarifying the meaning of sustainable business: Introducing a typology from business-as-usual to true business sustainability. Organization and Environment, 29(2), 156-174.

Appendix 3: Supplementary material Chapter three

A3.1 Supplementary material A: Data sources and processing

Data for all social-ecologic variables was searched for and gathered between January 2020 and July 2021. At that time, some of the necessary data was not available at the desired temporal or spatial scale. However, public databases are periodically updated, and new data may become available in the future.

A3.1.1 Hydrological variables

Hydrological time series were obtained from the Integrated network of gauging stations from the *Confederación Hidrográfica del Ebro*, belonging to the Spanish Ministry for the Ecological Transition and the Demographic Challenge (*Redes de Seguimiento Del Estado e Información Hidrológica*, 2021).

Monthly and annual streamflow data spanning from October 1999 to September 2019 were obtained from 6 different gauging stations. The monthly and annual volume of water stored in the Oliana Reservoir was also obtained for October 1999 to September 2019. The original annual data in this case correspond to hydrological years, spanning from October of a given year to September of the next year. Details on the original variables are available in Table A1.

A3.1.2 Climatic data

Historical monthly maximum temperature and monthly accumulated precipitation data from CRU-TS-4.0 (Harris *et al.*, 2014), downscaled with WorldClim 2.1 (Fick and Hijmans, 2017) were obtained for 1999-2018. In order to later extract the data, a total of 76 points were selected within the study area using ArcGIS® Desktop 10.6, version 10.6.0.8321 (Esri, 2017). As the spatial resolution of climate data was 2.5 minutes, corresponding to ca 21 km^2, a grid with 5x5 km cells was overlapped with a map of Alt Urgell and La Cerdanya counties. The coordinates of the 76 grid's label points intersecting with the study area were then extracted. Monthly climatic data from these 76 points were then extracted from the WorldClim .tif files using the *raster* package (Hijmans and van Etten, 2012) in R.

A3.1.3 Remote sensing-derived environmental data

Remote sensing normalised difference vegetation index (NDVI) at 250 m spatial resolution, maximum summer evapotranspiration (ET) at 500 m spatial resolution and maximum snow cover extent data at 500 m spatial resolution in Alt Urgell and La Cerdanya were extracted from NASA's Application for Extracting Analysis Ready Samples (AppEEARS Team, 2021). NDVI data was available at a temporal resolution of 16 days, between February 2000 and December 2020, ET data at eight-day temporal resolution between February 2000 and December 2019, and maximum snow cover extent data at an eight-day temporal resolution between February 2000 and December 2016. In the data provided, the pixel values for the NDVI data are the values produced at 16-day intervals, and for ET they are the sum of all eight days. In the case of maximum snow extent data, pixels are classified as “snow” if snow cover is found any day of the 8-day period. If another pixel type is found more than once, the pixel is classified as belonging to that type.

Data quality assessment

NDVI data

Pixels for each date were provided with a classification according to the quality and usefulness of the data. Only the pixels classified as “Highest quality”, “Lower quality” and “Decreasing quality” were considered as suitable, and data for a date was only used when the percentage of suitable pixels was higher than 90% of the total number of pixels. Otherwise, the data for that date was ruled out.

ET data

Pixels for each date were provided with a classification according to the quality of the data and presence of clouds. We considered as suitable the pixels classified as “High quality” with no clouds and “High quality” with mixed clouds, and only used data for a date when the percentage of pixels under these categories was higher than 70%.

Maximum snow cover extent data

The pixels for each date were classified as “snow”, “no snow”, “cloud” and “no decision”. Pixels classified as “cloud” were considered as uncertain. Therefore, data for a date was only used when the percentage of pixels classified as “cloud” or “no decision” remained under 10% of the total number of pixels.

A3.1.4 Land use data

We gathered data on land use types for the study region using 30m spatial resolution land use maps from Institut Cartogràfic i Geològic de Catalunya [ICGC] (1987-2002) and Grup de Recerca en Teledetecció i Sistemes d'Informació Geogràfica [Grumets, CREAF-UAB] (2007-2017) (Usos i Cobertes Del Sòl de Catalunya. Territori, 2020). Data was available at a temporal resolution of 5 years. Total surface (km2) was calculated for each land use type using ArcGIS software version 10.6.0.8321, following the categories: urban, roads, forests, and meadows, bushes, or fields.

A3.1.5 Biodiversity data

Mean annual butterfly abundance, richness, and Shannon Biodiversity Index from 2006 to 2019 was calculated based on weekly species census from a transect located in the study region provided by Museu de Ciències Naturals de Granollers as part of the project Catalan Monitoring Butterfly Scheme (CMBS) (*Catalan Monitoring Butterfly Scheme*, 2020).

Mean annual bird abundance, richness, and Shannon Biodiversity Index from 2002 to 2020 was provided by ICO (2020), based on census on breeding and winter season from 4-16 annual transects (average transect per year of 12.7).

A3.1.6 Social and economic data

Gross domestic product (GDP) variables

Due to the lack of GDP data at a smaller spatial scale, we used the total GDP, agriculture GDP and services GDP for the region of Lleida between 2000 and 2020 provided by INE (National Statistics Institute) (INE, 2023). Given that the GDP was heavily impacted by the COVID-19 pandemic in 2020 (Pinilla *et al.*, 2021), the year 2020 was calculated by averaging the previous 5 years.

Employment-related data and subsidies

Due to the lack of data for La Cerdanya and Alt Urgell on the annual scale, we used the total annual number of workers employed in the services sector and in agriculture and livestock between 2000 and 2020 in Lleida (INE, 2023).

In addition, we calculated the annual gross salary of the workers employed in the agriculture sector based on the salary per day of the permanent employees in agriculture between 2000 and 2017 (Ministerio de Agricultura Pesca y Alimentación - Gobierno de España, 2020a). To calculate the annual salary, we multiplied the daily salary by 30 (assuming 30 days per month) and by 12.

Finally, we also gathered data on annual public expenditure on subsidies to agriculture in Catalonia between 2000 and 2006 (Ministerio de Agricultura Pesca y Alimentación - Gobierno de España, 2020b) and between 2015-2020 (Generalitat de Catalunya, 2020).

Population data

registered as resident in January of each year between 2000 and 2020, as well as the seasonal population registered at quarterly intervals between 2002 and 2015, was available for both Alt Urgell and La Cerdanya. Both resident population and seasonal population data were obtained from Idescat (Idescat, 2020a, 2020b). For all three variables, totals for both counties were calculated.

Seasonal population numbers correspond to the result of subtracting the exits of the resident population leaving the municipality to the entries of non-resident population each trimester.

Second homes and tourism establishments data

The total annual number of second homes was available for 1991, 2001 and 2011 for Alt Urgell and La Cerdanya (Idescat, 2021a). For the tourism establishments, we gathered and added up the total annual number of hotels (Idescat, 2021b) and rural tourism establishments (Idescat, 2021c) between 2000 and 2020 for both Alt Urgell and La Cerdanya. For all three variables, totals for both counties were calculated.

Water consumption

Total declared water consumption for domestic uses, industry and services was available from 2005 to 2020 for both Alt Urgell and La Cerdanya counties (Idescat, 2021d). Totals for both counties were calculated. As the year 2020 showed a different trend than the rest due to the COVID-19 pandemic, this year was calculated by averaging the previous 5 years.

A3.1.7 Seasonal data calculations

For all variables available on an intra-annual scale for which we wanted a seasonal resolution, annual values for 6-months periods classified as “summer” or “winter” periods were computed as follows:

- The winter value for a given year was calculated over the months of October, November and December of the previous year and the months of January, February, and March of the current year. These annual winter values correspond to the temporal time scope of hydrological years as defined in the original hydrological data, and thus this seasonal separation enable us to match the semesters of all seasonal variables with each other (seasonal population and hydrological, climatic, and environmental variables)
- Summer values were calculated for the months of April to September of every given year.

When available data did not include all the months for a given season, these values were discarded, so that annual winter and summer values were always calculated with no missing months. The original data was taken from several different spatial data points (gauging stations for hydrological data, geographic points for climatic data, the two counties for data from NASA). The final mean winter and summer values thus correspond to the mean annual values for winter and summer across all spatial data points available. In the case of seasonal population data, the original data was on a trimester scale. As the total seasonal population seemed more relevant than the mean seasonal population, we summed up the trimester values corresponding to the temporal delimitations explained above, resulting on total winter and summer seasonal population values for Alt Urgell and Cerdanya as a whole.

As a result, we obtained:

- mean winter and summer values for the Segre River streamflow, the volume of water stored in the Oliana reservoir, snow cover and maximum temperature
- maximum summer values for NDVI and ET
- total accumulated precipitation and total seasonal population for winter and for summer, calculated by taking the sum of monthly or trimester values, respectively

Table A1. Final hydrological variables used in the models and original data used for their calculation, when needed. Data was extracted from the integrated network of gauging stations (Redes de Seguimiento Del Estado e Información Hidrológica, 2021).

Final variable	Original variable	UTM X H30 ETRS89	UTM Y H30 ETRS89	Location	Water body
Mean monthly streamflow (m^3/s)	Daily streamflow (m^3/s)	905.879	4.708.608	Puigcerdà	Segre River
		867.336	4.698.549	La Seu d’Urgell	Segre River
		866.737	4.699.421	La Seu d’Urgell	Valira River
		896.406	4.702.383	Isòvol	Segre River
		858.440	4.684.390	Organyà	Segre River
		855.055	4.668.639	Oliana	Segre River
Volume of water stored in the Oliana Reservoir per month (hm^3)	/	855.140	4.668.946	Oliana	Oliana Reservoir

A3.2 Supplementary material B: Missing data imputation

In the case of variables for which winter and summer values were calculated (environmental, climatic and seasonal population variables), we arranged the data into chronological time series with two values per year (winter followed by summer) to impute missing values on a semester scale. Missing values at the end of this time series were imputed using Holt-Winters filtering with a seasonal component using the package *forescast* (Hyndman and Khandakar 2008). For missing values at the beginning of the time series, the same procedure was used on the reversed time series. Once the imputations were done, the final chronological time series was split again into two distinct winter and summer annual variables to obtain the desired seasonal scale.

For the hydrological variables (summer and winter flow, annual flow, and annual volume), the only missing value was the year 2020, which was imputed by taking the average value of the years 2015-2019 for each variable.

All climatic variables were available only from winter 2000 to summer 2018. Winter and summer values for 2019 and 2020 were forecasted as described above.

For the environmental variables, ET data was available between February 2000 and December 2019, and snow cover data between February 2000 and December 2016. The value of snow cover for winter 2000 was forecasted using the reversed time series, as explained above. ET values for winter and summer 2020 and snow cover values from winter 2017 to summer 2020 were also forecasted using the methodology explained above.

In the case of land use data, time resolution was every 5 years and from 1997 to 2017. As we assumed a gradual variation in all land use variables, linear interpolation was carried out to impute annual values of each land use type from 2000 to 2017 and forecasting by Holt-Winters Filtering with no seasonal component was carried out to impute the years 2018-2020.

For bird biodiversity data, the only missing years were 2000 and 2001. These years were imputed using non-seasonal forecast by reversing the dataset using the package *forecast* (Hyndman and Khandakar 2008). The value for all three bird biodiversity variables for 2020 was an outlier due to circumstances linked to the COVID-19 pandemic. Thus, the value from 2020 was replaced by the average value from the previous 5 years for each variable. For butterfly biodiversity data, data were missing for the years 2000-2005 and 2020. The imputation of these missing values was done by fitting a linear regression to the years 2006-2019 and using the linear models to impute the missing values.

For the socio-economic data, all GDP (total GDP, agriculture GDP and services GDP), occupation (occupation in agriculture and occupation in services), resident population, and tourism establishments data had no missing values. The salary on agriculture was missing the years 2018-2020, which was forecasted using Holt-Winters Filtering with no seasonal component.

Seasonal population data was available from the first trimester of 2002 (second half of winter 2002) to the 4th semester of 2015 (summer 2015). Seasonal population values from winter 2000 to winter 2002, and from winter 2016 to summer 2020 were imputed with the *forecast* package, as explained above.

For second home data, there was only data available for the years 1981, 1991, 2001, 2011. The imputation of the missing values was done by fitting a linear regression to the available years and using the linear model to impute the missing values. For the data on subsidies to agriculture, the missing values between 2007 and 2014 was imputed using a Gompertz function with 4 parameters, which had a better fit than a linear model (AIC Gompertz = 479.8; AIC lm = 485). Finally, for water consumption, missing data from 2000-2004 was imputed using a linear model fitted with the data from 2005-2020.

A3.3 Supplementary material C: Hypotheses

A3.3.1 Hypothesised relationships linking socio-economic variables between them and with land-use variables

In the last decades, tourism and activity in the services sector have developed in the Catalan Pyrenees, supporting the local economy and slowing down local depopulation (Guirado González, 2014). It is therefore expected that *winter* and *summer seasonal populations* influence both the number of *second homes* in the region, as well as the number of *tourism establishments* and the *services GDP*. *Tourism establishments* are expected to influence the *services GDP* both directly and indirectly, through their expected effect on *occupation in services*. Thus, the GDP of the services sector is expected to be affected by the occupation in the sector, the seasonal populations, and tourism establishments through multiple direct and indirect paths. *Tourism establishments* are also expected to have a positive effect on the *resident population*, as the development of tourism has contributed to the revitalization of the Pyrenean economy and societies, counteracting depopulation (Vaccaro and Beltran, 2009). Moreover, the social and demographic changes of the region in the last decades, have promoted a process of naturbanization of the Catalan Pyrenees (Guirado González, 2014). This implies that positive effects of *resident population*, *winter seasonal population* and *summer seasonal population* on *urban areas* are to be expected, as well as a negative effect of *second homes* on *resident population*. As a consequence of the expansion of *urban areas,* infrastructures such as roads are also expected to increase in the area. At the same time, low vegetation areas, such as meadows and fields, are tightly linked to agricultural practices in the Central Pyrenees, and the abandonment of these activities leads to forest expansion (Lasanta-Martínez *et al.*, 2005). We expect to find similar relationships in our Pyrenees region. Thus, we expect *meadows, bushes, and fields* to be affected by both *occupation agriculture* and *forests*.

On the other hand, the EU's common agricultural policy (CAP) has been established since the 1960s to promote the agricultural sector. Under this and other policies, the Spanish Ministry of Agriculture, Fisheries and Food subsidises the agricultural sector (Ministerio de Agricultura, Pesca y Alimentación, 2016). We expect to see that reflected as a positive effect of *subsidies* on *occupation agriculture* and on agriculture GDP. Moreover, we expect the salary in agriculture to positively influence the occupation in the sector. Although there has been depopulation and a shift from an agriculture-based to a tourism-based economy in the Catalan Pyrenees, we still expect to find a positive effect of *resident population* and both *services GDP* and *agriculture GDP* on *total GDP*.

A3.3.2 Hypothesised relationships linking hydrological variables between them and with other types of variables

By definition, *water consumption* depends on *resident population* and on both *summer seasonal population* and *winter seasonal population*. Water from the Segre River in the study area is known to be extracted both from the Oliana reservoir and from the river for multiple uses (Confederación Hidrográfica del Ebro, 2015), so *water consumption* is expected to have a negative effect on *annual* *volume*, *summer flow* and *winter flow*. A potential relationship between *water consumption* and *annual flow* was not considered, as *annual flow* here is only used to connect hydrological, remote-sensing and climatic variables on the seasonal (winter/summer) scale with *annual volume* (as the Oliana reservoir is located downstream in the study area). *Annual flow* thus only depends on *winter flow* and *summer flow*.

In winter, snow accumulates in snowpacks, which act as water reservoirs until spring snowmelt (Sanmiguel-Vallelado *et al.*, 2017). We therefore expect to find a positive effect of *winter snow* and *summer snow* on *summer flow*, as well as a negative effect of *winter snow* on *winter flow*. In addition, *max winter temperature* and *max summer temperature* should respectively reduce *winter snow* and *summer snow*.

Precipitation runoff also represents an input of water to a river watershed, and most rainfall occurs in autumn in Mediterranean areas (Beguería *et al.*, 2003), so *winter flow* should increase with *winter precipitation*. In addition to human *water consumption* and climate-related factors, *forests* have also been shown to influence catchment water balance, reducing annual streamflow due to evapotranspiration (Wei and Zhang, 2010; Zhang *et al.*, 2001). It is reasonable to think that forests should have a negative effect on *winter flow* and *summer flow*, and *max summer ET* a negative effect on *summer flow*.

Evapotranspiration in mountain areas located in the North-Eastern Iberian Peninsula is influenced by water availability, and thus by precipitation and temperature, particularly in summer (Llorens *et al.*, 2010). *Max summer ET* is therefore expected to increase with *max summer temperature* and *summer precipitation*. Additionally, land evapotranspiration has been shown to increase with NDVI (Zhang *et al.*, 2015), so *max summer ET* may be positively related to *max summer NDVI* in the model. Similarly to ET, *max summer NDVI* values are expected to respond positively to *summer precipitation* and *max summer temperature*, as NDVI phenological patterns in the Mediterranean usually show a greenness intra-annual peak in early summer (Durante *et al.*, 2009; Sun *et al.*, 2013). As a vegetation productivity indicator, *max summer NDVI* should also show a positive response to *forests*.

A3.3.3 Hypothesised relationships linked to biodiversity variables

Urbanisation has been shown to cause extinction of bird species due to habitat loss (Dri *et al.*, 2021). Thus, we expect those variables linked to human expansion (*urban areas* and *roads*) to negatively impact all bird variables. While the same has been reported for butterflies (Stefanescu *et al.*, 2011), we do not expect to find a direct influence of urbanisation on butterflies, as urban areas in the study region are located far away from favourable habitats for butterflies. Instead, we hypothesise a direct influence of these favourable habitats, *meadows, bushes, and fields*, on all butterfly biodiversity variables (Bubová *et al.*, 2015). As these favourable habitats are crossed by road infrastructure, we hypothesise an indirect influence on butterfly biodiversity variables mediated through *roads*. Moreover, agricultural and livestock abandonment in European mountains have induced afforestation processes with multiple environmental consequences on landscape and biodiversity (MacDonald *et al.* 2000; Mantero *et al.* 2020). Some studies have found an overall positive effect of afforestation on restoring and maintaining bird communities (Graham *et al.* 2013; Regos *et al.*, 2016). Others have found the opposite trend (Zakkak *et al.* 2014). Thus, albeit we are unsure of the sign of the relationship, we expect an influence of *forests* on all bird variables.

Studies have reported an influence of increasing temperature linked to climate change on mountain bird populations (Freeman *et al.*, 2018; Lehikoinen *et al.*, 2019). A study on Spanish mountains of Sierra de Guadarrama also reported a negative effect of increasing temperatures on butterfly richness and composition (Wilson *et al.*, 2007). Thus, we expect an influence of temperature on all our biodiversity variables. As our data for both butterflies and birds are based on summer and spring censuses, we hypothesised *max summer temperature* to influence our biodiversity elements.

A3.4 Supplementary material D: Model evaluation

At the time when we conducted the analyses, GLS models were not implemented in the most updated version of the piecewiseSEM package. Therefore, version 1.2.1 was used.

Table D1. Stats for all hypothesized relationships. Significant (p-value<0.05) and marginally significant (p-value<0.1) relationships are shown in the last column. Relationships with the same response variable belong to the same model. Model details can be found in Table D2 of Appendix D.

Response	Predictor	Estimate	Std. error	Std. estimate	p-value	Sign.
total GDP	services GDP	0.9850	0.1406	0.8519	<0.001	***
total GDP	agriculture GDP	2.0698	0.7079	0.1037	0.0095	**
total GDP	resident population	206.6181	81.1512	0.0001	0.0209	*
agriculture GDP	occupation agriculture	30.2400	5.7761	0.8150	<0.001	***
agriculture GDP	subsidies	0.4050	0.3649	0.1728	0.2816	/
services GDP	tourism establishments	30488.4677	2630.6108	0.0211	<0.001	***
services GDP	occupation services	42.1225	17.7610	0.1479	0.0306	*
services GDP	winter seasonal population	-14.6888	39.1868	-0.0415	0.7127	/
services GDP	summer seasonal population	0.6890	20.3761	0.0154	0.9734	/
resident population	tourism establishments	0.0038	0.0002	0.1606	<0.001	***
resident population	second homes	-0.0001	5.84*1e-6	-0.1094	<0.001	***
occupation agriculture	salary agriculture	-1.5328	0.4327	-0.8453	0.0023	**
occupation agriculture	subsidies	0.0190	0.0107	0.3013	0.0931	.
occupation services	tourism establishments	126.0020	24.9174	0.0227	<0.001	***
second homes	summer seasonal population	0.2269	0.0382	0.7473	<0.001	***
second homes	1 year lagged residuals	0.6875	0.1935	0.1363	0.0024	**
second homes	winter seasonal population	0.1516	0.0763	0.2524	0.0633	.
tourism establishments	1 year lagged residuals	0.0052	0.0011	0.0787	<0.001	***
tourism establishments	winter seasonal population	0.0001	2.04*1e-5	0.1854	0.0017	**
tourism establishments	summer seasonal population	1.03*1e-5	9.99*1e-6	0.0591	0.303	/
water consumption	summer seasonal population	0.0306	0.0139	0.5896	0.0427	*
water consumption	winter seasonal population	0.0475	0.0299	0.4632	0.1302	/
water consumption	resident population	-0.0186	0.0152	-0.0001	0.2375	/
roads	1 year lagged residuals	1.1216	0.0685	0.8589	<0.001	***
roads	urban areas	0.0164	0.0014	0.6126	<0.001	***
urban areas	resident population	0.0008	0.0001	0.0002	<0.001	***
urban areas	summer seasonal population	0.0003	0.0001	0.3899	0.0015	**
urban areas	1 year lagged residuals	0.5172	0.1980	0.0807	0.0189	*
urban areas	winter seasonal population	0.0003	0.0002	0.2222	0.0599	.

meadows bushes fields	forests	-0.7568	0.0525	-0.8168	<0.001	***
meadows bushes fields	roads	-59.3897	21.3135	-0.1113	0.0127	*
meadows bushes fields	occupation agriculture	0.0012	0.0006	0.0456	0.0517	.
annual volume	annual flow	1.6146	0.4990	0.5672	0.0046	**
annual volume	water consumption	-0.0120	0.0050	-0.4213	0.0272	*
annual flow	summer flow	0.4057	0.0388	0.6971	<0.001	***
annual flow	winter flow	0.6061	0.0661	0.6122	<0.001	***
summer flow	max summer ET	1.8185	0.5336	0.7288	0.0039	**
summer flow	summer snow	0.0485	0.0145	0.5803	0.0045	**
summer flow	water consumption	-0.0249	0.0083	-1.4477	0.0091	**
summer flow	forests	0.1174	0.0407	1.4113	0.0113	*
summer flow	winter snow	0.0039	0.0021	0.3039	0.0868	.
winter flow	water consumption	0.0098	0.0070	0.9710	0.1785	/
winter flow	forests	-0.0436	0.0344	-0.8908	0.2236	/
winter flow	winter precipitation	-0.0060	0.0063	-0.2216	0.3555	/
winter flow	winter snow	0.0012	0.0019	0.1558	0.5372	/
max summer ET	max summer NDVI	75.2150	19.1277	0.5608	0.0011	**
max summer ET	max summer temperature	0.9818	0.3966	0.3603	0.0241	*
max summer ET	summer precipitation	-0.0046	0.0027	-0.2407	0.1022	/
max summer NDVI	forests	0.0002	0.0001	0.6386	0.0264	*
max summer NDVI	summer precipitation	1.43*1e-5	3.01*1e-5	0.1000	0.6404	/
max summer NDVI	max summer temperature	-0.0015	0.0052	-0.0750	0.7721	/
summer snow	max summer temperature	-46.7076	15.2864	-0.5740	0.0065	**
winter snow	max winter temperature	-186.2590	78.2518	-0.4793	0.0279	*
butterfly abundance	meadows bushes fields	0.0050	0.0012	0.2953	<0.001	***
butterfly abundance	max summer temperature	-0.1131	0.0934	-0.0888	0.2414	/
butterfly richness	meadows bushes fields	0.0037	0.0004	0.2157	<0.001	***
butterfly richness	max summer temperature	-0.0286	0.0342	-0.0222	0.4141	/
butterfly diversity	meadows bushes fields	0.0036	0.0007	0.9410	<0.001	***
butterfly diversity	max summer temperature	0.0183	0.0276	0.0638	0.5166	/
bird abundance	urban areas	-13.5069	3.7877	-2.6205	0.0026	**
bird abundance	roads	-181.6261	67.2455	-0.9425	0.0157	*
bird abundance	forests	0.7852	0.3008	2.3473	0.0189	*
bird abundance	max summer temperature	4.0190	5.3434	0.1470	0.4629	/
bird richness	forests	0.0018	0.0017	0.1705	0.3188	/
bird richness	urban areas	-0.0205	0.0215	-0.1277	0.3555	/
bird richness	roads	-0.2045	0.3621	-0.0341	0.58	/
bird richness	max summer temperature	0.0015	0.0214	0.0018	0.9441	/
bird diversity	1 year lagged residuals	0.1369	0.0828	0.0071	0.119	/
bird diversity	roads	0.1860	0.1139	0.0241	0.1232	/
bird diversity	max summer temperature	-0.0050	0.0066	-0.0046	0.4559	/
bird diversity	forests	-0.0002	0.0005	-0.0169	0.6805	/
bird diversity	urban areas	0.0006	0.0067	0.0028	0.9325	/

Table D2. Details of each linear, generalized linear (GLM), and generalised least squares (GLS) model used to build the network of interactions in piecewiseSEM. Significance of each pair relationships from the models can be found in Table D1 of Appendix D.

Number	Model formula	Model type	DF
1	*total_GDP ~ resident_population + agriculture_GDP + services_GDP*	GLS with AR1 correlation structure	17
2	*agriculture_GDP ~ subsidies + occupation_agriculture*	Linear model	18
3	*services_GDP ~ occupation_services + tourism_establishments + summer_seasonal_population + winter_seasonal_population*	GLS accounting for heteroskedasticity	16
4	*resident_population ~ tourism_establishments + second_homes*	GLM with Quasipoisson family	18
5	*occupation_agriculture ~ subsidies + salary_agriculture*	GLS with AR1 correlation structure	18
6	*occupation_services ~ tourism_establishments*	GLS with AR1 correlation structure	19
7	*second_homes ~ summer_seasonal_population + winter_seasonal_population + lagged_residuals*	Linear model	17
8	*tourism_establishments ~ summer_seasonal_population + winter_seasonal_population + lagged_residuals*	GLM with Poisson family	17
9	*water_consumption ~ summer_seasonal_population + resident_population + winter_seasonal_population*	Linear model	17
10	*roads ~ urban_areas + lagged_residuals*	Linear model	18
11	*urban_areas ~ resident_population + summer_seasonal_population + winter_seasonal_population + lagged_residuals*	Linear model	16
12	*meadows_bushes_fields ~ forests + roads + occupation_agriculture*	GLS with AR1 correlation structure	17
13	*annual_volume ~ water_consumption + annual_flow*	Linear model	18
14	*annual_flow ~ winter_flow + summer_flow*	Linear model	18
15	*summer_flow ~ summer_snow + winter_snow + max_summer_ET + forests + water_consumption*	Linear model	15
16	*winter_flow ~ winter_snow + winter_precipitation + forests + water_consumption*	Linear model	16
17	*max_summer_ET ~ max_summer_temperature + summer_precipitation + max_summer_NDVI*	Linear model	17
18	*max_summer_NDVI ~ max_summer_temperature + summer_precipitation + forests*	Linear model	17
19	*summer_snow ~ max_summer_temperature*	Linear model	19
20	*winter_snow ~ max_winter_temperature*	Linear model	19
21	*butterfly_abundance ~ meadows_bushes_fields + max_summer_temperature*	GLM with Quasipoisson family	18
22	*butterfly_richness ~ meadows_bushes_fields + max_summer_temperature*	GLM with Quasipoisson family	18
23	*butterfly_diversity ~ meadows_bushes_fields + max_summer_temperature*	GLS with AR1 correlation structure	18
24	*bird_abundance ~ roads + urban_areas + max_summer_temperature + forests*	GLS with AR1 correlation structure	16
25	*bird_richness ~ roads + urban_areas + max_summer_temperature + forests*	GLM with Quasipoisson family	16
26	*bird_diversity ~ roads + urban_areas + max_summer_temperature + forests + lagged_residuals*	GLM with Gamma family (link = log)	15