Applying geographical information technologies and multi criteria spatial planning in the sustainable management of forest ecosystem services

Goran Krsnik

http://hdl.handle.net/10803/689327

Universitat de Lleida

CTFC

PhD THESIS

Applying geographical information technologies and multi-criteria spatial planning in the sustainable management of forest ecosystem services

Goran Krsnik

To obtain the degree of Doctor at the University of Lleida

Doctorate Program in Forest and Environmental Management

Supervised by:

José Ramón González Olabarria

Jordi Garcia-Gonzalo

Tutored by:

Cristina Vega-Garcia

Solsona, 2023

Universitat de Lleida

TESI DOCTORAL

Applying geographical information technologies and multi-criteria spatial planning in the sustainable management of forest ecosystem services

Goran Krsnik

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida

Programa de Doctorat en Gestió Forestal i del Medi Natural

Directors:

José Ramón González Olabarria

Jordi Garcia-Gonzalo

Tutora:

Cristina Vega-Garcia

Solsona, 2023

Posvećeno baki Ljubici i didi Franji

Acknowledgments

Las primeras personas a las que quiero dar las gracias son mis directores. Gracias por haberme dado la oportunidad de formar parte del CTFC, compartir vuestras ideas, contar conmigo y por todo lo enseñado. Gracias por abrirme la puerta del mundo forestal y abrir nuevos horizontes en cuanto a la aplicabilidad de mis conocimientos en algo completamente nuevo para mí. También, gracias por la confianza, reflejada en la flexibilidad y la independencia que me habéis dado durante todo el proceso de mi desarrollo científico. Igualmente, os quiero dar muchos agradecimientos por haberme posibilitado colaborar con muchos científicos internacionales, por las estancias realizadas y por las incontables experiencias derivadas de ellas. Big thanks to all the collaborators and secondments hosts that directly or indirectly participated in this thesis, principally from Finland, USA and Chile.

Gracias a todos los compañeros y amigos que he conocido durante este proceso, dentro y fuera del CTFC, por escucharme, acompañarme, regalarme vuestro tiempo y formar parte de esta experiencia única. Pero, sobre todo gracias a los que sé que seguirán estando aquí para mucho más tiempo, and the ones that have been here sharing the moments from the very beginning. Moltes gràcies a tots els amics solsonins (i els de fora que s’han fet solsonins), per les incomptables experiències viscudes, els riures, el suport i la companyia.

Velika hvala obitelji, bližnjima i prijateljima na konstantnoj podršci, usprkos stotinama kilometara između nas. Hvala što ste od prvog trenutka vjerovali u mene, pratili me na ovom putovanju, ali i svim ostalim putovanjima koja su postala dio mene tokom ovog iskustva. Hvala na povjerenju, optimizmu, prihvaćanju i sudjelovanju u cijeloj pustolovini.

Solsona, gràcies per fer-te casa meva, per abraçar-me, acollir-me, obrir-me els nous horitzons, definir-me i fer-me créixer.

Institutional acknowledgments

The Agency for Management of University and Research Grants (AGAUR) of Government of Catalonia is thanked for the predoctoral scholarship (AGAUR-FSE 2020 FI_B2 00147).

The research work was partly founded by the Spanish Ministry of Science and Innovation (grant PID2020-120355RB-I00).

The research secondments were founded by the SuFoRun, Marie Sklodowska-Curie Research and Innovation Staff Exchange (RISE) Program (grant agreement No: 691149).

Table of contents

Abstract

The growing complexity of geospatial reality and rapid spatial changes, caused by the uncertainty of natural processes and rapid social development, have increased the need for strategic spatial planning, requiring more specific objectives each time. However, in such a scenario where heterogeneous factors influence decision-making, there is no single best solution, but rather several applicable alternatives based on trade-offs. Forest ecosystems, with their multifunctional nature, provide numerous services and benefits to human well-being. Ensuring their sustainability requires the application of an appropriate management strategy that maximizes the supply of ecosystem services while minimizing environmental risks and avoiding decision-making driven by narrow interests. In this situation, the application of a multi-criteria decision support framework, combined with geographical information technologies, significantly improves spatial planning actions by facilitating the identification of suitable management options. This thesis is structured around four studies that address these challenges. The first and second studies focus on identifying forest use suitability based on ecosystem services provision and forest biogeophysical characteristics, aiming to facilitate the selection of appropriate management options. The first study considers current forest features, while the second study simulates forest dynamics and enables the definition of long-term management strategies. The third study assesses urban green areas and utilizes comparison methods between two cities to address the relativity of urban ecosystem service provision and improve urban planning. The fourth study aims to enhance the framework for predicting fire behaviour to ensure the uninterrupted provision of ecosystem services. The results highlight the importance of multi-criteria spatial planning in forest management and demonstrate the excellent applicability of geographical information technologies and decision support tools in assessing complex spatial environmental issues. These tools

have the capacity to handle multi-objective analyses, enabling the evaluation of multiple choices for appropriate solutions and emphasizing the multifunctionality of forests. Our assessments also reveal several methodological and terminological constraints associated with ecosystem services-based environmental management. This thesis employs innovative spatial assessment tools and novel approaches to address these limitations, providing solutions and striving to achieve a more sustainable environment.

Resum

La creixent complexitat de la realitat geoespacial i els ràpids canvis espacials, causats per la incertesa dels processos naturals i el ràpid desenvolupament social, han augmentat la necessitat d'una planificació espacial estratègica, que requereix objectius cada vegada més específics. No obstant això, en un escenari on diversos factors heterogenis influeixen en la presa de decisions, no hi ha una única solució òptima, sinó diverses alternatives aplicables basades en compensacions. Els ecosistemes forestals, amb la seva naturalesa multifuncional, proporcionen nombrosos serveis i beneficis pel benestar humà. Garantir la seva sostenibilitat requereix l'aplicació d'una estratègia de gestió adequada que maximitzi el subministrament de serveis ecosistèmics, minimitzi els riscos ambientals i eviti la presa de decisions impulsada per interessos concrets. En aquesta situació, l'aplicació d'eines de suport a la presa de decisions multi criteri, combinada amb tecnologies de la informació geogràfica, millora significativament les accions de planificació espacial facilitant la identificació d'opcions de gestió adequades. Aquesta tesi s'estructura al voltant de quatre estudis que aborden aquests desafiaments. El primer i segon estudi se centren en identificar la idoneïtat de l'ús forestal en funció del subministrament de serveis ecosistèmics i les característiques biogeofísiques del bosc, amb l'objectiu de facilitar la selecció d'opcions de gestió adequades. El primer estudi considera les característiques forestals actuals, mentre que el segon estudi simula la dinàmica forestal i permet definir estratègies de gestió a llarg termini. El tercer estudi avalua les àrees verdes urbanes i utilitza mètodes de comparació entre dues ciutats per abordar la relativitat del subministrament de serveis ecosistèmics urbans i millorar la planificació urbana. El quart estudi té com a objectiu millorar el marc per predir el comportament del foc per garantir la provisió ininterrompuda de serveis ecosistèmics. Els resultats posen de manifest la importància de la planificació espacial multi criteri en la

gestió forestal i demostren l'excel·lent aplicabilitat de les tecnologies de la informació geogràfica i les eines de suport a la presa de decisions en l'avaluació de problemes ambientals espacials complexos. Aquestes eines tenen la capacitat de gestionar anàlisis multi objectiu, permetent l'avaluació de múltiples opcions per a solucions adequades i posant èmfasi en la multi funcionalitat dels boscos. Les nostres avaluacions també revelen diverses limitacions metodològiques i terminològiques associades a la gestió ambiental basada en serveis ecosistèmics. Aquesta tesi fa servir eines innovadores d'avaluació espacial i enfocaments nous per abordar aquestes limitacions, proporcionant solucions i intentant aconseguir un entorn més sostenible.

Resumen

La creciente complejidad de la realidad geoespacial y los rápidos cambios espaciales, causados por la incertidumbre de los procesos naturales y el rápido desarrollo social, han aumentado la necesidad de una planificación espacial estratégica, que requiere objetivos cada vez más específicos. Sin embargo, en un escenario donde varios factores heterogéneos influyen en la toma de decisiones, no existe una única solución óptima, sino varias alternativas aplicables basadas en compensaciones. Los ecosistemas forestales, con su naturaleza multifuncional, proveen numerosos servicios y beneficios para el bienestar humano. Garantizar su sostenibilidad requiere la aplicación de una estrategia de gestión adecuada que maximice la provisión de servicios ecosistémicos, minimice los riesgos ambientales y evite la toma de decisiones impulsada por determinados intereses. En esta situación, la aplicación de herramientas de apoyo a la toma de decisiones multicriterio, combinada con tecnologías de la información geográfica, mejora significativamente las acciones de planificación espacial facilitando la identificación de opciones de gestión adecuadas. Esta tesis se estructura en torno a cuatro estudios que abordan estos desafíos. El primer y segundo estudio se centran en identificar la idoneidad del uso forestal en función de la provisión de servicios ecosistémicos y las características biogeofísicas del bosque, con el objetivo de facilitar la selección de opciones de gestión adecuadas. El primer estudio considera las características forestales actuales, mientras que el segundo estudio simula la dinámica forestal y permite definir estrategias de gestión a largo plazo. El tercer estudio evalúa las áreas verdes urbanas y utiliza métodos de comparación entre dos ciudades para abordar la relatividad de la provisión de servicios ecosistémicos urbanos y mejorar la planificación urbana. El cuarto estudio tiene como objetivo mejorar el marco para predecir el comportamiento del fuego para garantizar la provisión ininterrumpida de servicios ecosistémicos. Los resultados destacan la importancia de la

planificación espacial multicriterio en la gestión forestal y demuestran la excelente aplicabilidad de las tecnologías de la información geográfica y las herramientas de apoyo a la toma de decisiones en la evaluación de problemas ambientales espaciales complejos. Estas herramientas tienen la capacidad de manejar análisis multiobjetivo, permitiendo la evaluación de múltiples opciones para soluciones adecuadas y haciendo hincapié en la multifuncionalidad de los bosques. Nuestras evaluaciones también revelan varias limitaciones metodológicas y terminológicas asociadas a la gestión ambiental basada en servicios ecosistémicos. Esta tesis emplea herramientas innovadoras de evaluación espacial y enfoques novedosos para abordar estas limitaciones, proporcionando soluciones e intentando conseguir un entorno más sostenible.

Sažetak

Brzorastuća složenost geoprostorne stvarnosti i neprekidne promjene u prostoru, uzrokovani neizvjesnošću prirodnih procesa i brzim društvenim razvitkom, povećali su potrebu za strateškim prostornim planiranjem, zahtjevajući svaki puta sve konkretnije ciljeve. Međutim, u situaciji gdje brojni i različiti čimbenici utječu na donošenje odluka, ne postoji jedinstveno i savršeno rješenje, već nekoliko primjenjivih mogućnosti temeljenih na kompromisima. Šumski ekosustavi, zahvaljujući svojoj višenamjenskoj prirodi, pružaju brojne usluge i dobiti te unaprjeđuju ljudsko blagostanje. Osiguranje njihove održivosti zahtjeva primjenu prikladnih strategija upravljanja koje maksimiziraju pružanje usluga šumskih ekosustava minimizirajući štetu na okoliš i izbjegavajući donošenje odluka vođenih interesima pojedinaca. Stoga, primjena okvira temeljenog na višekriterijskom donošenju odluka, u kombinaciji s geografskim informacijskim tehnologijama, značajno unaprjeđuje prostorno planiranje omogućujući određivanje prikladnog načina upravljanja. Ovaj doktorski rad sastoji se od četiri istraživanja koja pokušavaju odgovoriti na te izazove. Prva i druga studija usredotočeni su na određivanje prikladnosti korištenja šuma temeljenog na pružanju usluga ekosustava i šumskim biogeofizičkim značajkama, s ciljem da se olakša oređivanje podobnog izbora za upravljanje. Prva studija uzima u obzir trenutne značajke šuma, dok druga simulacijama predviđa promjene u šumama i omogućuje određivanje dugoročnih strategija za upravljanje. Treća studija analizira gradske zelene površine i primjenjuje metode usporedbe između gradova kako bi ispitala relativnost u pružanju usluga ekosustava u gradskom okolišu i unaprijedila planiranje gradova. Četvrta studija cilja na jačanje okvira za predviđanje ponašanja šumskih požara kako bi se osiguralo neprekidno pružanje usluga šumksih ekosustava. Ukupni rezultati naglašavaju važnost višekriterijskog prostornog planiranja u upravljanju šumama te dokazuju izvrsnu primjenu geografskih

informacijskih tehnologija i alata za donošenje odluka u složenim prostornim analizama. Takvi su alati sposobni podržati višeciljne analize, omogućujući vrjedovanje različitih izbora za pronalazak prikladnog rješenja te naglašavajući višenamjenska objilježja šuma. Naše analize također otkrivaju nekoliko nedostataka u metodologiji i nazivlju vezanih za upravljanje uslugama šumskih ekostustava. Stoga, s ciljem nadilaženja spomenutih nedostataka, ovaj doktorski rad primjenjuje inovativne alate za prostorne analize i nove pristupe u istraživanju te nudi rješenja u skladu s postizanjem održivog okoliša.

Chapter 1

INTRODUCTION

Spatial planning is an interdisciplinary activity that focuses on identifying long- or medium-term territorial objectives and strategies to address the coordination challenges among conflicting policies [1]. Its ultimate goal is to achieve sustainable development of the geographical space by considering all relevant variables and their behavioural characteristics in order to maximize benefits. Through the coordination of interests across sectors, spatial planning greatly facilitates the identification of priorities and simplifies decision-making processes [2]. The increasing complexity of geospatial processes and rapid spatial changes, at local, regional, national, and global levels, driven by rapid social development, have intensified the need for strategic spatial planning, which requires more specific objectives each time [3]. However, in such complex geospatial realities where multiple heterogeneous factors influence decision-making, there is typically no single best or straightforward solution, but rather several applicable alternatives based on trade-offs [4]. Furthermore, numerous authors emphasize the importance of gaining a better understanding of current and future challenges in order to make informed decisions and find the most suitable strategies [5]. Therefore, recognizing and considering all the factors that influence strategic planning are fundamental for comprehensive long-term spatial decision-making [6].

Spatial planning of the natural environment plays a crucial role in promoting sustainable development by assessing the strengths, weaknesses, and potentials of environmental resources to support spatial development [7]. This approach involves balancing human needs and economic growth with the preservation of natural ecosystems, considering ecosystem suitability and capacity. It ensures that environmental considerations are given equal importance to economic and social issues, leading to a balanced assessment of all relevant variables [8]. The significance and complexity of spatial planning for the natural environment are further amplified under current climate change conditions, characterized by unpredictable responses and altered environmental circumstances [9]. In such conditions, strategies must be adapted to effectively address and comprehend the spatial distribution of environmental and socio-economic values, including their potential changes [10]. Having information about the spatial component of the variables involved, facilitates the allocation of specific management actions, enabling the achievement of precise environmental and socio-economic objectives and the evaluation of trade-offs among competing management alternatives [11], [12]. As a result, more efficient spatial zoning of relevant variables can be achieved, leading to effective spatial restrictions on management or planning actions.

Forests are a vital component of the natural environment, covering approximately 30% of the world's land area. They have a significant connection to human populations, as three ecological zones classified as aggregated forest ecoregions are home to about three-quarters of humanity. This connection has developed through a long historical process of social and economic development [13]. Forest ecosystems provide a wide range of services to society, making them multifunctional and multiservice natural spaces. The management and sustainable use of their resources and lands are crucial to fulfil the social, economic, ecological, cultural, and spiritual needs of present and future generations [14]. Forest ecosystem services encompass the benefits provided by forests to society. They are commonly categorized into three groups: provisioning, regulating, and cultural services [15]. Effective spatial planning of forests is an essential step in comprehensive sustainable forest management. The goal is to sustain or improve the provision of specific benefits while minimizing adverse environmental effects. Achieving this requires adopting multifunctional approaches to managing forest lands [16]. Sustainable forest management aims to maintain or enhance the contribution of forests to human well-being, both in the present and for future generations, without compromising ecosystem integrity. It is widely accepted as the overarching objective for forest policy and practice [16]. However, the complexity of the problem and the diverse interests of stakeholders pose significant challenges to the application of sustainable forest management. Forests are recognized for their multifunctionality, but trade-offs among different services often hinder their simultaneous delivery at sustainable levels [17]. Therefore, effective forest management strategies must incorporate actions that maximize the provision of specific ecosystem services while minimizing adverse impacts on other services [18]. Decision-making processes in forest management are influenced by the perception of relevant criteria and the varying importance assigned to them by different social groups or stakeholders. The interests of these groups in utilizing forests play a crucial role in shaping their perspectives and priorities [19]. Developing objective and comprehensive management actions that consider the full range of issues and incorporate long-term strategic planning is a challenging process due to methodological and terminological constraints [20].

Ecosystem services and natural capital are inherently spatial by nature [21]. Therefore, spatial planning of forest ecosystem services is a valuable and necessary tool for achieving comprehensive and sustainable management of forest ecosystems. It helps overcome multiple constraints by embracing a broad and inclusive concept that encourages the consideration of landscape multifunctionality [22], [23]. Integrating the concept of ecosystem services into spatial planning reveals the spatial and temporal co-occurrences within a territory, providing a more complete understanding of the spatial reality. This enables the detection and resolution of spatial problems and facilitates the development of appropriate management strategies for the natural environment [24]. In this context, trade-offs between ecosystem services can be seen as "land-use or management choices that prioritize the delivery of one or more ecosystem services at the expense of others" [25]. Identifying and understanding these trade-offs can help determine the most suitable land use and corresponding management options to achieve forest sustainability.

Apart from natural environment, forests are present in urban, predominantly artificial, spaces. Despite having somewhat different characteristics, urban forests play a crucial role in providing multiple ecosystem services [26]. Urban green spaces are widely recognized as nature-based solutions that help address various challenges such as climate change mitigation, air purification, noise reduction, recreation, and scenic beauty [27]. With the continuous growth of urbanization and urban populations, the demand for urban ecosystem services is increasing, placing high pressures on urban green infrastructure [28]. Therefore, strategic management of urban green areas plays a significant role in long-term urban planning [29]. The urban environment can be modified relatively quickly, allowing for adaptation of urban ecosystem services provision to meet the needs of the population and align with urbanization trends [30]. However, to develop an appropriate plan, it is necessary to identify the current characteristics of urban ecosystems and determine the requirements for improving their performance. The lack of standardization, both in terminology and methodology, poses significant constraints in the assessment of urban ecosystem services [31]. In such a scenario, the development of comparison methods, either between cities or within a city, can be a valuable tool for addressing the necessary management actions related to urban green areas [32].

Fire is a principal disturbance factor that affects forests and forest ecosystem services in both rural and peri-urban areas [13]. While some authors emphasize the naturalness of fire processes and their potential benefits to humanity [33], the current climate change scenario and the increasing occurrence of large wildfires predominantly have a destructive impact on the provision of forest ecosystem services [34]. In such a scenario, defining fire management priorities and implementing fire prevention planning can significantly reduce the risk of fire occurrence and mitigate its negative influence on the supply of ecosystem services [35]. In addition to assessing fire risk and considering potential forest management options, having information on potential fire behaviour is crucial for planning effective mitigation actions and anticipating the impact of fires on natural resources [36]. Therefore, up-to-date and organized data on forest fuel characteristics, along with the evaluation of potential fire risk that can be easily utilized in fire behaviour simulators, are necessary requirements for implementing effective fire suppression management strategies that enable the multifunctional use of forest ecosystems.

Geospatial assessment of environmental processes is a challenging yet highly effective method for addressing spatial multifunctionality and identifying appropriate management strategies for specific territories to achieve long-term sustainability. The complexity of the environment and the need to consider numerous variables make this approach challenging, but it enables a comprehensive analysis and facilitates decision-making processes. In such scenarios, the application of multi-criteria decision-making methods significantly assists in evaluating prioritization and providing solutions. These methods are mathematical models that aid in decision-making when evaluating multiple conflicting criteria for various alternatives [37]. The use of such methods in environmental applications has substantially increased in recent decades [38]. Their strengths lie in the ability to combine economic, ecological, and social criteria and address interdisciplinary and complex environmental issues [39]. By incorporating the geospatial component into multi-objective decision-making, it becomes possible to determine spatial environmental processes, visualize and map them, and implement specific actions with spatial restrictions. Spatial multi-criteria evaluation combines spatial analysis, multi-criteria assessment, and decision-making, making it a powerful tool for environmentally applied analyses [40]. It integrates decision support tools with geographical information technologies, allowing for the consideration of both subjective and objective factors in decision-making. This enables participatory planning and the integration of scientific or technical knowledge with user preferences [41].

Geographical information technology uses computer-based tools to analyse spatial information into geographical information system (GIS). In GIS, real-world data is stored in a georeferenced database and can be displayed through digital cartography [42]. On the other hand, remote sensing techniques enable the gathering of geoinformation on the physical characteristics of the environment to be incorporated and analysed in GIS. The objective of geographical information technologies is to approximate geospatial reality by utilizing heterogeneous geodatabases that contain variables describing environmental processes. Spatial modelling establishes relationships between environmental components, analyses their occurrences, and provides spatially conditioned solutions. The strength of these models lies in their ability to use and process multiple data layers with different structures, spatial consistencies, and measurement scales. They establish diverse spatial dependencies and visually represent occurrences on a map [43]. Therefore, by implementing external mathematical or logical tools related to decision-making or multi-criteria analysis, geographical information technologies offer a comprehensive and powerful framework for addressing spatial complexity and providing solutions for strategic environmental evaluations. The broad application of geographical information technologies in environment-related issues is evident, including forest ecosystem services assessments [44]–[47], forest management [48]–[51], land use planning [52]–[54], forest fire evaluations [55]–[57], urban planning, and urban green area assessments [58]–[61], among others. The flexibility in geographical scale allows for the use of geographical information technologies in addressing environmental issues from local to global levels, adjusting their applicability based on solution-oriented spatial planning needs and possibilities. To facilitate the applicability of the results, particularly at the policy level, it is necessary to adapt decision-making processes to meet the needs of policymaking [62]. In terms of spatial planning for the natural environment, this implies the use of end-user-friendly methodologies that simplify spatial complexity without excluding any important components that need to be considered. In such scenarios, the application of multi-criteria spatial planning, combined with decision-making-oriented evaluation and assessed using geographical information technologies, emerges as the most suitable solution for strategic environmental management planning.

Following the hypothesis that the application of multi criteria spatial planning using geographical information technologies significantly improves the decision-making processes regarding the selection of appropriate management actions to achieve sustainable provision of forest ecosystem services, this thesis is attempting to address the following research questions:

1. How does the availability of spatial data influence and constrain decision-making processes concerning the management of forest ecosystem services?
2. What limitations do current research achievements face in terms of spatial planning for forest ecosystem services and fire risk management, and how can these limitations be addressed and improved?
3. Is the existing terminological and methodological framework sufficient to meet all the requirements for sustainable and strategic forest ecosystem services management?
4. To what extent can innovative spatial-based multi-criteria digital tools enhance the assessment of spatial issues related to forests, and how can these tools be effectively implemented?
5. How does the spatial scale impact the perception of forest ecosystem services provision and decision-making processes?
6. Can the analysis of forest ecosystem services provision serve as a basis for further assessment of forest ecosystem services management? How effective is it in decision-making processes and strategic spatial planning?
7. What are the limitations and constraints of geographical information technologies in applications related to the natural environment?

For that purpose, in this thesis, we conducted multi-criteria spatial planning using geographical information technologies. The analysis focused on forest ecosystem services, considering forests in both rural and urban environments, and incorporating fire as a major disturbance factor. Therefore, the main general objectives of the thesis are as follows:

1. To assess, organize, and prepare multiple spatial datasets related to forest ecosystem services and fire risk management in order to model and approximate the spatial reality for further analysis.
2. To address constraints associated with multi-criteria spatial planning of forest ecosystem services and fire risk management.
3. To improve the terminological and methodological framework concerning forest management and urban planning strategies.
4. To apply innovative spatial decision-support tools in the assessment of forest ecosystem services and develop a novel conceptual framework for fire behaviour prediction.
5. To evaluate the provision of forest ecosystem services and urban ecosystem services at the local, regional, and national levels.
6. To utilize the levels of ecosystem services supply to conduct analyses aimed at identifying appropriate spatial management strategies, such as forest use suitability assessments or comparisons of ecosystem services provision.
7. To employ geographical information technologies, including geographical information systems, remote sensing, and digital cartography, in the assessment of multi-criteria spatial planning.

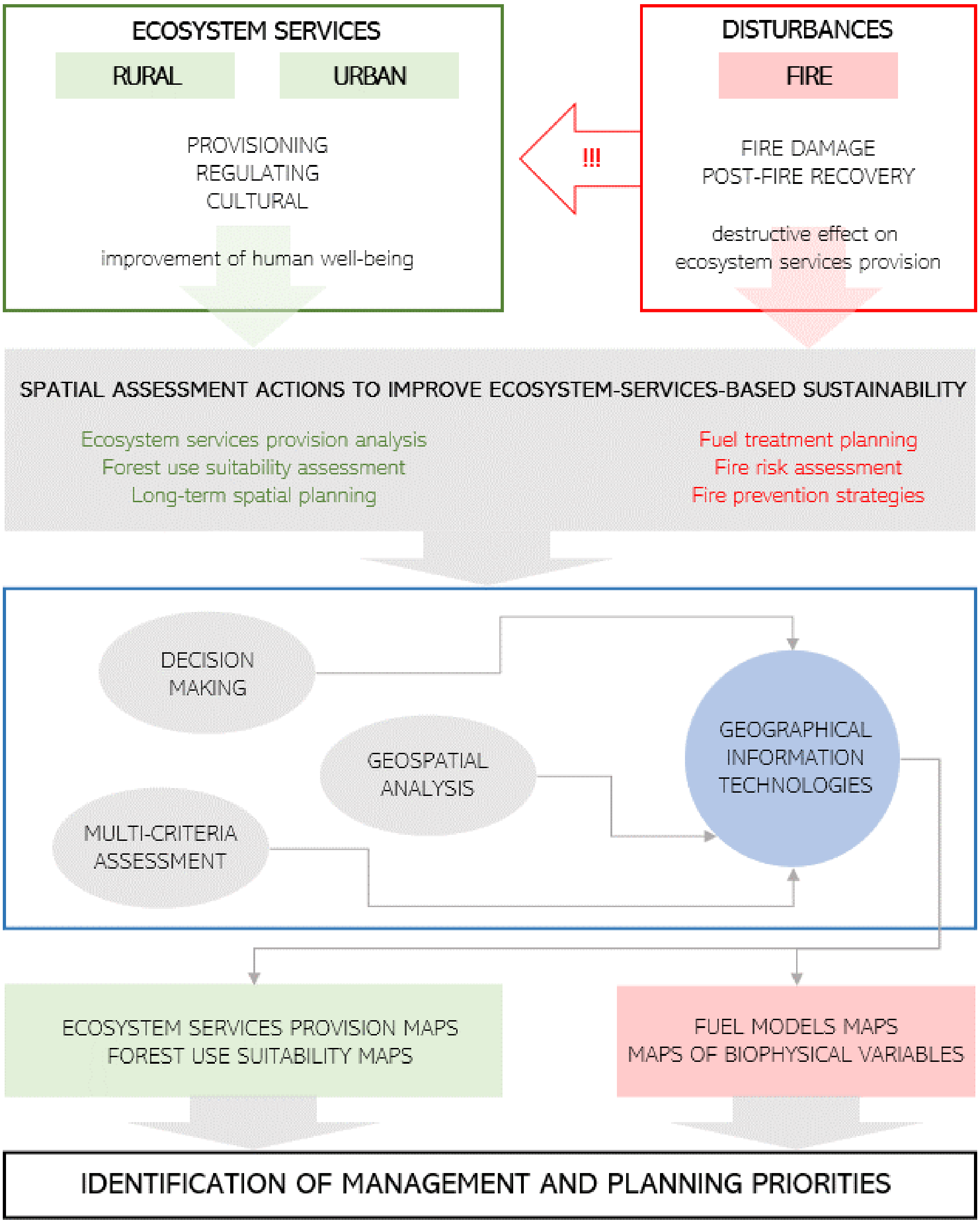


Figure 1. Theoretical framework of the thesis (schematic design)

References

[1] United Nations, “Spatial Planning - Key Instrument for Development and Effective Governance with Special Reference to Countries in Transition,” *Economic Commission for Europe*, pp. 1–56, 2008.

[2] G. Vigar, “Towards an integrated spatial planning?,” *European Planning Studies*, vol. 17, no. 11, pp. 1571–1590, 2009, doi: 10.1080/09654310903226499.

[3] L. Albrechts, “Strategic (spatial) planning reexamined,” *Environ Plann B Plann Des*, vol. 31, no. 5, pp. 743–758, 2004, doi: 10.1068/b3065.

[4] P. Allmendinger and G. Haughton, “Spatial planning, devolution, and new planning spaces,” *Environ Plann C Gov Policy*, vol. 28, no. 5, pp. 803–818, 2010, doi: 10.1068/c09163.

[5] A. Faludi, “The performance of spatial planning,” *Planning Practice and Research*, vol. 15, no. 4, pp. 299–318, 2000, doi: 10.1080/713691907.

[6] D. Caparros-Midwood, S. Barr, and R. Dawson, “Optimised spatial planning to meet long term urban sustainability objectives,” *Comput Environ Urban Syst*, vol. 54, pp. 154–164, 2015, doi: 10.1016/j.compenvurbsys.2015.08.003.

[7] M. Eggenberger and M. R. Partidário, “Development of a framework to assist the integration of environmental, social and economic issues in spatial planning,” *Impact Assessment and Project Appraisal*, vol. 18, no. 3, pp. 201–207, 2000, doi: 10.3152/147154600781767448.

[8] S. Gustafsson, B. Hermelin, and L. Smas, “Integrating environmental sustainability into strategic spatial planning: the importance of management,” *Journal of Environmental Planning and Management*, vol. 62, no. 8, pp. 1321–1338, 2019, doi: 10.1080/09640568.2018.1495620.

[9] V. M. Adams *et al.*, “Making time for space: The critical role of spatial planning in adapting natural resource management to climate change,” *Environ Sci Policy*, vol. 74, no. May, pp. 57–67, 2017, doi: 10.1016/j.envsci.2017.05.003.

[10] J. Lawler, J. Watson, and E. Game, “Conservation in the face of climate change: Recent developments,” *F1000Res*, vol. 4, pp. 1–9, 2015, doi: 10.12688/f1000research.6490.1.

[11] J. G. Álvarez-Romero *et al.*, “Integrated cross-realm planning: A decision-makers’ perspective,” *Biol Conserv*, vol. 191, pp. 799–808, 2015, doi: 10.1016/j.biocon.2015.07.003.

[12] A. Morán-Ordóñez *et al.*, “Analysis of Trade-Offs Between Biodiversity, Carbon Farming and Agricultural Development in Northern Australia Reveals the Benefits of Strategic Planning,” *Conserv Lett*, vol. 10, no. 1, pp. 94–104, 2017, doi: 10.1111/conl.12255.

[13] C. Lead *et al.*, “Forest and Woodland Systems,” *Area*, 2000.

[14] “Forest Principles,” United Nations Conference on Environment and Development, 1992.

[15] Millennium Ecosystem Assessment, *Ecosystems and Human Well-being : Current State and Trends , Volume 1*. 2005.

[16] J. A. Sayer, J. K. Vanclay, and N. Byron, “Technologies for sustainable forest management: Challenges for the 21st Century,” *Commonwealth Forestry Review*, vol. 76, no. 3, pp. 162–170, 1997.

[17] S. Wang and B. Fu, “Trade-offs between forest ecosystem services,” *For Policy Econ*, vol. 26, pp. 145–146, 2013, doi: 10.1016/j.forpol.2012.07.014.

[18] B. Martín-López, E. Gómez-Baggethun, M. García-Llorente, and C. Montes, “Trade-offs across value-domains in ecosystem services assessment,” *Ecol Indic*, vol. 37, no. PART A, pp. 220–228, 2014, doi: 10.1016/j.ecolind.2013.03.003.

[19] L. Diaz-Balteiro and C. Romero, “Making forestry decisions with multiple criteria: A review and an assessment,” *For Ecol Manage*, vol. 255, no. 8–9, pp. 3222–3241, 2008, doi: 10.1016/j.foreco.2008.01.038.

[20] B. Fisher, R. K. Turner, and P. Morling, “Defining and classifying ecosystem services for decision making,” *Ecological Economics*, vol. 68, no. 3, pp. 643–653, 2009, doi: 10.1016/j.ecolecon.2008.09.014.

[21] I. Tammi, K. Mustajärvi, and J. Rasinmäki, “Integrating spatial valuation of ecosystem services into regional planning and development,” *Ecosyst Serv*, vol. 26, no. November 2016, pp. 329–344, 2017, doi: 10.1016/j.ecoser.2016.11.008.

[22] A. Gret-Regamey, A. Walz, and P. Bebi, “Valuing ecosystem services for sustainable landscape planning in Alpine regions,” *Mt Res Dev*, vol. 28, no. 2, pp. 156–165, 2008, doi: 10.1659/mrd.0951.

[23] J. Niemelä *et al.*, “Using the ecosystem services approach for better planning and conservation of urban green spaces: A Finland case study,” *Biodivers Conserv*, vol. 19, no. 11, pp. 3225–3243, 2010, doi: 10.1007/s10531-010-9888-8.

[24] J. P. Rodríguez *et al.*, “Trade-offs across space, time, and ecosystem services,” *Ecology and Society*, vol. 11, no. 1, 2006, doi: 10.5751/ES-01667-110128.

[25] F. Turkelboom *et al.*, “When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning,” *Ecosyst Serv*, vol. 29, no. October 2017, pp. 566–578, 2018, doi: 10.1016/j.ecoser.2017.10.011.

[26] P. Bolund and S. Hunhammar, “Ecosystem services in urban areas,” *Ecological Economics*, vol. 29, no. 2, pp. 293–301, 1999, doi: 10.1016/S0921-8009(99)00013-0.

[27] M. L. Derkzen, A. J. A. van Teeffelen, and P. H. Verburg, “REVIEW: Quantifying urban ecosystem services based on high-resolution data of urban green space: An assessment for Rotterdam, the Netherlands,” *Journal of Applied Ecology*, vol. 52, no. 4, pp. 1020–1032, 2015, doi: 10.1111/1365-2664.12469.

[28] C. Luederitz *et al.*, “A review of urban ecosystem services: Six key challenges for future research,” *Ecosyst Serv*, vol. 14, pp. 98–112, 2015, doi: 10.1016/j.ecoser.2015.05.001.

[29] P. Kremer *et al.*, “Key insights for the future of urban ecosystem services research,” *Ecology and Society*, vol. 21, no. 2, 2016, doi: 10.5751/ES-08445-210229.

[30] M. L. Wilkerson *et al.*, “The role of socio-economic factors in planning and managing urban ecosystem services,” *Ecosyst Serv*, vol. 31, pp. 102–110, 2018, doi: 10.1016/j.ecoser.2018.02.017.

[31] P. Y. Tan *et al.*, “A conceptual framework to untangle the concept of urban ecosystem services,” *Landsc Urban Plan*, vol. 200, no. April, p. 103837, 2020, doi: 10.1016/j.landurbplan.2020.103837.

[32] A. Gret-Regamey, A. Gret-Regamey, A. Gret-Regamey, M. Galleguillos-Torres, A. Dissegna, and B. Weibel, “How urban densification influences ecosystem services - A comparison between a temperate and a tropical city,” *Environmental Research Letters*, vol. 15, no. 7, 2020, doi: 10.1088/1748-9326/ab7acf.

[33] J. G. Pausas and J. E. Keeley, “Wildfires as an ecosystem service,” *Front Ecol Environ*, vol. 17, no. 5, pp. 289–295, 2019, doi: 10.1002/fee.2044.

[34] J. V. Roces-Díaz, C. Santín, J. Martínez-Vilalta, and S. H. Doerr, “A global synthesis of fire effects on ecosystem services of forests and woodlands,” *Front Ecol Environ*, vol. 20, no. 3, pp. 170–178, 2022, doi: 10.1002/fee.2349.

[35] R. Mavsar and M. Kova, “Forest Policy and Economics Trade-offs between fi re prevention and provision of ecosystem services in Slovenia ☆,” *For Policy Econ*, vol. 69, pp. 62–69, 2013.

[36] M. G. Cruz and P. M. Fernandes, “Development of fuel models for fire behaviour prediction in maritime pine (Pinus pinaster Ait.) stands,” *Int J Wildland Fire*, vol. 17, no. 2, pp. 194–204, 2008, doi: 10.1071/WF07009.

[37] B. Ceballos, M. T. Lamata, and D. A. Pelta, “A comparative analysis of multi-criteria decision-making methods,” *Progress in Artificial Intelligence*, vol. 5, no. 4, pp. 315–322, 2016, doi: 10.1007/s13748-016-0093-1.

[38] M. Marttunen, J. Mustajoki, V. Lehtoranta, and H. Saarikoski, “Complementary use of the Ecosystem Service Concept and Multi-criteria Decision Analysis in Water Management,” *Environ Manage*, vol. 69, no. 4, pp. 719–734, 2022, doi: 10.1007/s00267-021-01501-x.

[39] V. Fontana *et al.*, “Comparing land-use alternatives: Using the ecosystem services concept to define a multi-criteria decision analysis,” *Ecological Economics*, vol. 93, pp. 128–136, 2013, doi: 10.1016/j.ecolecon.2013.05.007.

[40] M. R. Rahman, Z. H. Shi, and C. Chongfa, “Assessing regional environmental quality by integrated use of remote sensing, GIS, and spatial multi-criteria evaluation for prioritization of environmental restoration,” *Environ Monit Assess*, vol. 186, no. 11, pp. 6993–7009, 2014, doi: 10.1007/s10661-014-3905-4.

[41] V. M. Chowdary, D. Chakraborthy, A. Jeyaram, Y. V. N. K. Murthy, J. R. Sharma, and V. K. Dadhwal, “Multi-Criteria Decision Making Approach for Watershed Prioritization Using Analytic Hierarchy Process Technique and GIS,” *Water Resources Management*, vol. 27, no. 10, pp. 3555–3571, 2013, doi: 10.1007/s11269-013-0364-6.

[42] B. Leblon, “Geographic Information Technology,” *Encyclopedia of Natural Hazards*. Springer, pp. 385–386, 2013.

[43] F. W. Davis, “Environmental analysis using integrated GIS and remotely sensed data: some research needs and priorities,” *Photogramm Eng Remote Sensing*, vol. 57, no. 6, pp. 689–697, 1991.

[44] K. T. Nemec and C. Raudsepp-Hearne, “The use of geographic information systems to map and assess ecosystem services,” *Biodivers Conserv*, vol. 22, no. 1, pp. 1–15, 2013, doi: 10.1007/s10531-012-0406-z.

[45] B. C. Sherrouse, J. M. Clement, and D. J. Semmens, “A GIS application for assessing, mapping, and quantifying the social values of ecosystem services,” *Applied Geography*, vol. 31, no. 2, pp. 748–760, 2011, doi: 10.1016/j.apgeog.2010.08.002.

[46] B. Burkhard, F. Kroll, S. Nedkov, and F. Müller, “Mapping ecosystem service supply, demand and budgets,” *Ecol Indic*, vol. 21, pp. 17–29, 2012, doi: 10.1016/j.ecolind.2011.06.019.

[47] N. Fagerholm, E. Oteros-Rozas, C. M. Raymond, M. Torralba, G. Moreno, and T. Plieninger, “Assessing linkages between ecosystem services, land-use and well-being in an agroforestry landscape using public participation GIS,” *Applied Geography*, vol. 74, no. 2016, pp. 30–46, 2016, doi: 10.1016/j.apgeog.2016.06.007.

[48] H. Zeng, A. Talkkari, H. Peltola, and S. Kellomäki, “A GIS-based decision support system for risk assessment of wind damage in forest management,” *Environmental Modelling and Software*, vol. 22, no. 9, pp. 1240–1249, 2007, doi: 10.1016/j.envsoft.2006.07.002.

[49] M. Barrett, S. Sahay, and G. Walsham, “Information technology and social transformation: GIS for forestry management in India,” *Information Society*, vol. 17, no. 1, pp. 5–20, 2001, doi: 10.1080/019722401750067397.

[50] S. SH, “Application of Geographic Information System (GIS) in Forest Management,” *Journal of Geography & Natural Disasters*, vol. 05, no. 03, 2015, doi: 10.4172/2167-0587.1000145.

[51] M. Beckline, “Perspectives of Remote Sensing and GIS Applications in Tropical Forest Management,” *American Journal of Agriculture and Forestry*, vol. 5, no. 3, p. 33, 2017, doi: 10.11648/j.ajaf.20170503.11.

[52] I. Santé-Riveira, R. Crecente-Maseda, and D. Miranda-Barrós, “GIS-based planning support system for rural land-use allocation,” *Comput Electron Agric*, vol. 63, no. 2, pp. 257–273, 2008, doi: 10.1016/j.compag.2008.03.007.

[53] T. J. Stewart and R. Janssen, “A multiobjective GIS-based land use planning algorithm,” *Comput Environ Urban Syst*, vol. 46, pp. 25–34, 2014, doi: 10.1016/j.compenvurbsys.2014.04.002.

[54] T. T. Nguyen, A. Verdoodt, T. Van Y, N. Delbecque, T. C. Tran, and E. Van Ranst, “Design of a GIS and multi-criteria based land evaluation procedure for sustainable land-use planning at the regional level,” *Agric Ecosyst Environ*, vol. 200, pp. 1–11, 2015, doi: 10.1016/j.agee.2014.10.015.

[55] M. G. Gale, G. J. Cary, A. I. J. M. Van Dijk, and M. Yebra, “Forest fire fuel through the lens of remote sensing: Review of approaches, challenges and future directions in the remote sensing of biotic determinants of fire behaviour,” *Remote Sens Environ*, vol. 255, no. December 2020, p. 112282, 2021, doi: 10.1016/j.rse.2020.112282.

[56] T. Chu and X. Guo, “Remote sensing techniques in monitoring post-fire effects and patterns of forest recovery in boreal forest regions: A review,” *Remote Sens (Basel)*, vol. 6, no. 1, pp. 470–520, 2013, doi: 10.3390/rs6010470.

[57] M. Mohajane *et al.*, “Application of remote sensing and machine learning algorithms for forest fire mapping in a Mediterranean area,” *Ecol Indic*, vol. 129, no. June, p. 107869, 2021, doi: 10.1016/j.ecolind.2021.107869.

[58] F. Sun, J. Xiang, Y. Tao, C. Tong, and Y. Che, “Mapping the social values for ecosystem services in urban green spaces: Integrating a visitor-employed photography method into SolVES,” *Urban For Urban Green*, vol. 38, no. November 2018, pp. 105–113, 2019, doi: 10.1016/j.ufug.2018.11.012.

[59] A. Troy and M. A. Wilson, “Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer,” *Ecological Economics*, vol. 60, no. 2, pp. 435–449, 2006, doi: 10.1016/j.ecolecon.2006.04.007.

[60] J. Sieber and M. Pons, “Assessment of urban ecosystem services using ecosystem services reviews and GIS-based tools,” *Procedia Eng*, vol. 115, pp. 53–60, 2015, doi: 10.1016/j.proeng.2015.07.354.

[61] L. Grunwald, J. Heusinger, and S. Weber, “A GIS-based mapping methodology of urban green roof ecosystem services applied to a Central European city,” *Urban For Urban Green*, vol. 22, pp. 54–63, 2017, doi: 10.1016/j.ufug.2017.01.001.

[62] J. Holmes and R. Clark, “Enhancing the use of science in environmental policy-making and regulation,” *Environ Sci Policy*, vol. 11, no. 8, pp. 702–711, 2008, doi: 10.1016/j.envsci.2008.08.004.

Chapter 2

METHODOLOGY AND STRUCTURE

This doctoral thesis consists of four studies, each presented as a scientific article within Chapter 3. Although each study has its own specific research objectives and methodological framework, they all share a common approach focused on spatial planning. The thesis combines multi-criteria planning, decision-making processes, and spatial analyses using geographical information technologies. This approach is used in assessment of ecosystem-services-related spatial questions, at local, regional, and national level. Application of geographical information technologies in spatial environmental management implies the use of spatially enabled tools to handle multiple georeferenced databases. In this thesis, specific datasets consisted of multiple spatial layers were created for each study. The characteristics of the datasets are determined by the study area, geographical scale, and objectives of the study. We used geographical information systems, remote sensing, and digital cartography to collect, analyse and visualize data and results. ArcGIS 10.8.1. was used in geospatial analyses, combined with Ecosystem Management Decision Support (EMDS) (https://emds.mountain-viewgroup.com/) system to assess multi-criteria and decision-making assessment. EMDS is a spatially enabled decision support framework for environmental analysis and planning that incorporates several analytical components for geospatial logic modelling, hierarchical processing and strategic or tactical planning.

The first study, Article 1, focuses on analysing the provision of multiple forest ecosystem services in Catalonia and utilizing them as input for forest use suitability assessment. Forest use suitability refers to determining the most suitable forest use based on the biogeophysical characteristics of the forest. The objective is to develop management strategies that are customized to the specific requirements and conditions of the forest. A geospatial logic decision-support model is employed in this study, and a robustness analysis is conducted to identify the most appropriate forest use suitability alternative among five options: productive, protective, conservation-oriented, social, and multifunctional.

The second study, Article 2, builds upon the first article by introducing simulations to assess variables that quantify the provision of forest ecosystem services. Unlike the first study, which focused on static variables, this research incorporates temporally dynamic variables based on simulations of forest changes. The methodological approach is similar to the previous study, assessing the provision of forest ecosystem services while considering their future characteristics and identifying forest use suitability. By incorporating temporal development of the forest, the study aims to define long-term management strategies based on the obtained results. The study area corresponds to the territory of Spain, and the analysis is specifically applied to forest stands with the presence of *Pinus sylvestris*.

The third study, Article 3, focuses on the significance of urban green areas and the ecosystem services they provide. It evaluates different methods for comparing the provision of ecosystem services among urban areas, aiming to enhance management actions in urban green areas. The cities of Barcelona, Spain, and Santiago, Chile are used as examples to highlight environmental inequality. The study aims to assess the relativeness in provision of urban ecosystem services by employing geospatially enabled decision support models. It also emphasizes the need for improved methodological approaches in assessing urban ecosystem services.

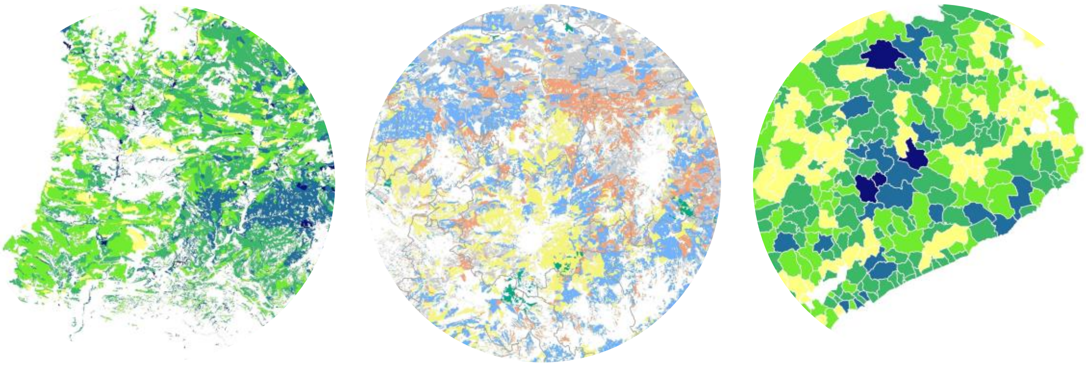
The fourth study, Article 4, focuses on assessing the impact of fire, the primary disturbance affecting forests and the provision of forest ecosystem services. It utilizes various geospatial modeling tools and remote sensing techniques to develop a server-based database that includes essential variables for predicting fire behavior at the regional level. The objective of the study is to enhance decision-making processes related to the prevention and management of forest fires in Catalonia.

Chapter 3

THESIS ARTICLES

Article 1

FOREST USE SUITABILITY: TOWARDS DECISION-MAKING-ORIENTED SUSTAINABLE MANAGEMENT OF FOREST ECOSYSTEM SERVICES



Under review in *Geography and Sustainability* (2023)

Krsnik G.; Reynolds, M.,K.; Murphy, P.; Paplanus, S.; Garcia-Gonzalo, J.; González Olabarria, J.R.

Forest Use Suitability: Towards Decision-Making-Oriented Sustainable Management of Forest Ecosystem Services

Abstract: Management of forest lands considering multi-functional approaches is the basis to sustain or enhance the provision of specific benefits, while minimizing negative impacts to the environment. Defining a desired management itinerary to a forest depends on a variety of factors, including the forest type, its ecological characteristics, and the social and economic needs of local communities. A strategic assessment of the forest use suitability (FUS) (namely productive, protective, conservation-oriented, social and multifunctional) at regional level, based on the provision of forest ecosystem services and trade-offs between FUS alternatives, can be used to develop management strategies that are tailored to the specific needs and conditions of the forest. The present study assesses the provision of multiple forest ecosystem services and employs a decision model to identify the FUS that supports the most present and productive ecosystem services in each stand in Catalonia. For this purpose, we apply the latest version of the Ecosystem Management Decision Support (EMDS) system, a spatially oriented decision support system that provides accurate results for multi-criteria management. We evaluate 32 metrics and 12 associated ecosystem services indicators to represent the spatial reality of the region. According to the results, the dominant primary use suitability is social, followed by protective and productive. Nevertheless, final assignment of uses is not straightforward and requires an exhaustive analysis of trade-offs between all alternative options, in many cases identifying flexible outcomes, and increasing the representativeness of multifunctional use. The assignment of forest use suitability aims to significantly improve the definition of the most adequate management strategy to be applied.

Keywords: forest ecosystem services, decision making, forest use suitability, multiobjective management, geospatial analysis

1. Introduction

Ecosystem services (ESs) are benefits to society provided by ecosystems and are considered essential for human well-being [1]. The scientific framework for ESs has been developed to improve management of Earth’s ecosystems in order to ensure their conservation and sustainable use, considering an anthropogenic interpretation of ecological functions [2]. The concept has been developed as a way to balance societal demand for ESs and the capacity of ecosystems to deliver them to the society and is being incorporated into decision-making processes [3]. Several research groups have stressed the importance of a multidisciplinary approach when evaluating ESs, considering both social and environmental features, to obtain a realistic overview of the geospatial relations among ESs and, thus, apply an appropriate strategy to their management [4]–[6]. To maintain the flow of benefits to people while maintaining ecosystems, an appropriate management strategy needs be considered [4], [7]. Up to the present, the role of ESs in decision-making for land governance has not received sufficient attention [8]. As a result, the vulnerability of ecosystems and insufficient consideration of their sustainability in environmental management actions has frequently led to ecosystem degradation and associated losses in ES supply [9]–[11]. Therefore, several authors have stressed the importance of developing of ES-based approaches [12], [13], their application in spatial management of ecosystems [14], [15], and effective implementation in national and regional governing policies [16], [17].

Mapping the provision of ESs has been recommended as the first step towards a comprehensive management plan [18], [19]. However, the provision of ESs is affected by complex geospatial processes, with often unique effects of diverse factors such as forest structure and composition (and more generally depending on the broader biophysical or social context) on ES provision. Interdependencies and trade-offs among ESs further complicate the development of management plans. Consequently, quantifying the characteristics of ES indicators while accounting for this complexity is an important step in evaluating ESs and their provision by forests [20]. The modelling required to implement this type of spatial quantification is a challenging task [21]–[23] due to the different nature and scale of factors influencing the provision of ESs and related methodological constraints [24]–[27]. Another relevant aspect to be considered when mapping ESs, with an intention of supporting decision making, is the diverse types of benefits provided [28], usually categorized according to the Millennium Ecosystem Assessment (MEA) as provisioning, regulating and cultural [2]. Typically, a forest provides several ESs, whose yield and importance depend on the scale, the allocation, and the intrinsic characteristics of the forest. Therefore, a multifunctional and interdisciplinary approach to forest management is crucial to maintain forest ecosystem sustainability [29]. Sayer et al. [30] have defined forest sustainability as “maintaining or enhancing the contribution of forests to human well-being, both of present and future generations, without compromising their ecosystem integrity,” thus implying the importance of forest ESs in forest management strategies. While forests are usually seen as multifunctional, due to trade-offs among the different services they provide, they usually cannot simultaneously deliver high levels of multiple services in a sustainable way [31]. An efficient forest management strategy developed around the concept of obtaining the maximum yield of multiple ESs requires management actions that, when focussed on maximizing one particular ES, also minimize the negative impacts on provision of others [32].

Decision-making concerning use of forest resources is complex because it typically needs to consider competition between diverse planning strategies, such as conflicts between timber harvesting and conservation-oriented or recreation-oriented management actions [33]. As the complexity of decisions increases, identification of an appropriate management alternative becomes more difficult. Thus, the decision process is strongly influenced by the perception of relevant criteria and their relative importance assigned by different social groups or stakeholders, and depending on the latter's primary interest in forest use [34]. One solution to decrease the complexity of any type of forest planning problem is to reduce the number of potential management actions that can be implemented on a particular forest stand. In practice, this is often achieved by normative models that limit management practices on, for example, conservation-oriented areas, riparian forests, or places where forest plays a crucial role in protecting downstream lands from landslides [35]. An alternative approach to limit the management alternatives to be considered in a planning problem is to identify for which use a forest unit is best suited, based on the ESs that it provides [36]. For this purpose, it is necessary to assess the provision of ESs at a regional scale, evaluate trade-offs among the ESs that each spatial component provides, and identify forest use suitability (FUS) through multi-criteria-based decision making. Determining FUS (namely productive, protective, conservation-oriented, social, or multifunctional use in our application) in a systematic way draws on the concept of a compartment model to pre-define potential management options better suited to the forest unit's biogeophysical and socio-economic reality. In other words, we should use our knowledge of the current ESs supported by each stand to identify the most suitable FUS for each stand – that is, an FUS which tends to support those ESs already most present and productive in the stand. Each FUS comes with suites of management actions that should be adopted over time. In that terms, productive use is mostly associated to management goals and ecosystem services that maximize the economic profitability of the forest. Protective use highlights the actions that mitigate harmful natural processes. Conservation-oriented use aims to increase the habitat value of the forest. Social use empowers non-material and abstract values that influence human physical and mental health. Finally, multifunctional use acts as a combination of two or more of the previous uses and objectives, and is assigned when more than one alternative is considered as the most suitable one. We implemented this framework in our study area, the autonomous community of Catalonia, Spain. Despite numerous ES-related studies that have been done in recent decades, stimulated by an increased interest in research on global forest ESs [27], [37], [38], there is relatively little research concerning assessment of the provision of ESs aiming to identify FUS at a regional level and, consequently, define appropriate management strategies based on the FUS concept at this scale.

Research solutions for managing ESs have varied widely [39], ranging from survey-based questionnaires [28], to mathematical or statistical models [29], to explicit decision-making tools [40]. In this study, we demonstrate application of new functionality in the Ecosystem Management Decision Support (EMDS) system, a spatially enabled decision support framework for environmental analysis and planning [41], [42], that can support problems such as the strategic regional allocation of FUS in Catalonia, Spain. While the results presented are specific to the Catalan region of Spain, the methods and the underlying EMDS technology have potential global application to the problem of managing for provision of ecosystem services based on the concept of forest use suitability.

2. Material and Methods

2.1 Study area and data sources

The study was performed in Catalonia, which is situated in north-eastern Spain. It covers approximately 32,000 km^2, and about 42% of the area is classified as forest and woodland [43]. About 75% of forest land is privately owned and excessively fragmented, potentially complicating the development and implementation of effective forest management plans in the region [44]. Moreover, about 40% of the total Catalan forest area is under the Natura 2000 EU protection framework, while 11% of forest lands are under special national protection policies [45]. Catalonia is a highly populated area, with approximately 7.8 million inhabitants in 2020, and with a population density of 242.3 inhabitants per square kilometre [46]; 43% of its population is concentrated in the metropolitan area of Barcelona [29]. The area is orographically diverse, with elevations ranging from sea level to >3000 m [45] and with strong influences on climate, ranging from semi-arid to Mediterranean-influenced subarctic climates [47].

We used stand-level data from the 1:50,000 Spanish Forest Map (SFM) and the Catalan municipalities as spatial scales to calculate metrics. Only SFM polygons classified as continuous forest cover were taken into analysis, and only municipalities with at least 5% continuous forest cover were considered in this study [48]. Based on these selection criteria, the study area included 25,408 forest stand polygons from the SFM and 779 of the 947 Catalan municipalities (Figure 1). A detailed listing of data used to calculate the ES metrics used in this study are presented later (Table 1).

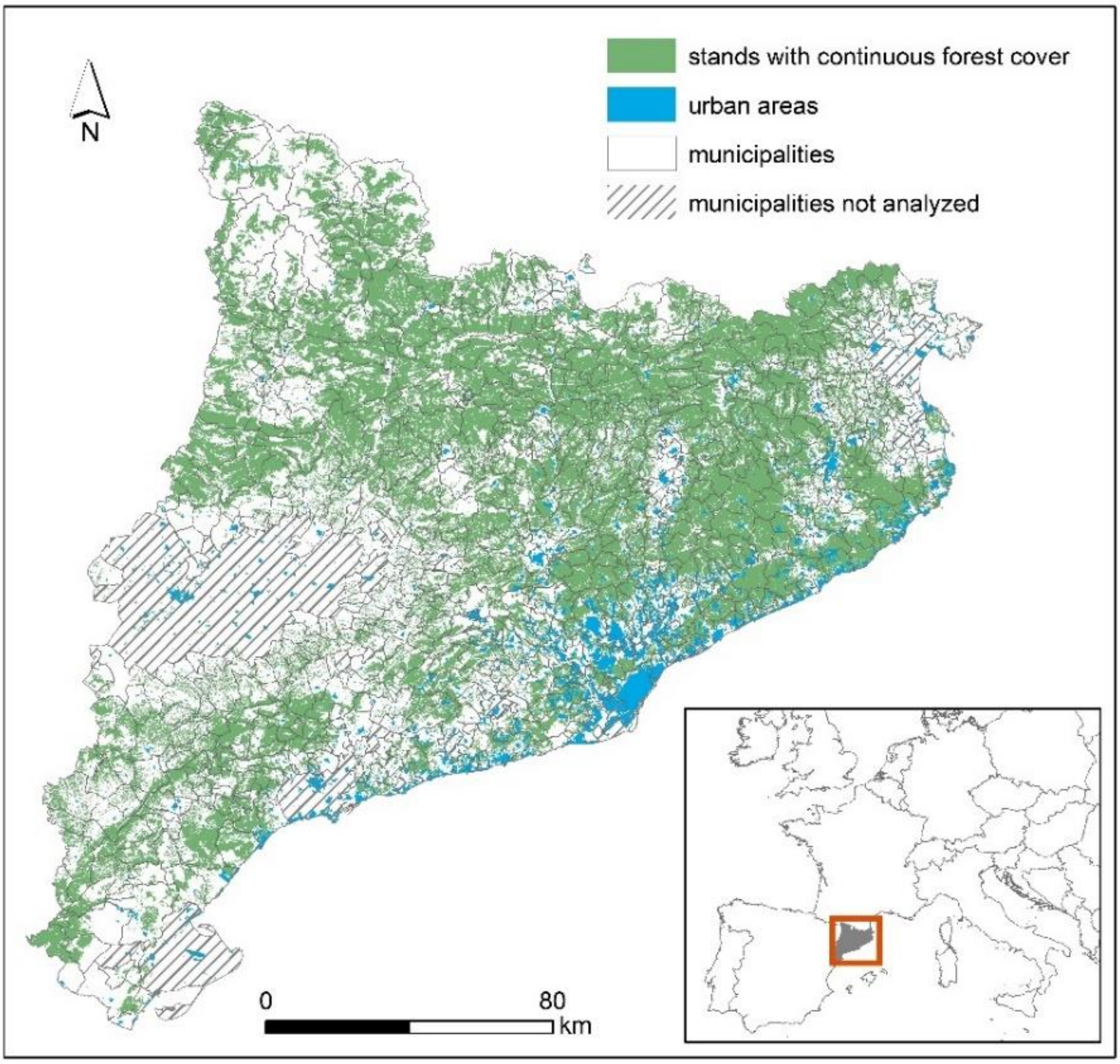


Figure 1. Study area and relevant data layers

2.2. Conceptual design

The main objective of the study is to define, and spatially assign, FUS at the stand level, based on the ability of forest stands to maximize indicators for the provision of ecosystem services. To meet this goal, the project was implemented in four steps (Figure 2):

1) *Define indicators for forest ecosystem services (FES) in terms of sets of metrics.* In this step, an initial analysis of data availability was done to identify as many relevant metrics as possible. Metrics are variables that collectively quantify each ecosystem service indicator and, consequently, the provision of FES. Based on available data, a set of 12 FES indicators was established.
2) *Analyse the provision of forest ecosystem services at the forest stand*. Once FES had been established, in the second step, by using geospatial logic-based modelling, their provision at each stand was quantified. Values of FES provision were used as input for FUS assignment.
3) *Assess forest use suitability (FUS) at the forest stand.* Using a multi-criteria decision support tool, in this step the suitability of each stand to be used and managed in a certain way was evaluated, considering its evidence for FES provision. For that purpose, a suitability score for each of five defined FUS alternatives was calculated, with FUS alternatives being either productive, protective, conservation-oriented, social, or multifunctional uses.
4) *Analyse robustness between suitability alternatives.* In this final step, the FUS performance scores obtained in the previous step were ranked from highest to lowest, resulting in a final FUS priority list (primary, secondary FUS, etc.). Once the scores had been ranked, differences between them were analysed, aiming to define the most appropriate FUS for each stand.

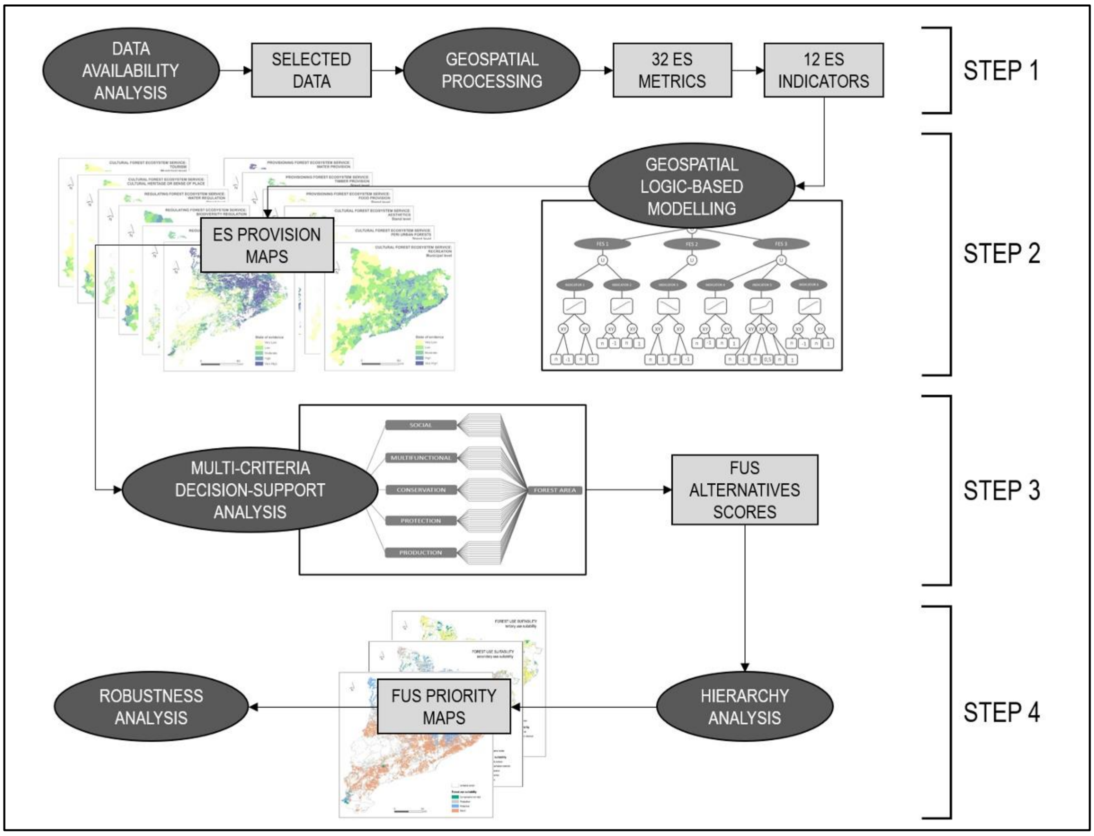


Figure 2. Conceptual design of the study

2.2.1. Definition of forest ecosystem services (FES) indicators

Definition of FES indicators was the first step towards the complete ES analysis. An FES Indicator for an ES is a composite score for a stand where high value indicates likely provision of the ES, and low scores indicate the ES is likely absent. It was required to define as many indicators as possible to approximate existing biogeophysical processes and social concerns in a comprehensive way. Therefore, a detailed analysis of data availability was undertaken to detect spatial data that could be used to define, and consequently quantify, FES. We selected 32 datasets that were eligible to properly define FES indicators. In this paper, we refer to these datasets as metrics. Metrics selection was based on literature review, trying to implement as many metrics as possible, and considering data availability for the established spatial resolution. Determined by this selection process, 12 FES indicators were defined. Each FES was evaluated by one or more selected metrics that quantify the provision of the FES (Table 1). We used original data or geoprocessing operations in ArcMap 10.8 to obtain desired units for each metric. Some metrics were calculated using equations based on literature review. All FES metrics were spatially adapted to one of two spatial scales, depending on their source (Table

1)(Archive 1). Details of the computations for each FES indictor are presented in section 2.2.2 below. The MEA methodological framework was used to process and organize data. Therefore, three FES groups were established: provisioning, regulating and cultural.

Table 1. Selected 32 metrics used to evaluate each of the 12 FES indicators

FES groups and FES indicators[a]	**FES metrics**	**Spatial scale**	**Units**
PROVISIONING			
Timber provision	Road density	Stand	m/m^2
	Time cost	Stand	h/m
	Wood biomass	Stand	t/ha
	Forest productivity	Stand	m^3/ha/year
Water provision	Total water runoff	Stand	mm/year
Food provision	Pine nuts production	Stand	categorical 0-1
	Cork production	Stand	categorical 0-1
	Mushroom production	Stand	kg/ha/year
REGULATING			
Water regulation	Riparian forests	Stand	%
	Forest cover	Stand	%
Climate regulation	CO_2 sequestration	Stand	t/ha
Soil protection	Laminar erosion	Stand	t/ha/year
	Mass movements	Stand	index
	Aeolian erosion	Stand	index
	Desertification risk	Stand	index
Biodiversity regulation	Natural reserves	Municipality	%
	Peripheric protected areas	Municipality	%
	Threatened species areas	Municipality	%
	Singular habitats	Municipality	%
	Natura 2000 network	Municipality	%
	Spots of national interest	Municipality	%
	Natural parks	Municipality	%
CULTURAL			
Peri urban forests	Distance to the cities	Stand	m
Aesthetics	Scenic beauty	Stand	index
Recreation	Hiking trails	Municipality	km/km^2
	Hunting areas	Municipality	%
	Population density	Municipality	hab./km^2
Cultural heritage or sense of place	Monumental trees	Municipality	number
	Cultural sights	Municipality	number/km^2
Tourism	Rural accommodation	Municipality	number/km^2
	Cultural sights	Municipality	number/km^2
	Spots of national interest	Municipality	%
	Natural parks	Municipality	%
	Camping areas	Municipality	number/km^2
	Visitor centers	Municipality	number

[a] In this column, the 12 FES indictors are categorized by the three FES groups, which are indicated in italics and all upper case.

Provisioning services are the products people obtain from the ecosystems [2]. In this category, we selected 8 metrics to represent and define three forest ESs. Four indicators to define timber provision were considered:

1. Estimated wood biomass was calculated and spatially adapted to each stand of the forest area based on the values from the Map of Biophysical Variables of Catalonia obtained with LiDAR-based technology [49].
2. Forest productivity values, on the other hand, were estimated by the MITECO and were spatially adapted to our scale [50].
3. Density of roads suitable for wood extraction machinery was obtained from the road network map 1:5,000 and topographic map of Catalonia 1:25,000 adapted by the Forestal Catalana (Generalitat of Catalonia) for the PORF assessment purposes [51], [52].
4. Time cost of access to each forest stand was adopted from the PORF study made by the Forestal Catalana [51], [52].

We used three indicators to describe potential production of non-wood forest products in Catalan forests, defining food provision. The Bonet et al. [53] model was used to estimate potential mushroom productivity by forest ecosystems in Catalonia. On the other hand, both for pine nuts and cork, we used data from the SFM to define the potential production capability in the area [48]. To represent water provision, we used estimated data on total annual runoff provided by the national Ministry of Agriculture, Fisheries and Food [54].

Regulating services are the benefits people obtain from the regulation of ecosystem processes [2]. In this category we selected 14 metrics to represent and define four forest ESs. We used Natura 2000 sites and all classes from the ENPE category (Special Protection Natural Areas), from the Catalan System of Natural Protected Areas, [55], [56], to assess the biodiversity regulation service. Additionally, we included the cartographic dataset of Natural Habitats of High Priority [57], and areas considered to have presence of threatened flora or fauna species [58]. We used the percentage of forest canopy cover from the Map of Biophysical Variables of Catalonia and riparian forest cover from the SFM in each forest stand to estimate water regulation service [48], [49]. Carbon sequestration was used to represent climate regulation, based on LiDAR data [49]. Finally, we implemented four estimated metrics from the National Soil Erosion Inventory to assess soil protection services: laminar erosion potential, mass movement potential, aeolian erosion risk and desertification risk [59], [60]. All values are categorical and estimated based on the main geophysical characteristics: precipitation, geological features and relief.

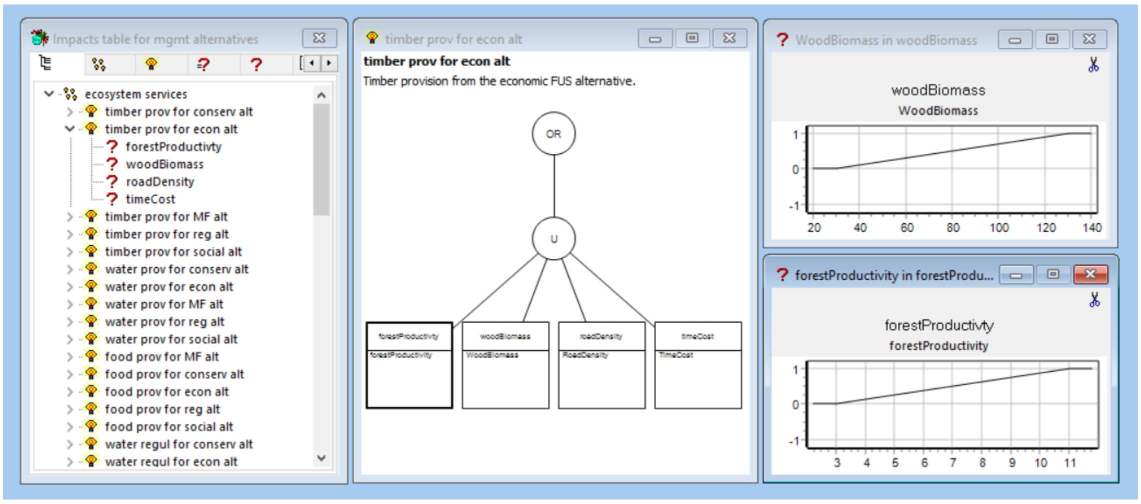
Cultural services are “nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, recreation, reflection, and aesthetic experiences” [2]. In this category we selected 12 metrics to represent four forest ESs. Three metrics were used to assess recreational use of forests. We used an official government database of hunting areas to detect shares of forests used for that recreational activity [61]. The availability and potential demand of recreation services was represented by the density of officially approved hiking trails, and statistics on population density [46], [62]. To estimate touristic use of forests we selected six metrics. Out of the protected natural areas, we considered two categories as of touristic interest (natural parks, and spots of national interest) due to their significant landscape, educational characteristics, and visitor-oriented policy [55]. Simultaneously, we considered the number of visitor centres located within the forest-related areas of interest as well as number of bed places in rural accommodation and camping areas per square kilometre, which were used as proxies to estimate potential demand of forest-oriented touristic activities [46]. Moreover, archaeological and paleontological sites and cultural heritage monuments located within forests were used to represent potential touristic attractions [63]. The latter two metrics, together with monumental trees [64] were considered to define a cultural heritage or sense-of-place indicator, aiming to designate historical, symbolic, and cultural significance of forests. An aesthetic value of forest was obtained using a model developed by Blasco et al. [65] that implements an index for scenic beauty. Additionally, we introduced a special category for peri-urban forests, depending on the distance to the nearest urbanized area with more than 10,000 inhabitants [46].

2.2.2. Analysis of the provision of forest ecosystem services

After the definition of FES indicators in the previous step, in this step we proceed to quantify their provision using the previously selected metrics. For that purpose, a geospatially based logic model was created in NetWeaver Developer [[66], hereafter NetWeaver], an analytical component of the EMDS spatial decision support framework [41]. It uses a specific measure of the strength of evidence to quantify the provision of each of the 12 FES. The model helps to approximate relations between metrics and FES, assigning them the degree of significance, type of relationship, dependency, and requirements for being considered as relevant. In this way, each FES indicator (Table 1) was quantified by a unique set of rules applied to the metrics that define it.

NetWeaver logic models are constructed as networks of networks, in which the strength of evidence of dependent networks is logically derived from evidence provided by antecedent networks [66]. This recursive architecture terminates in elementary networks whose only antecedents are data, which we refer to as metrics in this particular application. All strength of evidence metrics originate in the elementary networks, which each use a fuzzy membership function to express the degree of support for a logical proposition provided by an observed data value (Table 2). The evidence metrics originating at the elementary networks are successively propagated upward through the network structure, passing from antecedent to dependent networks through logic operators that specify how to combine the sources of evidence. The NetWeaver model for supporting the analysis of FUSs in Catalonia contains 60 distinct logic networks, representing all possible combinations of the 12 FES and the five FUSs. This combinatorial architecture was required to eventually account for different sets of relevant FES, depending on which FUS was being evaluated in the subsequent decision modelling step described in section 2.2.3.

The logic design of the model was greatly facilitated by NetWeaver's graphical method of model design, but the graphic representation of the logic makes it impractical to present the complete architecture of our model in the paper, so we include documentation of the full model in HTML (Archive 2). However, we include a graphic of the logic for evaluating the contribution of timber provision to the economic FUS to explain additional details of the logic processing (Figure 3). The evaluation of timber provision considers four metrics (Table 1), each evaluated by a fuzzy membership function (Table 2). The U operator (Figure 3) is NetWeaver's Union, which specifies that the measures of strength of evidence for the four metrics are logically combined as a weighted average. Each of the 60 logic networks likewise use the U operator to combine lines of evidence. While, technically, U computes a weighted average of evidence measures, our model does not specify any weighting on the antecedents, so the results are always the simple average of evidence measures from the antecedents. As a practical matter, the effect of the operator is to treat the lines of evidence as additive, in a sense, and therefore compensatory. In other words, low evidence values on one metric can be compensated by high values on others.



timber prov for econ alt

Timber provision from the economic FUS alternative.

Figure 3. Graphic of the logic for evaluating the contribution of timber provision to the economic FUS. The lefthand frame displays a partial view of the network components with the outline expanded under the alternative for timber provision in the economic context. The middle frame displays the details of the logic specification for the latter alternative. The righthand frame displays two examples of how arguments are defined in NetWeaver to compute the measures of strength of evidence for the metrics, woodBiomass and forestProductivity.

Table 2. Thresholds defining the fuzzy membership function for each elementary network.

Indicator Metric	No evidence	Full evidence	Indicator Metric	No evidence	Full evidence
Road density	0	0.008	Desertification risk	1	4
Time cost	0.004484	0.003474	Natural reserves	0	5
Wood biomass	30	130	Peripheric protected areas	0	25
Forest productivity	3	11	Threatened species	0	4
Total water runoff	15	300	Singular habitats	2	35
Pine nuts production	0	1	Natura 2000 network	5	55
Cork production	0	1	Spots of national interest	0	25
Mushroom production	0	10	Natural parks	0	60
Distance to the cities	1200	400	Hiking trails	0	0.75
Scenic beauty	1.3	1.77	Hunting areas	10	80
Riparian forests	0	10	Population density	15	350
Forest cover	10	80	Monumental trees	0	4
CO_2 sequestration	15	50	Cultural goods	0	0.4
Laminar erosion	1	7	Rural accommodation	0	1.8
Mass movements	1	5	Camping areas	0	60
Aeolian erosion	1	3	Visitor centers	0	1

After running the NetWeaver model in EMDS, twelve maps showing evidence for the provision of each FES were produced. Whereas there are 60 possible maps, representing all combinations of FESs and FUSs, there are only 12 unique maps because, for the purposes of this study, the specification of evidence for provision of an FES is independent of FUS. Lastly, we note that NetWeaver's strength of evidence metric is a continuous variable, but the latter maps are symbolized into five classes of very low to very high solely for purposes of display.

2.2.3. Assessment of forest use suitability

The 12 maps of FES provision obtained in the previous step were used as input data in the decision-modelling phase (step 3 in Figure 2) of the FUS assessment process. The objective of this step is, based on the FES provision features of each stand, to compute the utility of forest use alternatives with respect to the provision of ES, which could subsequently be used as a basis for future strategic management planning. For that purpose, we evaluated the relationship between the provision of each of the 12 FES and each of the five FUS alternatives. Each evaluation considered the contribution that the provision of certain FES at the forest stand level makes to the overall performance of FUS. Continuing with the example from Figure 3, the evaluation question here is "To what degree does evidence of timber provision contribute to the conclusion that the FUS of the stand is the primary productive alternative?". These contributions were evaluated by assigning weights to each of the 60 logic models created in the previous step, in which each logic model represents one FES-FUS relationship (Table 3). For example, we assumed that a forest with strong evidence of timber provision is mostly suited to the productive use alternative (0.6), followed by protective and multifunctional uses (0.2), but with no contribution to the conservation-oriented and social uses (0). Note that the weights of one FES across alternatives sums to 1. The weights presented in Table 3 are preliminary, established by authors, and are to be checked and, if needed, corrected through participatory planning. Combining results from steps 2 and 3 (Figure 2), each management unit receives a utility score for each of the five FUS alternatives, with higher scores indicating higher suitability of the forest stand for an FUS.

Table 3. Weights quantifying the relative contribution of ES relationship between FES to the benefits of each FUS alternative. Bold numbers indicate the weight of highest contributing FES associated to a suitable uses of the forest.

FES INDICATORS	**FUS ALTERNATIVES**				
	MULTI-FUNCTIONAL	*PRODUCTIVE*	*PROTECTIVE*	*CONSERVATION*	*SOCIAL*
TIMBER PROVISION	0.2	**0.6**	0.2	0	0
WATER PROVISION	0.2	0.4	0.2	0.2	0
FOOD PROVISION	0.2	0.45	0	0.1	0.25
WATER REGULATION	0.2	0	0.4	0.4	0
CLIMATE REGULATION	0.2	0	**0.7**	0.1	0
SOIL PROTECTION	0.2	0	**0.7**	0.1	0
BIODIVERSITY REGULATION	0.2	0	0	**0.8**	0
AESTHETICS	0.2	0	0	0.1	**0.7**
PERI-URBAN FORESTS	0.2	0	0.15	0.15	0.5
TOURISM	0.2	0.2	0	0.2	0.4
RECREATION	0.2	0.15	0	0	**0.65**
CULTURAL HERITAGE	0.2	0	0	0.3	0.5

FUS suitability assessment was done using the Criterium Decision Plus (CDP) tool based on the Analytic Hierarchy Process (AHP) to derive weights on decision criteria [67]. The method also uses the Simple Multi-Attribute Rating Technique (SMART) to normalize attributes into utility scores (from 0 to 1). The goal of this assessment is to identify the most appropriate FUS alternative, of the five previously defined, based on the indicators that FESs are thriving on the stand (Figure 4). The purpose of the CDP model in this section is to implement that identification for each stand. The weights in Table 3 quantify the relative contribution of each ES, if present and fully productive on the stand, to the benefits of each FUS. These weights express expert opinion (see last sub-section of the Discussion Section.)

The nodes below the CDP goal are the five FUS. The lowest criteria are the 12 ES indicators for each FUS. The alternatives are the stands, and their ratings values represent the indicator score for each ES under each FUS – the strength of evidence that the ES is thriving (in the terms of each FUS) imported from the outputs of the 60 NetWeaver networks. When the CDP model is executed on a stand, a weighted sum estimate of how well the existing set of ESs on that stand support the FUS is generated at each FUS node – the value of that estimate being the contribution of that FUS node to the stands' overall decision score. In this work, we interpret that estimate for each FUS as a proxy for its suitability to guide future management of that stand.

Using the Classic MCDA Analysis tool in the EMDS, the CDP model was applied to each stand, and the estimate of suitability for each FUS extracted and added to the GIS table for every stand in the study area. Whereas in the Classic EMDS the alternatives would be different management actions, in this case the FUS are the true alternatives, encoded in the CDP model as top-level criteria. Custom code was added to the EMDS to extract and record the scores for the five FUS for each forest polygon.

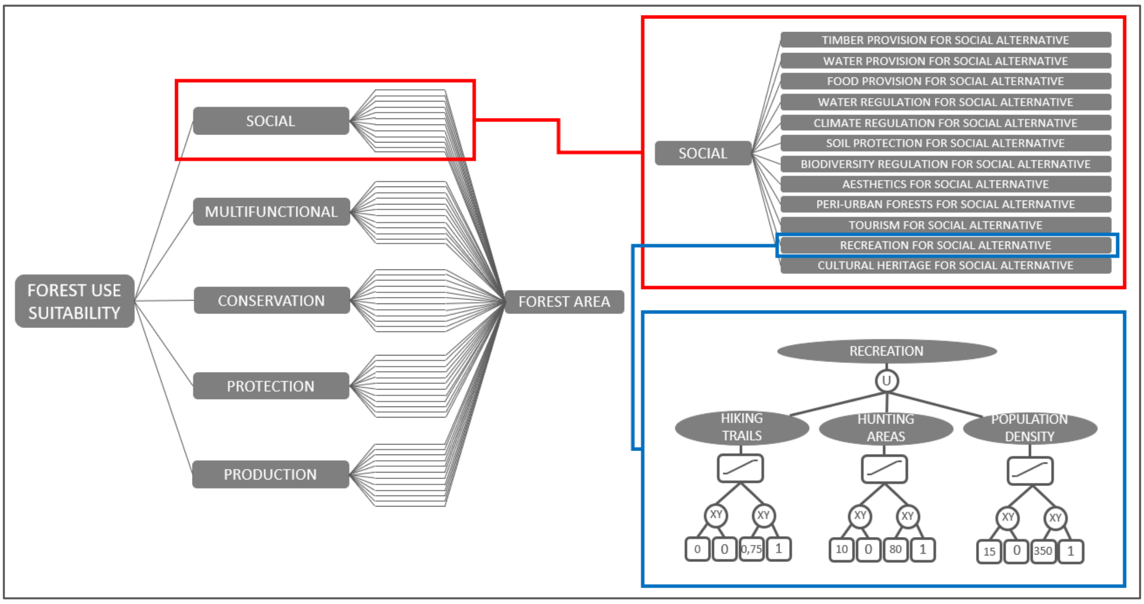


Figure 4. Schematic design of CDP model. The left-hand pane shows the overall MCDA model, with the five FUSs being the nodes to the right of the Goal. The upper right pane zooms into show the 12 FES indicators under that FUS, and the lower right pane shows 3 networks in the Net Weaver model that calculate the strength of evidence that that ES is thriving on that forest stand.

2.2.4. Assignment of FUS priorities and robustness analysis

In step 4 of the overall assessment (Figure 2), FUS performance (e.g., utility) scores for each stand obtained in the previous step were numerically ordered from highest to lowest, resulting in a hierarchical distribution of FUS alternatives. The alternative achieving the highest performance score was interpreted as the primary FUS alternative or, in other words, the most suitable forest use alternative of the five defined in this study, whereas the alternative with the lowest score was considered the least suitable. By defining the rank in which a FUS is represented in a stand, it was possible not only to map the distribution of primary, secondary and tertiary FUS across the region, but also to detect if there were spatial relations among them. To further evaluate the relation between FUSs, we created transition matrix tables to identify how often a primary FUS is associated to a specific secondary FUS, and how often such secondary FUS is associated to a tertiary FUS.

Robustness analysis between primary and secondary FUS was undergone for each stand showing the strength of the difference between FUS performance scores. For that purpose, secondary FUS performance scores were subtracted from the primary ones, and the resulting differences were grouped into quintiles. When the difference is very small, the secondary FUS might be considered as also highly most suitable, together with the primary alternative. On the contrary, in case of very large differences, the importance of the secondary FUS decreases considerably. These scores can be used as a method to balance representativity by switching from primary to secondary FUS and vice versa. This process was done using the ArcGIS 10.8 software (Environmental Systems Research Institute)[1], as well as the EMDS 8.7 ArcMap Add-Inn (https://emds.mountain-viewgroup.com/).

3. Results

3.1 Forest ecosystem services provision

The provision of the FES was not defined by a common pattern (Figure 5). While some forest ES present clear highland (north) – lowland (south) spatial distribution, others were more associated with distance from the sea. Water provision and climate regulation, for example, were mainly associated with mountains, where those FES yielded higher provision values and strength of evidence. A similar, but slightly less pronounced, spatial pattern occurred in the cases of food provision and soil regulation. On the other hand, peri urban forests and recreation, and in general most of the cultural services, are characterised by very high provision values near coastal areas, where most of the population is concentrated. Tourism and cultural heritage values have rather irregular spatial pattens. Nevertheless, in both cases, stronger evidence of provision was clustered in the north-eastern part of Catalonia, while lower provision values are located to the west. Similarly, very strong evidence of timber provision can be seen in the central and northern coastal areas. Finally, water regulation and biodiversity regulation values have heterogeneous spatial distributions with no clear pattern defined. In general, high values of provisioning and regulating forest ESs correspond to the mountainous areas of Catalonia, while cultural services are more clustered in the coastal region.

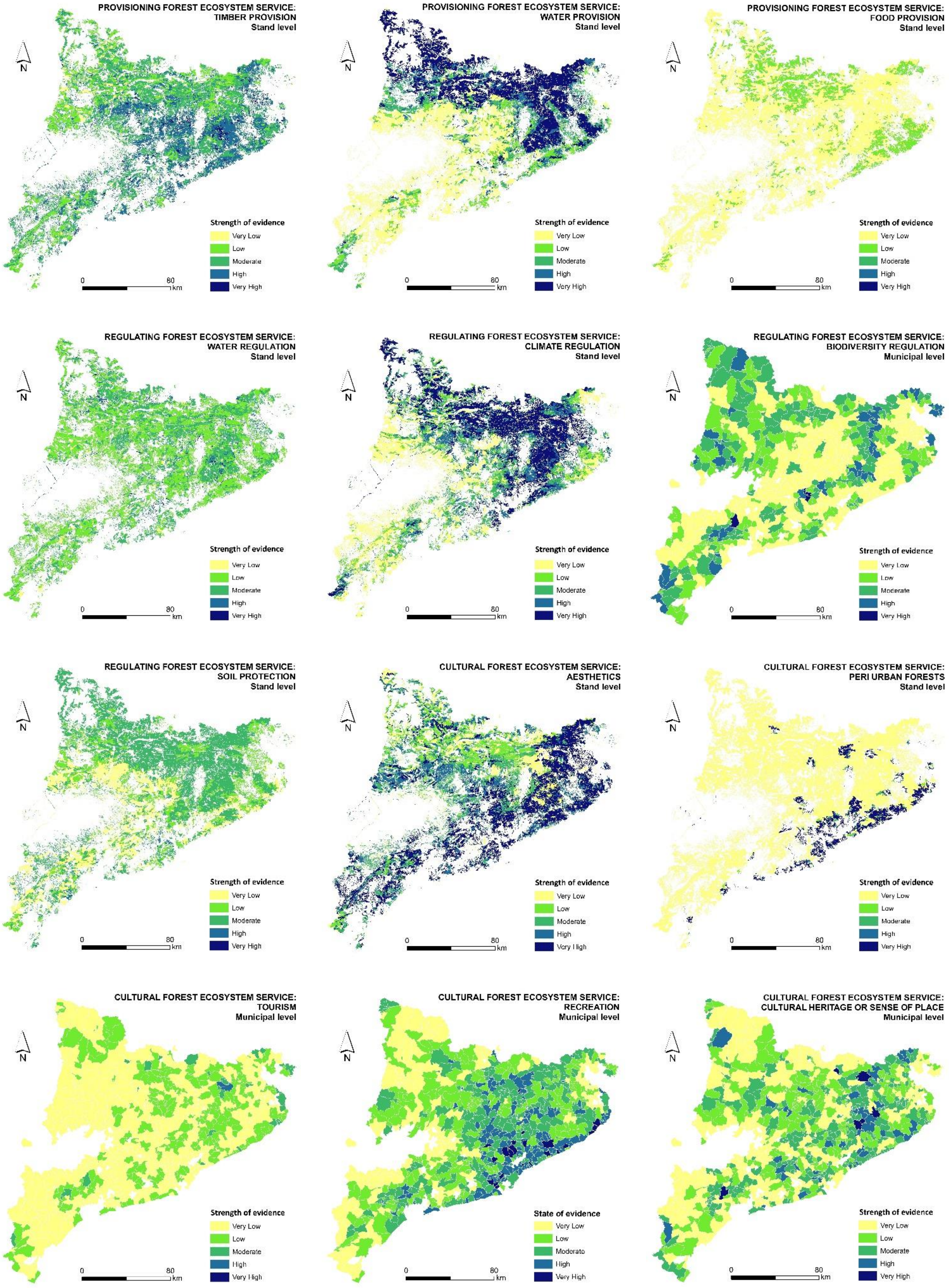


Figure 5. Maps of provision of each of 12 analyzed forest ecosystem services.

3.2. Forest use suitability

Forest use suitability maps are shown on Figure 6. The suitability map for primary use shows the option that obtained the highest score among the five possible FUS alternatives. According to the estimated FES provision values and the weights defined to relate them to specific FUS, the dominant primary use suitability was social (45% of stands), followed by protective (30%) and productive (23%) uses, while conservation-oriented and multifunctional uses were seldom selected as the top use associated with forested lands (Figure 6a). Regarding the spatial allocation of the FUSs selected as the primary option, they show rather clustered patterns. Forests with social use suitability were aggregated in coastal, central, and southern parts of Catalonia, being more dispersed toward the north-east. On the other hand, protective use suitability predominated in the northern part of Catalonia, corresponding to the Pyrenees mountains and the Catalan Transversal Range. Allocation of forests selected for productive use had a more dispersed spatial pattern. Although being more present in the mountainous regions, allocation to productive use was also found in the southern lowlands. Finally, conservation-oriented use stands were mostly located in the south of our study area, with several specific spatially limited locations scattered around the territory, while no forest was selected for multifunctional use as a primary alternative.

When evaluating the secondary use suitability, the distribution of the different FUSs is less clear than the primary ones (Figure 6b). Productive use was selected as the most common secondary suitability option (31%), since it is the dominant secondary option to primary protective use and often considered as the best alternative to primary social FUS (Table 4). Protective use comes close in terms of secondary use representation (27%), being associated with forest whose primary use was productive or social. A forest use that gained representation when its prevalence as second most highly rated was considered, was multifunctional use. Because 38% of forest stands with social use as the primary option have multifunctional as their secondary use, this use reached 21% of forest stands when considered a secondary option. The representation of multifunctional use as important, even if not selected as primary option, was further reflected when considering it as a third ranked option (Figure 6c) In the case of conservation-oriented use, considering the stands where it appeared as the primary or secondary choice, its prevalence was limited to 5% of the stands, and even by adding its presence as a tertiary use, its suitability was by far the least selected.

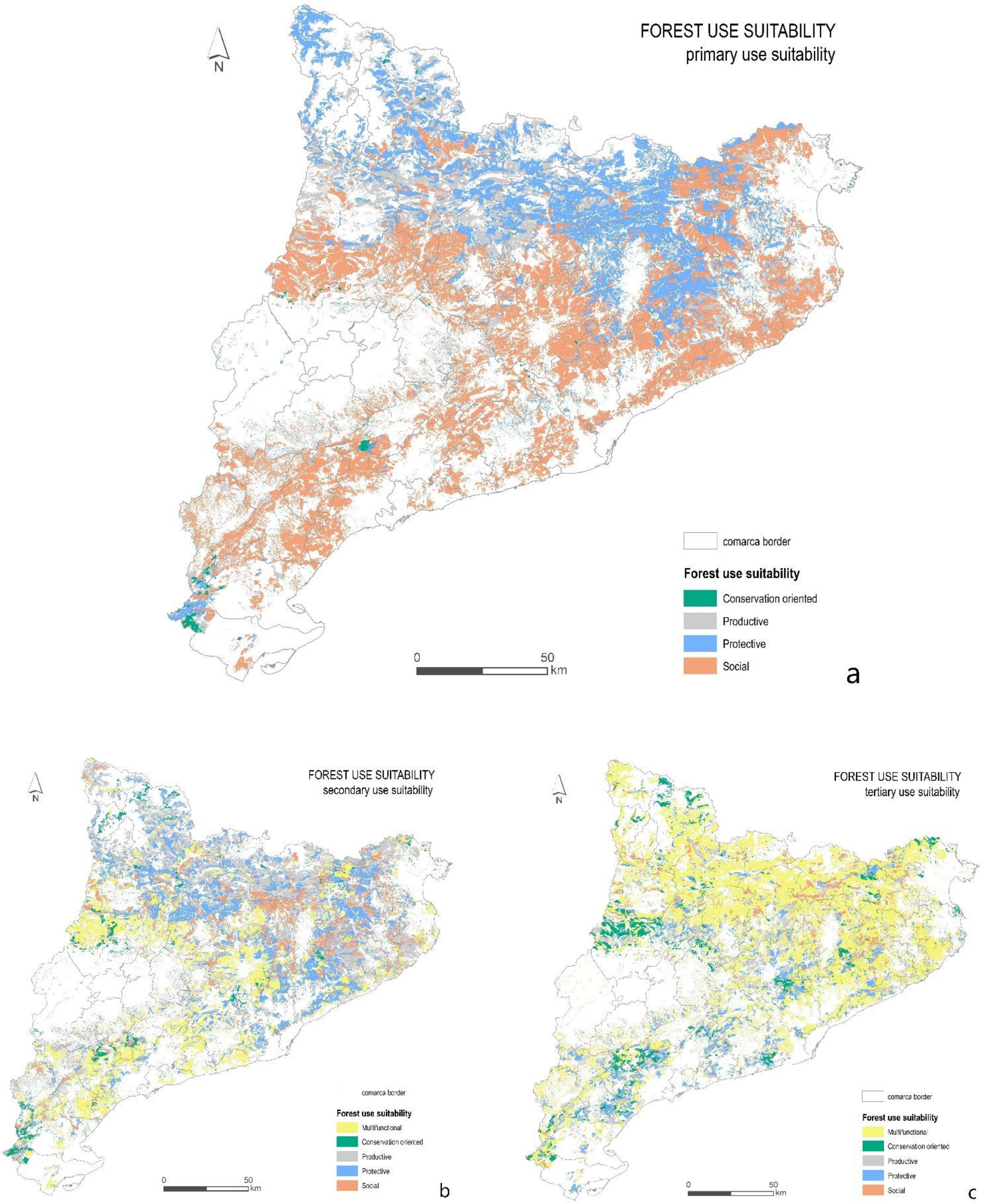


Figure 6. Maps of forest use suitability

The robustness analysis between primary and secondary FUS performance scores is shown on Figure 7. Large differences between the highest and the second highest suitability score can be observed in the coastal region and central Catalonia. Most stands in these areas were assigned to the social alternative as the most suitable one. Small differences in primary and secondary FUS performance scores predominate in the northern (mountainous) regions of Catalonia where productive and protective primary FUS are mostly present.

Table 4. Matrix table of relationship between primary and secondary FUS

		Secondary FUS (% of Primary FUS)				
Primary FUS	% of total plots	Productive	Protective	Con.-oriented	Social	Multifunctional
Productive	23,18	x	**56,36**	6,59	29,28	7,75
Protective	30,66	**60,07**	x	3,84	28,97	7,12
Conservation-oriented	1,01	43,73	18,94	x	31,75	5,57
Social	45,14	26,92	31,2	3,18	x	38,7
Multifunctional	0	x	x	x	x	x

Table 5. Matrix table of relationship between secondary and tertiary FUS

		Tertiary FUS (% of Secondary FUS)				
Secondary FUS	% of total plots	Productive	Protective	Con.-oriented	Social	Multifunctional
Productive	31,02	x	5,71	4,83	7,56	81,89
Protective	27,34	7,17	x	2,38	6,44	84
Conservation-oriented	4,14	15,95	9,34	x	6	68,71
Social	16	13,9	9,96	2,26	x	73,87
Multifunctional	21,51	35,22	42,04	16,22	6,53	x

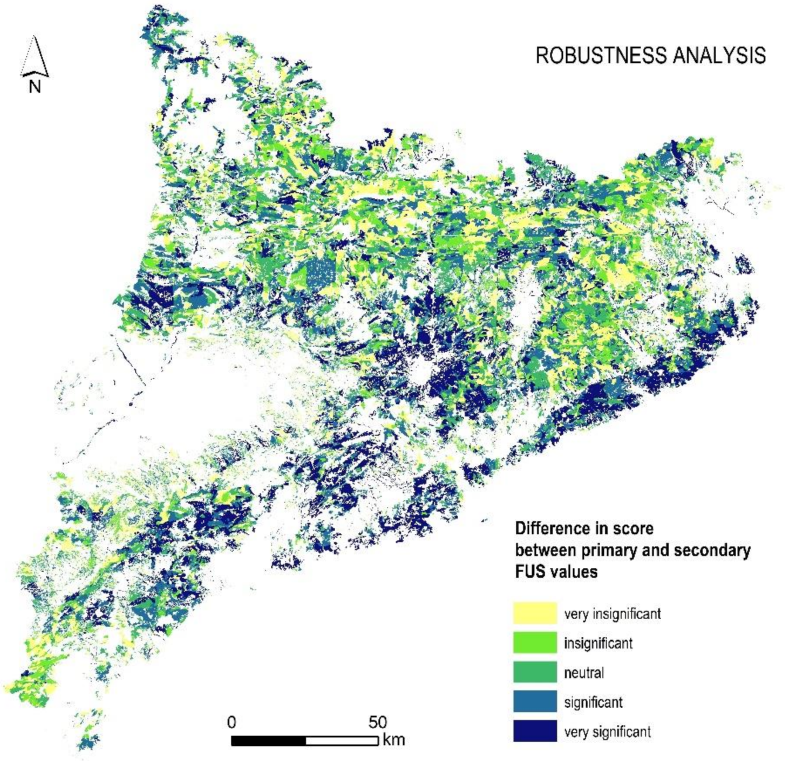


Figure 7. Robustness analysis between primary and secondary FUS score values.

4. Discussion

In this study, we applied a novel methodological approach in FES assessment regarding sustainable management of FES supply. We tried to overcome the problem of methodological and terminological constraints in assessment of ecosystem services, aiming to ease the incorporation of the framework into decision making processes and management strategies [68]. The complexity of the FES concept makes it difficult to implement a comprehensive study, and the challenges are exacerbated by the large number of actors involved, who have diverse interests and objectives, so the effort to improve environmental decision-making processes is significantly hindered [69], [70]. We consider that solution-oriented research arises as an answer to the problem. Namely, FES-related studies tend to evaluate the supply of ecosystem services, analysing the potential of its provision and influence on human well-beings, but without giving possible solutions to enhance desired provision in terms of defining the most appropriate management strategy [10]. We assume that such definition would help to eliminate, or at least minimize, potentially conflicting interest-related choices and thus significantly facilitate decision-making processes. For that purpose, we introduced a new term, forest use suitability, aiming to improve on the strategy for ES-oriented forest management. Although the approach originates in other fields [71], [72] and it hasn't yet been used in forestry, its logical background and applicability align with our goals. The principles of the concept focus on the capability of the physical environment or different ecosystems to support certain land uses [73], [74]. The term land use suitability has been used, among other applications, in agriculture to determine suitable lands for agricultural use [71], land use planning to assess economic competitiveness and sustainable development [75], urban planning for urban development [72], and assessment of rural tourism, aiming to define the most appropriate touristic activities in different rural landscapes [76]. The common goal of all such studies is to encourage decision makers to implement the concept in environmental policies and long-term strategies. Following this model, we wanted to apply the same idea in forest management. We consider that the definition of forest use suitability, based on FES supply, is the first step towards sustainable management of forest ecosystems, maximizing its natural potential and minimizing environmental risk. In this study, we refer to forest use suitability as a static variable because the metrics used to define it represent current supply of FES and, therefore, it cannot be used in long-term forest management. Nevertheless, by implementation of metrics based on temporal simulations that would describe forest characteristics in the future, we could define proper long-term management strategies to be applied. In this study, our goal was to introduce a new methodological approach to sustainable management of FES, leaving the incorporation of dynamic variables and definition of appropriate long-term management strategies for future work. Likewise, because we are not defining specific actions resulting from the FUS assignment, in this study FUS categories are defined only by their descriptive names (productive, protective, conservation-oriented, social and multifunctional), as a guide for potential management directions.

Our results depict the heterogeneous characteristics of Catalan forests. Although the FUS alternatives are easily discernible in the maps, their interpretation is more complex. Firstly, the primary FUS map cannot necessarily be interpreted as the most appropriate alternative without considering secondary, and possibly tertiary, FUS alternatives and the trade-offs between them. We decided to use categorical FUS outcomes, aiming to clearly distinguish FUS alternatives, excluding absolute values on the FUS map representation. Therefore, having in mind the multifunctional character of the forests, it is important to consider differences in scores between alternatives and the patterns among primary-secondary and secondary-tertiary FUS alternatives. The management implications are different when the primary FUS score is significantly higher than the secondary one compared to when these two values are similar. For example, when the difference in FUS scores is large, we assume that it is not necessary to consider so strongly the secondary alternative when choosing an appropriate management strategy. Conversely, when the primary and secondary FUS scores have similar values, the secondary FUS alternative should also be carefully considered in decision making. Through the robustness evaluation, and identifying the level of multifunctionality of forest stands, we thus gain more flexibility to adjust the distribution of FUSs across the region and potentially achieve a more balanced representation, considering all possible alternatives. Moreover, the patterns of FUS alternatives in certain combinations present challenges regarding the selection of management strategies. For example, while the social FUS can easily be combined with other alternatives, FUS combinations such as productive-protective and protective-productive might not share compatible management options. Therefore, the FUS maps should not be interpreted as fixed results, but rather flexible alternatives that can be adjusted accordingly.

Both the results and their interpretation presented here strongly depend on the metrics used to define each ecosystem service. Data availability is limited which hindered the selection of FES indicators [77]. Although the biggest part of the variables represents actual supply, due to lack of data, some FES were represented by their capacity. There is a clear difference between these two types of metrics, although they are commonly used simultaneously in ecosystem services assessments [29], [78]. Some metrics could have clearly been used to define various FES. For example, riparian forests and forest cover could be relevant to both water regulation and water provision, mushroom production and hunting areas for food provision and recreation, time cost for timber provision and recreation etc. Nevertheless, except two metrics, we decided to use each metric only once to maintain comprehensiveness of the study and clearly distinguish among the FESs. Lack of variable standardization and official data for cultural ESs, as well as difficulties to measure intangible benefits, caused problems when choosing cultural metrics [79]. For example, instead of possibly more complete open-source data, we used only homologised hiking trails to define recreational use of the forests. On the other hand, to identify soil protection and biodiversity regulation, we used official national/regional model-based databases instead of research-based equations, due to the lack of available data at the MFE 50 level. In addition, some small temporal mismatches likely exist between the selected metrics because they are originated in different data sources. However, despite certain drawbacks caused by data availability and heterogeneous data sources, all the data were collected from verified and validated datasets and provide accurate information and representation of ESs. Moreover, using and combining data from different sources results in a more complete and comprehensive assessment covering a wider range of FESs [29].

Regarding the methodology, despite its limited use in Europe up to the present time, and the even more limited application in FES assessment, application of the EMDS system helped to resolve challenging spatial problems, combining strategic and tactical planning in detailed spatial resolutions, representing significant advances in FES assessment [80], [81]. The EMDS system satisfied several requirements needed to accomplish our objectives. Firstly, approximation of geospatial reality, including connections, relations, weights, criteria, and results, is done in a transparent and user-friendly way, using a relatively simple model interface that helps to understand topic complexity. These features of EMDS enabled interactive collaboration between scientists and end-users, facilitating its application in participatory planning. Related to that, EMDS facilitates combining expert knowledge and scientific methods, mostly by weighting processes, but also in evaluating criteria and network relations. Moreover, the system deals with lack of data in a simple and effective way. Therefore, FESs represented by only one metric due to lack of data, such as water provision or aesthetics, were not undervalued in comparison to other FES defined by more metrics, such as biodiversity regulation, and vice versa. The methodology and interpretation of results are also efficient thanks to well established terminology.

For this study, a completely new functionality was added in EMDS to join NetWeaver and CDP models to assess FUS alternative selection. Nevertheless, some system weaknesses must be addressed. Firstly, the system does not inherently consider the proximity of features. That is, all the metrics are analysed based on independent spatial data units and differences between neighbouring units are not taken into account. Although it is difficult to avoid this issue in this type of analysis, it is obvious that there are no such borders in FES provision in the natural environment. Consequently, significantly different management actions could be applied in adjacent forested areas. Considering spatial proximity and accounting for it in logic models can avoid this issue, but EMDS leaves it to the GIS analyst supporting an analysis to pre-process the landscape units to attribute each unit (e.g., forest stands in this case) with relevant data about its neighbours. Secondly, the possibility to visualize a data histogram for each metric would have improved the process of assigning evidence thresholds and helping to explain to end-users or decision makers how observed values are converted into evidence values and how the distribution varies depending on assigned thresholds. These charting capabilities were not available at the time of this study, but advanced charting features have been added to EMDS in the latest release of version 8.7.

Lastly, weight assignment is necessary in any decision-making process [82]. In this study, we used the knowledge and experience of the authors to assign weights and parameters, without implementing a participatory planning process. However, all decision processes are inevitably subjective, being influenced by weights in decision models and parameters in logic models for example, and choices about model structures generally. And, of course, because different user groups bring different perspectives, participatory planning is crucial to avoid potential interest-oriented decisions [83], [84]. Nevertheless, because the main objective of this study was to introduce new concepts and methodological features to facilitate assessment of forest ESs, we did not apply a participatory planning process in this first step, leaving it for future work. The EMDS system, and particularly NetWeaver and CDP modelling, facilitates group discussion and effective implementation of knowledge-based evaluation using science-based data. Our longer-term goal, after presenting an innovative approach to assess and manage forest ESs in this study, is to proceed with a detailed evaluation of weights, logic parameters, and model structures through group decision making processes and design of relevant management strategies that account for long term-perspectives.

5. Conclusions

In this study, we successfully implemented an application of the EMDS system, which is an innovative and spatially enabled decision support framework for environmental analysis and planning, to overcome methodological constraints regarding the sustainable management of forest ecosystem services. For that purpose, a new term, forest use suitability, was introduced. We assigned the most suitable alternative of forest use to each stand of Catalan forests, considering characteristics for provision of forest ecosystem services, and aiming to identify the most appropriate long-term management strategies. The assignment of an FUS tended to be spatially clustered, with different FUSs exhibiting different spatial patterns. The assignment of forest use suitability was not necessarily regarded as a fixed outcome, because, after analysing trade-offs among them, alternative choices can be considered. Additional research is required to incorporate participatory planning and dynamic metrics, as well as to define and assign long-term management actions.

Endnotes: [1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Author contributions: All authors participated on the conceptualization of the project. G.K. implemented the data preparation, analysis and wrote an initial draft. K.M.R., P.M. and S.P. supervised the development and implementation of EMDS framework. G.K., J.R.G.O. and J.G.G. analysed the results. All authors participated in in editing process of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Catalan government predoctoral scholarship (AGAUR-FSE 2020 FI_B2 00147), SuFoRun Marie Sklodowska-Curie Research and Innovation Staff Exchange (RISE) Program (Grant agreement No: 691149) and Spanish Ministry of Science and Innovation (PID2020-120355RB-IOO)

Conflict of interest: The authors declare no conflicts of interest in the preparation of this work.

References

[1] A. J. Castro, B. Martín-López, M. García-LLorente, P. A. Aguilera, E. López, and J. Cabello, “Social preferences regarding the delivery of ecosystem services in a semiarid Mediterranean region,” *J Arid Environ*, vol. 75, no. 11, pp. 1201–1208, Nov. 2011, doi: 10.1016/j.jaridenv.2011.05.013.

[2] Millennium Ecosystem Assessment, *Ecosystems and Human Well-being : Current State and Trends , Volume 1*. 2005.

[3] A. P. García-Nieto, M. García-Llorente, I. Iniesta-Arandia, and B. Martín-López, “Mapping forest ecosystem services: From providing units to beneficiaries,” *Ecosyst Serv*, vol. 4, pp. 126–138, 2013, doi: 10.1016/j.ecoser.2013.03.003.

[4] B. Egoh, B. Reyers, M. Rouget, D. M. Richardson, D. C. le Maitre, and A. S. van Jaarsveld, “Mapping ecosystem services for planning and management,” *Agric Ecosyst Environ*, vol. 127, no. 1–2, pp. 135–140, 2008, doi: 10.1016/j.agee.2008.03.013.

[5] C. Anton *et al.*, “Research needs for incorporating the ecosystem service approach into EU biodiversity conservation policy,” *Biodivers Conserv*, vol. 19, no. 10, pp. 2979–2994, 2010, doi: 10.1007/s10531-010-9853-6.

[6] E. M. Bennett *et al.*, “Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability,” *Curr Opin Environ Sustain*, vol. 14, pp. 76–85, 2015, doi: 10.1016/j.cosust.2015.03.007.

[7] A. S. van Jaarsveld *et al.*, “Measuring conditions and trends in ecosystem services at multiple scales: The Southern African Millennium Ecosystem Assessment (SAfMA) experience,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 360, no. 1454, pp. 425–441, 2005, doi: 10.1098/rstb.2004.1594.

[8] K. Petz and A. P. E. van Oudenhoven, “Modelling land management effect on ecosystem functions and services: A study in the Netherlands,” *Int J Biodivers Sci Ecosyst Serv Manag*, vol. 8, no. 1–2, pp. 135–155, 2012, doi: 10.1080/21513732.2011.642409.

[9] P. Ericksen, J. de Leeuw, M. Said, S. Silvestri, and L. Zaibet, “Mapping ecosystem services in the Ewaso Ng’iro catchment,” *Int J Biodivers Sci Ecosyst Serv Manag*, vol. 8, no. 1–2, pp. 122–134, 2012, doi: 10.1080/21513732.2011.651487.

[10] G. C. Daily *et al.*, “Ecosystem services in decision making: Time to deliver,” *Front Ecol Environ*, vol. 7, no. 1, pp. 21–28, 2009, doi: 10.1890/080025.

[11] J. P. Schägner, L. Brander, J. Maes, and V. Hartje, “Mapping ecosystem services’ values: Current practice and future prospects,” *Ecosyst Serv*, vol. 4, pp. 33–46, 2013, doi: 10.1016/j.ecoser.2013.02.003.

[12] H. Tallis and S. Polasky, “Mapping and valuing ecosystem services as an approach for conservation and natural-resource management,” *Ann N Y Acad Sci*, vol. 1162, pp. 265–283, 2009, doi: 10.1111/j.1749-6632.2009.04152.x.

[13] J. Niemelä *et al.*, “Using the ecosystem services approach for better planning and conservation of urban green spaces: A Finland case study,” *Biodivers Conserv*, vol. 19, no. 11, pp. 3225–3243, 2010, doi: 10.1007/s10531-010-9888-8.

[14] M. J. Metzger, R. Leemans, and D. Schröter, “A multidisciplinary multi-scale framework for assessing vulnerabilities to global change,” *International Journal of Applied Earth Observation and Geoinformation*, vol. 7, no. 4, pp. 253–267, 2005, doi: 10.1016/j.jag.2005.06.011.

[15] A. D. Guerry *et al.*, “Modeling benefits from nature: Using ecosystem services to inform coastal and marine spatial planning,” *Int J Biodivers Sci Ecosyst Serv Manag*, vol. 8, no. 1–2, pp. 107–121, 2012, doi: 10.1080/21513732.2011.647835.

[16] I. Bouwma *et al.*, “Adoption of the ecosystem services concept in EU policies,” *Ecosyst Serv*, vol. 29, no. March 2017, pp. 213–222, 2018, doi: 10.1016/j.ecoser.2017.02.014.

[17] M. Berbés-Blázquez, J. A. González, and U. Pascual, “Towards an ecosystem services approach that addresses social power relations,” *Curr Opin Environ Sustain*, vol. 19, pp. 134–143, 2016, doi: 10.1016/j.cosust.2016.02.003.

[18] G. W. Luck *et al.*, “Quantifying the contribution of organisms to the provision of ecosystem services,” *Bioscience*, vol. 59, no. 3, pp. 223–235, 2009, doi: 10.1525/bio.2009.59.3.7.

[19] R. Harrington *et al.*, “Ecosystem services and biodiversity conservation: Concepts and a glossary,” *Biodivers Conserv*, vol. 19, no. 10, pp. 2773–2790, 2010, doi: 10.1007/s10531-010-9834-9.

[20] K. J. Bagstad, F. Villa, D. Batker, J. Harrison-Cox, B. Voigt, and G. W. Johnson, “From theoretical to actual ecosystem services: Mapping beneficiaries and spatial flows in ecosystem service assessments,” *Ecology and Society*, vol. 19, no. 2, 2014, doi: 10.5751/ES-06523-190264.

[21] N. D. Crossman, B. Burkhard, and S. Nedkov, “Quantifying and mapping ecosystem services,” *Int J Biodivers Sci Ecosyst Serv Manag*, vol. 8, no. 1–2, pp. 1–4, 2012, doi: 10.1080/21513732.2012.695229.

[22] S. Wolff, C. J. E. Schulp, and P. H. Verburg, “Mapping ecosystem services demand: A review of current research and future perspectives,” *Ecol Indic*, vol. 55, pp. 159–171, 2015, doi: 10.1016/j.ecolind.2015.03.016.

[23] A. Troy and M. A. Wilson, “Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer,” *Ecological Economics*, vol. 60, no. 2, pp. 435–449, 2006, doi: 10.1016/j.ecolecon.2006.04.007.

[24] S. Wang, B. Fu, Y. Wei, and C. Lyle, “Ecosystem services management: An integrated approach,” *Curr Opin Environ Sustain*, vol. 5, no. 1, pp. 11–15, 2013, doi: 10.1016/j.cosust.2013.01.003.

[25] F. Eigenbrod *et al.*, “The impact of proxy-based methods on mapping the distribution of ecosystem services,” *Journal of Applied Ecology*, vol. 47, no. 2, pp. 377–385, 2010, doi: 10.1111/j.1365-2664.2010.01777.x.

[26] Y. Hou, B. Burkhard, and F. Müller, “Uncertainties in landscape analysis and ecosystem service assessment,” *J Environ Manage*, vol. 127, pp. S117–S131, 2013, doi: 10.1016/j.jenvman.2012.12.002.

[27] K. McDonough, S. Hutchinson, T. Moore, and J. M. S. Hutchinson, “Analysis of publication trends in ecosystem services research,” *Ecosyst Serv*, vol. 25, pp. 82–88, 2017, doi: 10.1016/j.ecoser.2017.03.022.

[28] T. Simončič and A. Bončina, “Are forest functions a useful tool for multi-objective forest management planning? Experiences from Slovenia,” *Croatian Journal of Forest Engineering*, vol. 36, no. 2, pp. 293–305, 2015.

[29] J. v. Roces-Díaz *et al.*, “Assessing the distribution of forest ecosystem services in a highly populated Mediterranean region,” *Ecol Indic*, vol. 93, no. October 2016, pp. 986–997, 2018, doi: 10.1016/j.ecolind.2018.05.076.

[30] J. A. Sayer, J. K. Vanclay, and N. Byron, “Technologies for sustainable forest management: Challenges for the 21st Century,” *Commonwealth Forestry Review*, vol. 76, no. 3, pp. 162–170, 1997.

[31] S. Wang and B. Fu, “Trade-offs between forest ecosystem services,” *For Policy Econ*, vol. 26, pp. 145–146, 2013, doi: 10.1016/j.forpol.2012.07.014.

[32] B. Martín-López, E. Gómez-Baggethun, M. García-Llorente, and C. Montes, “Trade-offs across value-domains in ecosystem services assessment,” *Ecol Indic*, vol. 37, no. PART A, pp. 220–228, 2014, doi: 10.1016/j.ecolind.2013.03.003.

[33] J. Ananda and G. Herath, “A critical review of multi-criteria decision making methods with special reference to forest management and planning,” *Ecological Economics*, vol. 68, no. 10, pp. 2535–2548, 2009, doi: 10.1016/j.ecolecon.2009.05.010.

[34] L. Diaz-Balteiro and C. Romero, “Making forestry decisions with multiple criteria: A review and an assessment,” *For Ecol Manage*, vol. 255, no. 8–9, pp. 3222–3241, 2008, doi: 10.1016/j.foreco.2008.01.038.

[35] M. Selkimäki, J. R. González-Olabarria, A. Trasobares, and T. Pukkala, “Trade-offs between economic profitability, erosion risk mitigation and biodiversity in the management of uneven-aged Abies alba Mill. stands,” *Ann For Sci*, vol. 77, no. 1, 2020, doi: 10.1007/s13595-019-0914-z.

[36] P. Reed and G. Brown, “Values suitability analysis: A methodology for identifying and integrating public perceptions of ecosystem values in forest planning,” *Journal of Environmental Planning and Management*, vol. 46, no. 5, pp. 643–658, 2003, doi: 10.1080/0964056032000138418.

[37] S. Maestre-Andrés, L. Calvet-Mir, and J. C. J. M. van den Bergh, “Sociocultural valuation of ecosystem services to improve protected area management: a multi-method approach applied to Catalonia, Spain,” *Reg Environ Change*, vol. 16, no. 3, pp. 717–731, 2016, doi: 10.1007/s10113-015-0784-3.

[38] I. Bidegain, C. Cerda, E. Catalán, A. Tironi, and C. López-Santiago, “Social preferences for ecosystem services in a biodiversity hotspot in South America,” *PLoS One*, vol. 14, no. 4, 2019, doi: 10.1371/journal.pone.0215715.

[39] M. J. Martnez-Harms and P. Balvanera, “Methods for mapping ecosystem service supply: A review,” *Int J Biodivers Sci Ecosyst Serv Manag*, vol. 8, no. 1–2, pp. 17–25, 2012, doi: 10.1080/21513732.2012.663792.

[40] K. J. Bagstad, D. J. Semmens, S. Waage, and R. Winthrop, “A comparative assessment of decision-support tools for ecosystem services quantification and valuation,” *Ecosyst Serv*, vol. 5, pp. 27–39, 2013, doi: 10.1016/j.ecoser.2013.07.004.

[41] K. M. Reynolds and P. F. Hessburg, “An Overview of the Ecosystem Management Decision-Support System,” *Environmental Science and Engineering*, pp. 3–22, 2014, doi: 10.1007/978-3-642-32000-2_1.

[42] K. Reynolds, S. Paplanus, B. Miller, and P. Murphy, “Design features behind success of the ecosystem management decision support system and future development,” *Forests*, vol. 6, no. 1, pp. 27–46, 2015, doi: 10.3390/f6010027.

[43] Centre de Recerca Ecològica i Aplicacions Forestals., “Mapa de Cobertes del Sòl de Catalunya v4 (Land Cover Map of Catalonia v4).” CREAF, Ministry of Agriculture, Livestock, Fisheries and Food, Ministry of Home A airs and Ministry of Territory and Sustainibility, Generalitat of Catalonia, Barcelona, Spain, 2009.

[44] L. Coll, J. R. González-Olabarria, B. Mola-Yudego, T. Pukkala, and C. Messier, “Predicting understory maximum shrubs cover using altitude and overstory basal area in different Mediterranean forests,” *Eur J For Res*, vol. 130, no. 1, pp. 55–65, 2011, doi: 10.1007/s10342-010-0395-y.

[45] J. v. Roces-Díaz *et al.*, "The spatial level of analysis affects the patterns of forest ecosystem services supply and their relationships," *Science of the Total Environment*, vol. 626, pp. 1270–1283, 2018, doi: 10.1016/j.scitotenv.2018.01.150.

[46] G. of C. Catalan Statistics Institute, "IDESCAT (Official statistics of Catalonia)," 2015. https://www.idescat.cat/?lang=es (accessed Mar. 12, 2021).

[47] G. Krsnik *et al.*, "Regional level data server for fire hazard evaluation and fuel treatments planning," *Remote Sens (Basel)*, vol. 12, no. 24, pp. 1–17, 2020, doi: 10.3390/rs12244124.

[48] MITECO, "The Spanish Forest Map 1:50000," 2006. https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/mfe50.aspx (accessed Mar. 02, 2021).

[49] Cartographic and Geological Institut of and Catalonia, "Map of Biophysical Variables of Catalonia." Ministry of Agriculture, Livestock, Fisheries and Food and Ministry of Territory and Sustainibility, Generalitat of Catalonia, Barcelona, Spain, 2016.

[50] "Potential forest productivity map," *Ministry for the Ecological Transition and the Demographic Challenge*, 2000. https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/productividad_potencial.aspx (accessed Apr. 15, 2021).

[51] "Plans for Forest Recource Management (PORF)." Ministry of Agriculture, Livestock, Fisheries and Food, Generalitat of Catalonia, 2003.

[52] Generalitat of Catalonia, "Forestal Catalana." http://forestalcatalana.gencat.cat/es (accessed Mar. 09, 2021).

[53] J. A. Bonet, J. R. González-olabarria, and J. M. D. E. Aragón, "Mushroom Production as an Alternative for Rural Development in a Forested Mountainous Area," vol. 11, pp. 535–543, 2014, doi: 0.1007/s11629-013-2877-0.

[54] M. Legal, "ESCORRENTÍA TOTAL ANUAL Página 1 de 6," pp. 2–7, 2005.

[55] G. of C. Department of Territory and Sustainability, "System of Natural Protected Areas." http://mediambient.gencat.cat/ca/05_ambits_dactuacio/patrimoni_natural/senp_catalunya/ (accessed Mar. 11, 2021).

[56] G. of C. Department of Territory and Sustainability, "Special Protection Natural Areas (ENPE)." http://mediambient.gencat.cat/ca/05_ambits_dactuacio/patrimoni_natural/senp_catalunya/el_sistema/els_espais_naturals_de_proteccio_especial/ (accessed Mar. 11, 2021).

[57] G. of C. Department of Territory and Sustainability, "Natural Habitats of High Priority." http://mediambient.gencat.cat/ca/05_ambits_dactuacio/patrimoni_natural/sistemes_dinformacio/habitats/habitats_terrestres/habitats-de-catalunya/hic/ (accessed Mar. 11, 2021).

[58] G. of C. Department of Territory and Sustainability, "Areas of floristic or faunistic interest." https://territori.gencat.cat/ca/01_departament/12_cartografia_i_toponimia/bases_cartogr

afiques/medi_ambient_i_sostenibilitat/bases_miramon/territori/arees-dinteres-faunistic-i-floristic/ (accessed Mar. 11, 2021).

[59] M. Ministry of Agriculture, Fisheries and Food, "National Soil Erosion Inventory." https://www.mapa.gob.es/es/desarrollo-rural/temas/politica-forestal/inventario-cartografia/inventario-nacional-erosion-suelos/default.aspx (accessed Mar. 11, 2021).

[60] M. Ministry of Agriculture, Fisheries and Food, "Desertification in Spain." https://www.mapa.gob.es/es/desarrollo-rural/temas/politica-forestal/desertificacion-restauracion-forestal/lucha-contra-la-desertificacion/lch_espana.aspx (accessed Mar. 15, 2021).

[61] F. and F. G. of C. Department of Agriculture, Stocking, "Hunting in Catalonia." http://agricultura.gencat.cat/ca/ambits/medi-natural/casa/ (accessed Mar. 12, 2021).

[62] "Homologated hiking trails network," *Catalan Excursionist Federation*. https://senders.feec.cat/ (accessed Mar. 12, 2021).

[63] Generalitat of Catalonia, "Geoportal of Cultural Heritage of Catalonia." https://sig.gencat.cat/portalsigcultura.html (accessed Mar. 12, 2021).

[64] G. of C. Department of Territory and Sustainability, "Monumental trees of Catalonia." http://mediambient.gencat.cat/ca/05_ambits_dactuacio/patrimoni_natural/arbres-monumentals/ (accessed Mar. 12, 2021).

[65] E. Blasco, J. R. González-Olabarria, P. Rodriguéz-Veiga, T. Pukkala, O. Kolehmainen, and M. Palahí, "Predicting scenic beauty of forest stands in Catalonia (North-east Spain)," *J For Res (Harbin)*, vol. 20, no. 1, pp. 73–78, 2009, doi: 10.1007/s11676-009-0013-3.

[66] B. Miller and M. Saunders, "NetWeaver Reference Manual," no. September 2002, p. 127, 2006.

[67] P. Murphy and J. Solan, "Infoharvest." http://www.infoharvest.com/ihroot/index.asp (accessed Feb. 21, 2023).

[68] B. Fisher, R. K. Turner, and P. Morling, "Defining and classifying ecosystem services for decision making," *Ecological Economics*, vol. 68, no. 3, pp. 643–653, 2009, doi: 10.1016/j.ecolecon.2008.09.014.

[69] J. Hauck, C. Görg, R. Varjopuro, O. Ratamäki, and K. Jax, "Benefits and limitations of the ecosystem services concept in environmental policy and decision making: Some stakeholder perspectives," *Environ Sci Policy*, vol. 25, pp. 13–21, 2013, doi: 10.1016/j.envsci.2012.08.001.

[70] Y. Laurans, A. Rankovic, R. Billé, R. Pirard, and L. Mermet, "Use of ecosystem services economic valuation for decision making: Questioning a literature blindspot," *J Environ Manage*, vol. 119, pp. 208–219, 2013, doi: 10.1016/j.jenvman.2013.01.008.

[71] H. Akinci, A. Y. Özalp, and B. Turgut, "Agricultural land use suitability analysis using GIS and AHP technique," *Comput Electron Agric*, vol. 97, no. November 2017, pp. 71–82, 2013, doi: 10.1016/j.compag.2013.07.006.

[72] R. Liu, K. Zhang, Z. Zhang, and A. G. L. Borthwick, "Land-use suitability analysis for urban development in Beijing," *J Environ Manage*, vol. 145, no. December, pp. 170–179, 2014, doi: 10.1016/j.jenvman.2014.06.020.

[73] R. W. McDowell *et al.*, “The land use suitability concept: Introduction and an application of the concept to inform sustainable productivity within environmental constraints,” *Ecol Indic*, vol. 91, no. December 2017, pp. 212–219, 2018, doi: 10.1016/j.ecolind.2018.03.067.

[74] J. Malczewski, “GIS-based land-use suitability analysis: A critical overview,” *Prog Plann*, vol. 62, no. 1, pp. 3–65, 2004, doi: 10.1016/j.progress.2003.09.002.

[75] F. Joerin, M. Thérialult, and A. Musy, “Using GIS and outranking multicriteia analysis for land-use suitability assesment,” *International Journal of Geographical Information Science*, vol. 15, no. 2, pp. 153–174, 2001, doi: 10.1080/13658810051030487.

[76] Ç. Kaptan Ayhan, T. Cengiz Taşlı, F. Özkök, and H. Tatlı, “Land use suitability analysis of rural tourism activities: Yenice, Turkey,” *Tour Manag*, vol. 76, no. July 2019, 2020, doi: 10.1016/j.tourman.2019.07.003.

[77] J. Maes *et al.*, “Mapping ecosystem services for policy support and decision making in the European Union,” *Ecosyst Serv*, vol. 1, no. 1, pp. 31–39, 2012, doi: 10.1016/j.ecoser.2012.06.004.

[78] L. Yahdjian, O. E. Sala, and K. M. Havstad, “Rangeland ecosystem services: Shifting focus from supply to reconciling supply and demand,” *Front Ecol Environ*, vol. 13, no. 1, pp. 44–51, 2015, doi: 10.1890/140156.

[79] D. Satz *et al.*, “The challenges of incorporating cultural ecosystem services into environmental assessment,” *Ambio*, vol. 42, no. 6, pp. 675–684, 2013, doi: 10.1007/s13280-013-0386-6.

[80] M. Marques, K. M. Reynolds, S. Marques, M. Marto, S. Paplanus, and J. G. Borges, “A participatory and spatial multicriteria decision approach to prioritize the allocation of ecosystem services to management units,” *Land (Basel)*, vol. 10, no. 7, 2021, doi: 10.3390/land10070747.

[81] N. A. Povak *et al.*, “A decision support tool for the conservation of tropical forest and nearshore environments on Babeldaob Island, Palau,” *For Ecol Manage*, vol. 476, no. November, p. 118480, 2020, doi: 10.1016/j.foreco.2020.118480.

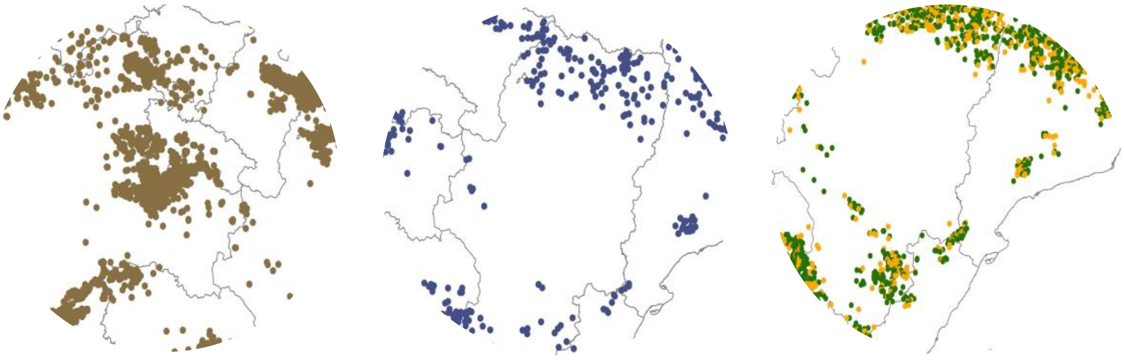
[82] M. Acosta and S. Corral, “Multicriteria decision analysis and participatory decision support systems in forest management,” *Forests*, vol. 8, no. 4, pp. 215–216, 2017, doi: 10.3390/f8040116.

[83] S. Menzel, E. M. Nordström, M. Buchecker, A. Marques, H. Saarikoski, and A. Kangas, “Decision support systems in forest management: Requirements from a participatory planning perspective,” *Eur J For Res*, vol. 131, no. 5, pp. 1367–1379, 2012, doi: 10.1007/s10342-012-0604-y.

[84] H. Goosen, R. Janssen, and J. E. Vermaat, “Decision support for participatory wetland decision-making,” *Ecol Eng*, vol. 30, no. 2 SPEC. ISS., pp. 187–199, 2007, doi: 10.1016/j.ecoleng.2006.11.004.

Article 2

ASSESSING THE DYNAMICS OF FOREST ECOSYSTEM SERVICES TO DEFINE FOREST USE SUITABILITY



Submitted in *Frontiers in Forests and Global Change* (2023)
Krsnik G.; Reynolds, M.,K.; Aquilué, N.; Mola-Yudego, B.; Pecurul, M.;
Garcia-Gonzalo, J.; González Olabarria, J.R.

Assessing the Dynamics of Forest Ecosystem Services to Define Forest Use Suitability

Abstract: Adopting a multi-criteria approach in forest management is essential for maintaining or improving specific benefits while minimizing negative environmental impacts. Determining the appropriate long-term management approach for a forest requires considering heterogeneous environmental and social factors, as well as over-time changes in forest characteristics. Conducting a strategic assessment of forest use suitability (FUS) (namely productive, protective, conservation-oriented, social and multifunctional) at the national level, taking into account the dynamins in provision of forest ecosystem services and the trade-offs between FUS alternatives, can guide the development of customized management strategies and policies that align with the specific requirements and conditions of the forest. In this study, we evaluate the supply and over-time changes of diverse ecosystem services of *Pinus sylversitris* stands in Spain and utilize a decision model to determine the most suitable forest use alternative (FUS) that maximizes the provision of these services. To achieve this, we utilize the last version of Ecosystem Management Decision Support (EMDS) system, a spatially focused decision support tool capable of generating precise results for multi-criteria assessment. We simulated forest growth over a 100-year period and evaluated changes in forest ecosystem services over the studied period. According to the results, the dominant FUS is protective. Nevertheless, for the final assignment of FUS, an exhaustive trade-off analysis between all alternatives is required, resulting in flexible outcomes and increased multifunctionality.

Keywords: long-term forest management strategies, spatial environmental planning, spatial modelling, multi-criteria analysis, geographical information technologies in forestry

1. Introduction

Decision making on forest management is a challenging process that involves ecological, socioeconomical and political processes, requiring a large number of potentially conflicting factors that need to be considered [1]. Inadequate management practices and their impacts can significantly influence the provision of ecosystem services (ESS) and lead to environmental degradation, emphasizing the importance of defining environmental and sustainability goals in strategic planning [2] [3]. Forests typically provide numerous ESS, whose yield depends on forests' intrinsic characteristics [4], but often, due to trade-offs between services they provide, they are not able to deliver high levels of multiple ecosystem services in a sustainable way [5]. Therefore, efficient management strategies that focus on maximizing specific uses while minimizing the negative impacts on the provision of other ESS, should be at the base of sustainable planning [6]. In this context, employing multi-criteria approaches can help navigate the complexity of environmental decision-making processes, facilitating the identification of appropriate management options, even though they may not explicitly consider uncertainties or future changes in the environment [7] [8]. Forest characteristics are constantly changing, causing fluctuations in ESS provision [9], [10], and because of that, definition of management strategies based solely on current characteristics of forest features may imply negative impact on the development of future ecosystems [10].

Sustainable mid-term and long-term forest management, aiming at ensuring adequate provision of multiple forest ecosystem services (ESS), requires projections of forest dynamics [11] [12]. Understanding both spatial and temporal variations of forest changes provides a long-term perspective of vegetation patterns and improves decision making [13] [14]. Moreover, the complexity of decision-making processes regarding sustainable planning strategies often encompasses competition between diverse interest-related uses and may result in ineffective and destructive long-term decisions [15][16]. Therefore, models that can forecast forest dynamics and that highlight aggregate features of forest yield, including forest ecosystem services supply, can facilitate choosing an appropriate long-term management strategy [17][18]. Identifying the uses to which a forest is best suited, based on the ESS it will provide, and reducing the number of potential management alternatives to be considered in a planning exercise, help to identify an adequate management strategy, discard non-efficient management options, and improve spatial planning [18].

Mathematical and simulation models have proven to be useful tools in the quantitative evaluation of ecosystem shifts, employing various extrapolation methods to assess forest dynamics [19] [20]. These models provide a means to approximate future forest characteristics and the associated supply of ESS. Together with the mapping and quantification of ESS provision, forest dynamics simulations are recommended as the first step towards a comprehensive long-term management plan [21] [22].

Spatial modelling of the ESS indicators is a challenging task due to the heterogeneous nature of factors influencing their provision and the diverse range of benefits they encompass [23] [24]. While assignment of an appropriate management strategy directly depends on spatial modelling processes, the comprehensiveness and veracity of the models are crucial for decision making [25]. Incorporation of dynamic metrics (variables that are related to the intrinsic characteristics of the forest that can be simulated over time) significantly limits the selection of possible indicators to approximate environmental processes in the forest, but gives a broader overview of future characteristics, and enables more accurate long-term planning [26]. Additionally, terminological constraints have hindered the development of such a framework due to the lack of consensus in ESS-related studies [27]. For this reason, we assert it is necessary to assess the provision of forest ESS, considering forest dynamics and changes in ESS supply, evaluate trade-offs among ESS that each spatial component provides at different stages of forest characteristics simulation, and assign an appropriate mid-term or long-term use through multi-criteria-based decision making. This concept aims to identify the most applicable management alternatives considering present and future forest unit's socio-economic and biogeophysical reality. In other words, the knowledge of current and future ESS, and their dynamics, supported by each stand, is used to identify the most suitable forest use for each stand. Each forest use suitability (FUS) (namely productive, protective, conservation-oriented, social, and multifunctional) is associated to the management action that should be adopted over time. In those terms, productive FUS supports maximization of economic profitability of the forest and related ESS. Protective FUS is associated with long-term goals that mitigate harmful natural or human-induced processes. Conservation-oriented FUS highlights the habitat value of the forest. Social FUS aims to increase non-material values that contribute to human physical and psychological health. And multifunctional FUS combines two or more of the previous vocations. Despite an increasing number of studies that have been done on ESS assessment [24], there is only limited research on ESS dynamics and their relationship to long-term forest management decision making.

Decision-making regarding forest management and forest ESS has had heterogeneous methodological approaches [28] [29]. In this study, we apply the Ecosystem Management Decision Support (EMDS) system, a decision support framework for environmental spatial analysis and planning, to a selection of Spanish forest lands [30] [31]. EMDS can handle the complexity of multiobjective strategic decision making regarding the allocation of FUS in Spain, and has potential global application.

2. Material and methods

2.1. Study area

The study area encompasses all Spanish forest stands with presence, dominant or not, of Pinus sylvestris (Figure 1). We used the 3rd Spanish National Forest Inventory (NFI3) to select a total of 10.033 plots [32]. Regarding wood volume, Pinus sylvestris represents 14% of total wood volume in Spain, and with approximately 153 million. m3, is the second most abundant species in the country. As the dominant species, it covers an area of approximately 1 million ha. Spanish forests are predominantly privately-owned (approx. 70%) and exhibit high spatial fragmentation, which significantly hinders effective long-term forest management planning [33] [34].

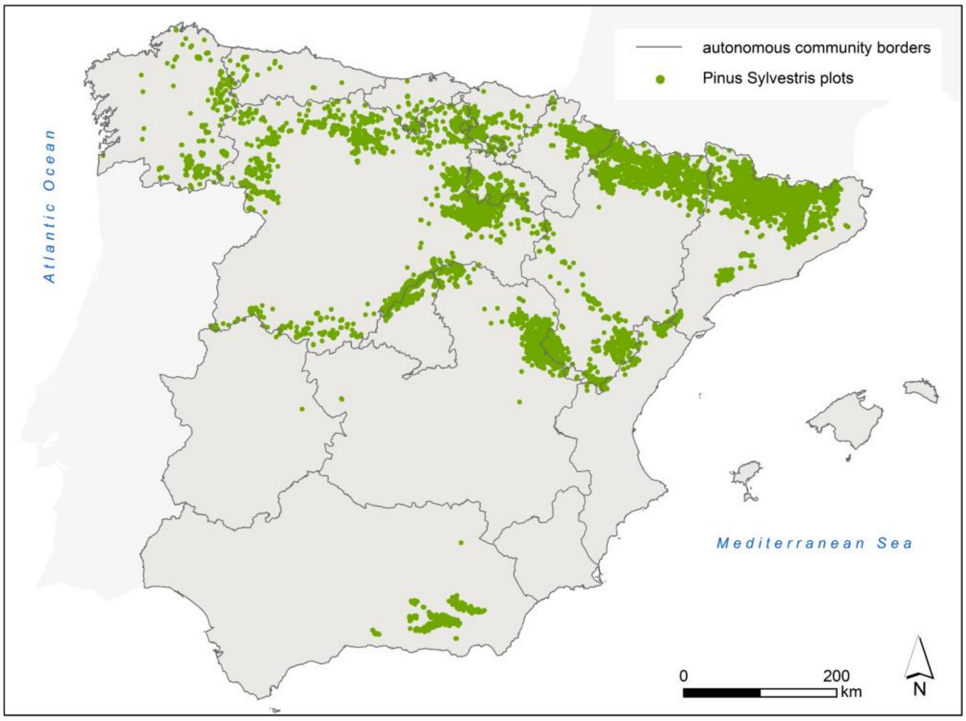


Figure 1. Study area and forest plots with presence of *Pinus sylvestris.*

2.2. Conceptual design

The main objective of the study is to define, and spatially assign, FUS for each plot of the Spanish forests with the presence of Pinus sylvestris. The assignment is based on temporal simulations of forest characteristics and considers ecosystem services dynamics to define the most suitable forest use. To meet this goal, the study was organized in four steps:

1. *Define indicators of forest ESS in terms of sets of metrics.* In this step, 13 metrics were identified after an initial analysis of data availability. They were used as input in forest use suitability assessment. Dynamic metrics were simulated over time in the next step, while static metrics were used directly in the FUS analysis.
2. *Simulate forest dynamics and changes in ESS provision.* Forest dynamics of 10.033 inventory plots were simulated over a 100-year period with a forest management and dynamics modelling framework based on empirical individual tree growth, mortality, and ingrowth models. The model outputs were related to 9 dynamic metrics, that were directly related to the biophysical characteristics of a forest plot.
3. *Assess forest use suitability (FUS) for each plot.* In this step, a multi-criteria decision support tool was used to obtain a suitability score for each of the five FUS alternatives considered: productive, protective, conservation-oriented, social, or multifunctional. Estimated current and future provisioning of ESS was used as input in the FUS assessment, as well as the results of a participatory analysis to obtain the relative importance of forest ESS to identify FUS.
4. *Analyse of robustness among the FUS alternatives*. The FUS performance scores obtained in the preceding step were arranged in order from highest to lowest, producing a final prioritized list of FUS options (primary, secondary FUS, and so on). Subsequently, the differences between these scores were examined with the goal of determining the most suitable FUS for each individual stand.

A detailed description of each step follows.

2.2.1. Definition of forest ESS indicators

The first step in the FUS analysis consists of a definition of forest ESS provision. ESS approximate existing biogeophysical processes and social concerns in the forest environment. They are defined by datasets of as metrics that can be either dynamic or static. Dynamic metrics are those that can be derived from a forest's biophysical variables (such as height, biomass, diameter, etc.) and whose characteristics can be simulated over time. Static metrics are not related to such variables, and their temporal dynamics cannot be extrapolated. Selection of the metrics was done based on data availability, trying to define as many dynamic metrics as possible. In total, 13 metrics were selected to define 13 forest ESS, 9 of which were dynamic (Table 1). Forest ESS definition followed the Millennium Ecosystem Assessment (MEA) [35]. Therefore, a forest ESS indicator is a composite score for a stand in which a high value indicates likely provision of the ESS, and low scores indicate that the ESS are likely absent. All data were geoprocessed using ArcMap 10.8 to derive suitable metrics for subsequent analysis.

Table 1. Selected 13 metrics to describe 13 forest ecosystem services.

Forest ESS and *ESS groups*	**Forest ESS metrics**	**Metrics description**	**Metrics type**	**Unit**
PROVISIONING SERVICES				
Timber provision (stock)	Wood biomass	Mean value of timber volume, 50/100 years	Dynamic	m^3/ha
Timber provision (growth)	Productivity	Volume difference, year 2100-2000 / year 2050-2000	Dynamic	m^3/ha
Water provision	Water bodies	Distance to waterflows and lakes	Static	metres
REGULATING SERVICES				
Climate regulation (change)	CO_2 change	Difference in stock, year 2100-2000 / year 2050-2000	Dynamic	t/ha
Climate regulation (stock)	CO_2 storage	Mean storage value, 50/100 years	Dynamic	t/ha
Biodiversity regulation	Diversity index	Shannon index; mean value, 50/100 years	Dynamic	Index
Habitat protection	Protection	Natura 2000 network	Static	Categorical (0/1)
Soil protection	Erosion probability	Mean value of erosion probability index, 50/100 years	Dynamic	-
Protection from disturbances	Fire	Proportion of dead trees in case of fire; mean value, 50/100 years	Dynamic	-
CULTURAL SERVICES				
Aesthetics	Scenic beauty	Scenic beauty index; mean value, 50/100 years	Dynamic	-
Natural heritage	Big trees	>70 cm in diameter; mean value, 50/100 years	Dynamic	Number of trees/ha
Peri-urban forests	Accessibility	Distance to the cities >20 000 inhabitants	Static	metres
Recreation	Hiking	Distance to the official hiking trails	Static	metres

Provisioning services are the products people obtain from the ecosystems [35]. We selected three metrics to quantify two ESS; the metrics for calculating timber provision were calculated using the NFI3 data [32], while the dataset for water provision was obtained from the Catalan Government digital database [36]. Regulating services are the benefits people obtain from the regulation of ecosystem processes [35]. We defined four regulating ESS using six metrics. All dynamic metrics data are provided by the NFI3, while data on the Natura 2000 network is available from the Catalan Government database. We used the equation of Selkimäki et al. [37] to assess the erosion probability and the equation of González Olabarria et al. [38] to evaluate fire disturbances risk. Cultural services are nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, recreation, reflection, and aesthetic experiences [35]. Here, four metrics were used to quantify four ESS. We used the Catalan Government database to assess accessibility, official hiking trails to evaluate recreation [39], NFI3 data for health assessment, and the equation of Blasco et al. [40] to calculate the scenic beauty index.

2.2.2. Simulation of the forest dynamics and changes in ESS provision

Forest dynamics simulation was done to estimate future forest characteristics and, therefore, quantify the provision of forest ESS in order to identify FUS and appropriate long-term strategies. The dynamics were simulated from year 2000 to 2100, in 10-year increments, excluding management, and assuming future climate remains as the reference period (1981-2015) for the simulation period. Future forest dynamics were estimated with the FORMES projection system, a modular modelling framework that simulates forest dynamics under changing climatic conditions and forest management if required [41]. It has been specially designed to understand and explore the long-term effects of alternative forest management approaches, fire, and climate on forest structure and composition. The forest dynamics models included in FORMES allow the estimation of variation of the live biomass for a determined period/simulation scenario. To do so, it includes a set of empirical, climate-sensitive, individual-tree, distance-independent models to simulate forest stands dynamics. Tree-level models consider individual trees as the basic unit for simulating growth, mortality, and ingrowth processes, which enables a more detailed and flexible description of stand structure, composition, and simulation of alternative management treatments than stand-level models. Distance-independent models operate assuming an average spatial pattern of individuals and have similar predictive performance than distance-dependent models (which require explicit tree spatial coordinates) but are less computationally demanding than the latter.

2.2.3. Forest use suitability (FUS) assessment

We proceed to establish the relationship between ESS and FUS alternatives, quantify ESS provision and assess the FUS identification. To accomplish this, we implemented a three-step analysis:

I. The first step involves two components that established and evaluated the relationship between ESS and FUS. Firstly, a participatory workshop utilizing Delphi principles is conducted to identify the ESS indicators that best describe each of the FUS alternatives [42]. Secondly, an Analytic Hierarchy Process (AHP) is applied to assign weights to each ESS indicator, determining their relative importance or contribution in selecting the most suitable FUS alternative for a forest stand [43].
II. Geospatial-based logic modelling with NetWeaver Developer [[44], referred to as NetWeaver hereafter], an analytical component of the EMDS spatial decision support framework, was performed to quantify the provision of each of 13 forest ESS (Table 1), based on selected metrics from the previous step.
III. An assignment of FUS alternatives to each stand was performed, based on suitability scores obtained as a combination of the results from the step I and II.; using Criterium Decision Plus (CDP) [45], another analytical component of EMDS framework.

Aiming to identify the forest ESS indicators that best contribute to the definition of each of four FUS alternatives, a workshop based on the Delphi principles was conducted. Eleven young experts from different forestry-related fields were asked, using the 5-point Likert scale, to evaluate the degree of contribution of each of 13 selected ESS metrics to the definition of each FUS. Both positive and negative contributions were considered. An example of the evaluation question is “To what degree does evidence of recreation contribute to the conclusion that the FUS of the stand is the primary social alternative?” All pair-wise ESS-FUS combinations were evaluated using the same approach. Results were presented to the participants and jointly discussed. After the discussion, the same questionnaire was repeated. From the second questionnaire, the five most highly rated ESS metrics per each FUS were identified. In the second part of the workshop, an AHP analysis was conducted using only five selected metrics per FUS. In the AHP analysis, all selected ESS metrics were compared, asking which of each pair is more important, and how much more important, for a specific FUS. As a result, weights for each ESS metric were obtained, quantifying the importance that a specific ESS has in the FUS assignment process (Table 2). For example, a forest with strong evidence of timber provision (growth) is most suited to the productive use alternative (0.35), less suited to the protective use (0.09), and not suited to the conservation-oriented and social use alternative. On the other hand, strong evidence of biodiversity regulation best supports the conservation-oriented alternative (0.36), has negative influence for the productive-use alternative (0.09), and does not contribute to the protective- and social-use alternatives.

Table 2. The weights quantifying the relative contribution of relationship between ESS to the benefits of each FUS alternative.

Forest ESS	**FUS**			
	Productive	Protective	Conservation-oriented	Social
Timber provision (stock)	0.24	0.15	0	0
Timber provision (growth)	0.35	0.09	0	0
Water provision	0	0	0.16	0.10
Climate regulation (stock)	0	0.14	0	0
Climate regulation (change)	0.11	0	0	0
Biodiversity regulation	0.09	0	0.36	0
Habitat protection	0	0	0.20	0
Soil protection	0	0.25	0.12	0
Disturbances	0.21	0.37	0	0
Aesthetics	0	0	0	0.32
Natural heritage	0	0	0.16	0.12
Peri-urban forests	0	0	0	0.24
Recreation	0	0	0	0.23

Once selected the metrics that define each FUS, forest ESS provision was quantified using the NetWeaver logic model that employs a specific measure of the strength of evidence. Data for each metric, , were used to derive the strength of evidence, based on a fuzzy membership function that expresses the degree of support for a logical proposition provided by an observed data value [44]. In other words, observed data values were transformed into the strength of evidence values (ranging from 0 (no evidence, or no provision of ESS) to 1 (full evidence, or full provision of ESS)) by establishment of thresholds that designate the degree of ESS provision (Table 3). Thresholds for the functions were assigned based on the 10th and 90th percentiles of the observed data distribution, with several exceptions for which the percentile approach was not applicable. Thresholds were defined separately for the 50-year and 100-year simulation datasets. Typically, NetWeaver models implement a complex network structure (e.g., networks of networks), but for purposes of this study, each logic network only consisted of one elementary network (e.g., without antecedents). In total, 52 logic networks were created, representing all possible combinations of the 13 ESS and four FUS alternatives (Figure 2, which shows the structure of the model and includes graphics of the logic for evaluating the contribution of timber provision (stock) to the protective FUS, and recreation to the social FUS).

Table 3. Thresholds defining fuzzy membership function to quantify the provision of forest ESS.

Forest ESS	**FUS**							
	Productive		Protective		Conservation-oriented		Social	
	Fuzzy rule 50 years [0-1]	Fuzzy rule 100 years [0-1]	Fuzzy rule 50 years [0-1]	Fuzzy rule 100 years [0-1]	Fuzzy rule 50 years [0-1]	Fuzzy rule 100 years [0-1]	Fuzzy rule 50 years [0-1]	Fuzzy rule 100 years [0-1]
Timber provision (stock)	80-375	115-426	80-375	115-426	-	-	-	-
Timber provision (growth)	0.59-2.6	0.89-3.45	0.59-2.6	0.89-3.45	-	-	-	-
Water provision	-	-	-	-	300-50	300-50	300-50	300-50
Climate regulation (stock)	-	-	108-505	157-582	-	-	-	-
Climate regulation (change)	0.85-3.68	1.3-5	-	-	-	-	-	-
Biodiversity regulation	0.99-0	0.99-0	-	-	0-0.99	0-0.99	-	-
Habitat protection	-	-	-	-	0-1	0-1	-	-
Soil protection	-	-	0.07-0.99	0.14-0.99	0.99-0.07	0.99-0.14	-	-
Disturbances	0.08-0	0.05-0	0.08-0	0.05-0	-	-	-	-
Aesthetics	-	-	-	-	-	-	0.04-0.09	0.04-0.1
Natural heritage	-	-	-	-	0-10	0-10	0-10	0-10
Peri-urban forests	-	-	-	-	-	-	25000-1000	25000-1000
Recreation	-	-	-	-	-	-	1000-0	1000-0

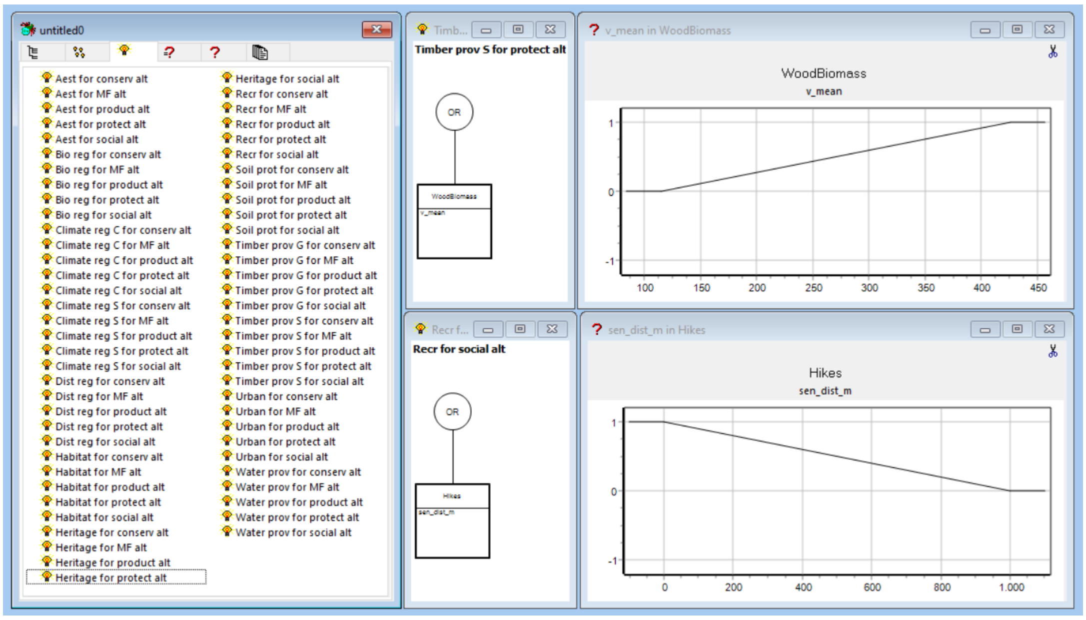


Figure 2. Graphic of the logic for evaluating the contribution of timber provision to the protective FUS and recreation to the social FUS. The lefthand frame displays a view of the network components. The middle frames display the details of the logic specification for two mentioned alternatives. The righthand frames display two examples of how arguments are defined in NetWeaver to obtain the measure of strength of evidence for two metrics, wood biomass and hiking.

With forest ESS provision values being obtained, ESS indicators that are most suited to define each FUS being identified, and weights for each ESS indicator being assigned, we proceeded with the last step of the FUS suitability assessment. The objective of this assessment is to compute the utility of FUS alternatives with respect to the provision of ESS, which could subsequently be used as a basis for long-term strategic management planning. The CDP model, based on the Analytic Hierarchy Process to derive weights on decision criteria, was implemented for each stand [45]. The method also uses the Simple Multi-Attribute Rating Technique (SMART) to normalize attributes into utility scores (from 0 to 1). The nodes below the CDP goal are the four FUS (multifunctional use is not included in the model, because it is defined later, based on the trade-offs between other four FUS). The lowest criteria are the 13 ESS metrics for each FUS (Figure 3). The CDP model structure (Figure 3) is a novel implementation of an AHP model, in which the alternatives being evaluated are actually the four FUS criteria, because the model is executed on each forest polygon to determine the best performing FUS alternative for that polygon. The scores for each forest polygon are obtained from the outputs of the 52 NetWeaver networks. The CDP model produces a weighted sum estimate at each FUS node, executed on a polygon, indicating how well the existing ESS on that polygon support the FUS. This estimate is treated as a measure of the FUS's suitability for guiding the stand's future management. The Classic MCDA Analysis tool in EMDS was adapted to apply the CDP model to each stand and extract an estimate of FUS for every stand in the study area. Custom code was integrated into the EMDS to extract and record the FUS scores for each forest polygon.

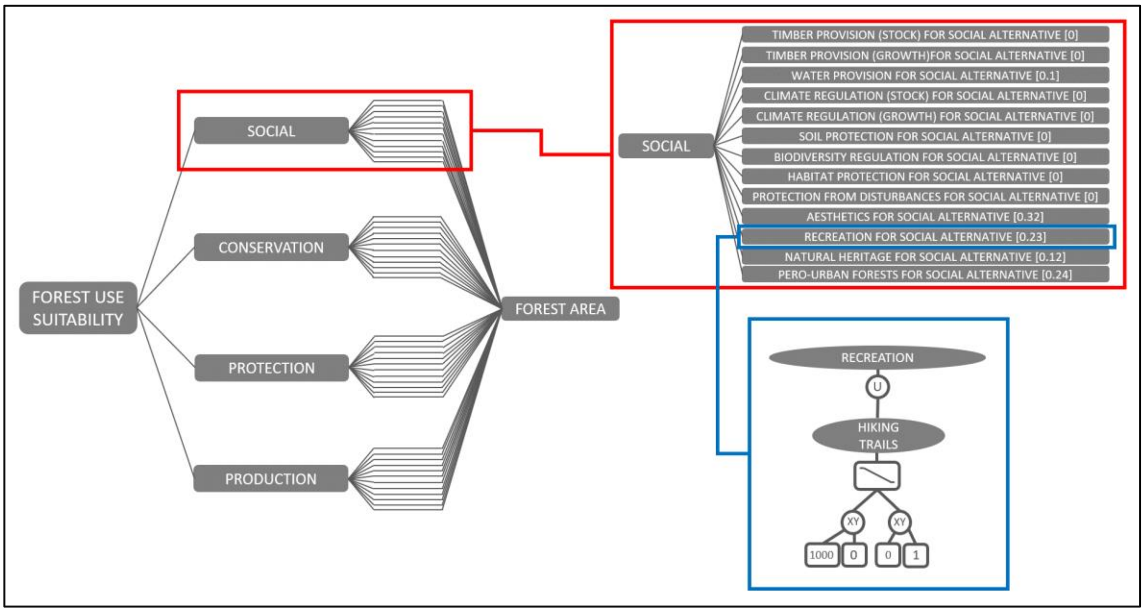


Figure 3. Schematic design of CDP model. The left-hand pane shows the overall MCDA model, with the four FUSs being the nodes to the right of the Goal. The upper right pane zooms in to show the 13 forest ESS metrics under that FUS with corresponding weights, and the lower right pane shows the network in the Net Weaver model that calculates the strength of evidence that that ecosystem service is thriving on that forest stand.

2.2.4. Assignment of FUS priorities, robustness analysis and identification of multifunctional FUS

In the fourth step of the overall assessment, the performance scores for each stand's FUS (e.g., utility) obtained in the previous step were organized in numerical order, creating a hierarchical distribution of FUS alternatives. The FUS alternative with the highest performance score was considered the primary option, representing the most suitable forest-use alternative among the four assessed in this study. Conversely, the alternative with the lowest score was regarded as the least suitable. By assigning ranks to the representation of FUS in a stand, we were able to not only map the distribution of primary, and secondary FUS across the region, but also identify any spatial relationships between them. Additionally, to determine the frequency of association between a primary FUS and a specific secondary FUS, we constructed transition matrix tables.

Each stand underwent a robustness analysis to assess the strength of the difference between primary and secondary FUS. This analysis involved subtracting the secondary FUS performance scores from the primary FUS scores. When the difference was minimal, it indicated that the secondary FUS could be considered highly suitable, along with the primary alternative. Conversely, when the difference was significant, the importance of the secondary FUS diminished considerably. These scores served as a means to balance representativeness by allowing a switch between the primary and secondary FUS options and, consequently, identify multifunctional FUS. If the disparity in performance between two FUS options in a plot was relatively small, falling within a 20% threshold of the largest difference observed, the plot was categorized as potentially being suitable for multifunctional use. The analysis was conducted using the ArcGIS 10.8 software by Environmental Systems Research Institute1 (ESRI) and the EMDS 8.7 ArcMap Add-Inn, which can be accessed at https://emds.mountain-viewgroup.com/.

3. Results

3.1. Forest dynamics simulation

Figure 4 shows results of the forest dynamics simulation. We show the changes of only two most indicative variables of forest growth: diameter at breast hight (dbh) and basal area (ba). Mean values for the study area are shown. Both variables increased their values over the simulated period. Mean diameter increased form 15 cm to 65 cm over 100 years, while basal area values grew from 20 m2/ha to 47 m2/ha. In both cases, the increment in faster over the first half of the simulated period, being slowed down after the year 2050. Such change is more obvious in case of basal area.

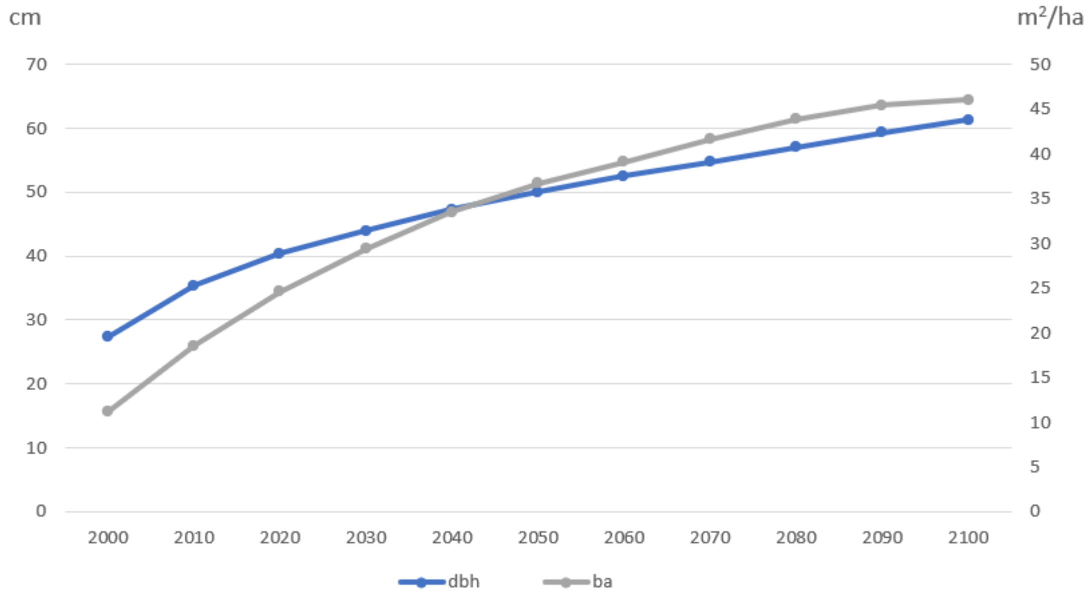


Figure 4. Graphical representation of simulated forest dynamics; dbh – diameter at breast height, ba – basal area (year 2000 to year 2100)

3.2. Forest use suitability

Primary forest use suitability based on a 100-year simulation is shown on Figure 5. The suitability maps display the option that received the highest score among the four available FUS alternatives. Taking into account the simulated forest dynamics, the provision of selected forest ecosystem services (ESS), and the assigned weights for a specific FUS, the dominant primary use suitability was found to be protective, representing 64% of the stands. It was followed by productive (19%), conservation-oriented (13%), and social (3%) alternatives. When considering the spatial allocation of the primary FUS alternatives, a similar pattern can be observed, although with varying spatial densities. All four alternatives are present throughout the study area, but the frequency of conservation-oriented and social alternatives being identified as the most suitable decreases in the north-western parts of Spain, while their presence increases in the central area. On the other hand, the productive alternative is more prevalent in the north and exhibits lower density in the central part of the study area. The protective alternative demonstrates a high dominance across all areas. It is important to highlight that each polygon is assigned only one primary and one secondary use. However, given the large size of the study area and the resolution of the displayed figures, it may appear that a single polygon has multiple primary uses.

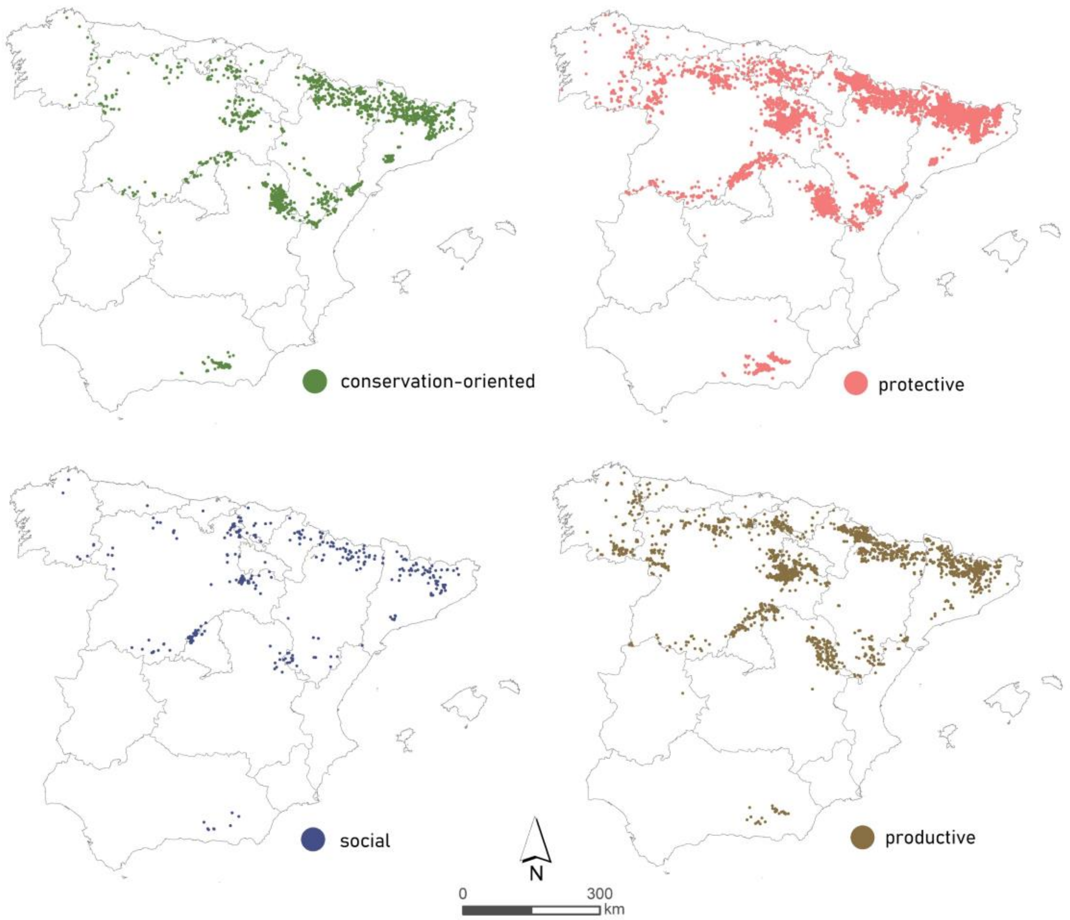


Figure 5. Maps of primary forest use suitability based on 100-year simulation

When examining the secondary use suitability based on a 100-year simulation, the spatial distribution of the various FUS alternatives follows a similar pattern to that of the primary FUS. However, there are changes in the frequency of occurrence (Figure 6). The productive use is the most common secondary suitability option, accounting for 59% of the cases. This is primarily due to its role as the dominant secondary option to the primary protective and social uses (Figure 7). The secondary protective use has a relatively high presence at 24%, as it is the dominant secondary option to the productive and conservation-oriented alternatives. On the other hand, the conservation-oriented (10%) and social (7%) alternatives were identified as secondary FUS in significantly fewer cases. While the productive and protective secondary alternatives are distributed proportionally across the study area, the conservation-oriented and social alternatives are largely absent in the north-western provinces. The values obtained from the 50-year simulation, for both primary and secondary FUS, do not show significant differences compared to the 100-year simulation results, except in the case of the primary social alternative.

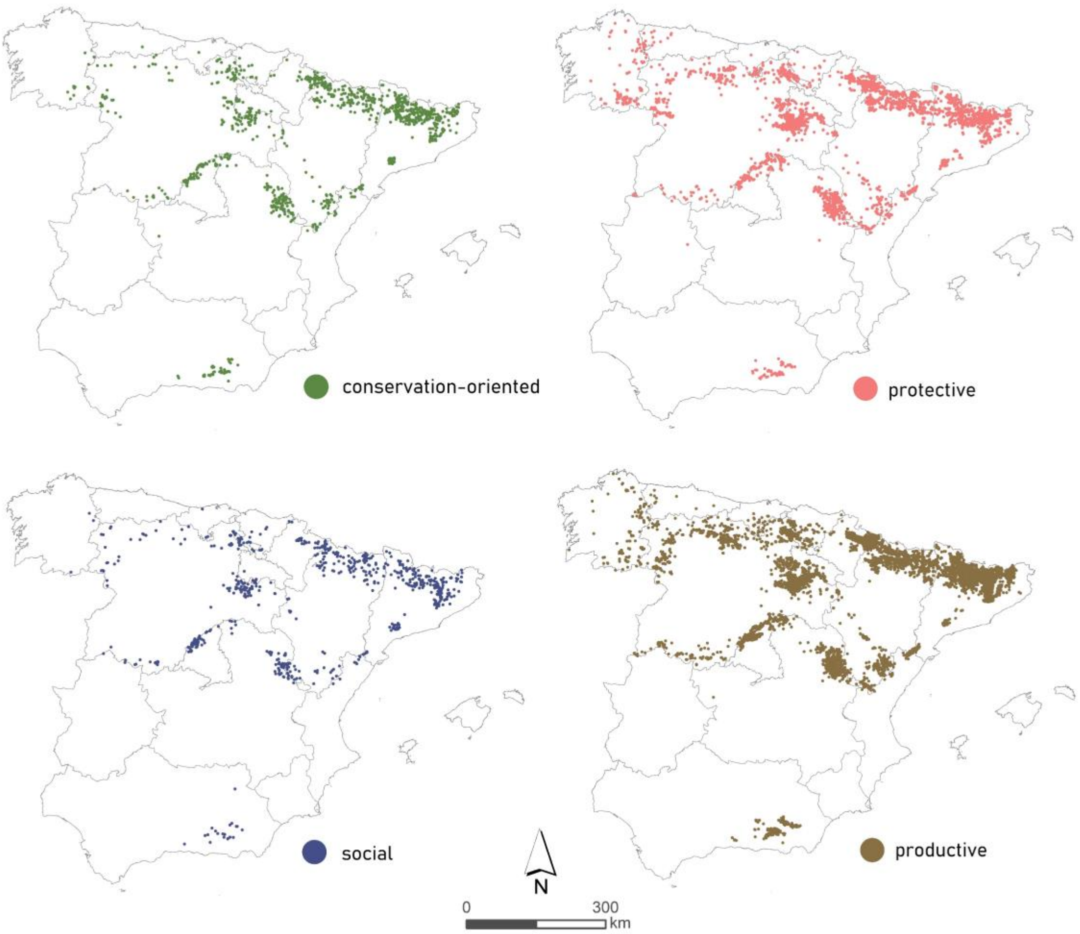


Figure 6. Maps of secondary forest use suitability based on 100-year simulation

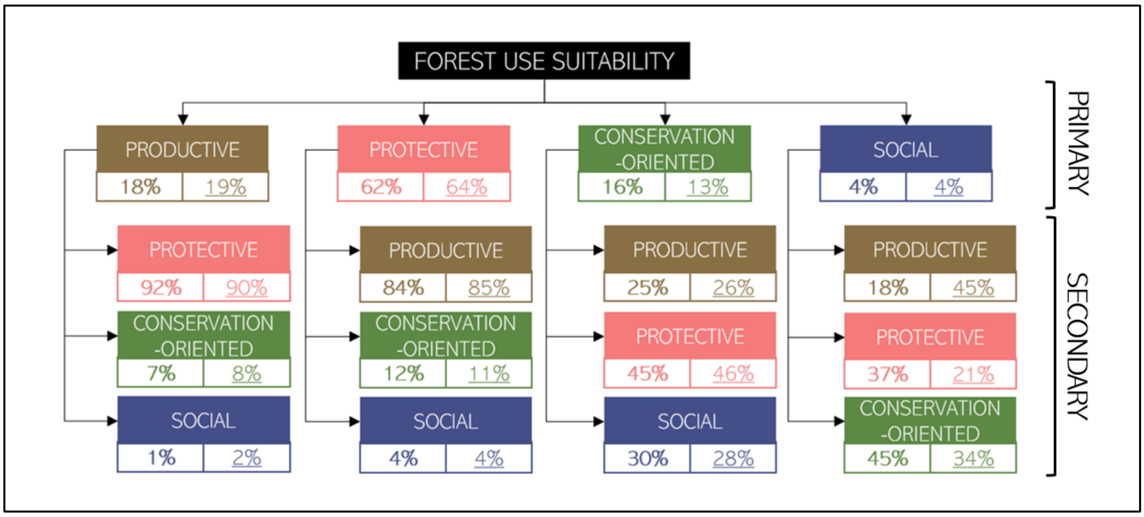


Figure 7. Graphical representation of relationship between primary and secondary FUS showing the frequency each alternative is identified as primary, and how often each alternative is identified as secondary to each of the primary ones (values on the left side of each alternative correspond to a 50-year simulation; values on the right side of each alternative correspond to a 100-year simulation)

The results of the robustness analysis, comparing the primary and secondary Forest Use Suitability (FUS) based on a 100-year simulation, are depicted in Figure 8. Only the plots with a difference score falling within the 20% threshold of the maximum observed difference are shown, as they are considered potentially multifunctional. Out of the total number of plots, 35% have a difference value lower than 10% of the maximum difference score recorded, indicating a high level of multifunctionality. Additionally, 57% of the plots fall within the 20% threshold, further demonstrating the significant presence of multifunctional forests. Spatially, the forests with potential multifunctional FUS are proportionally distributed throughout the study area.

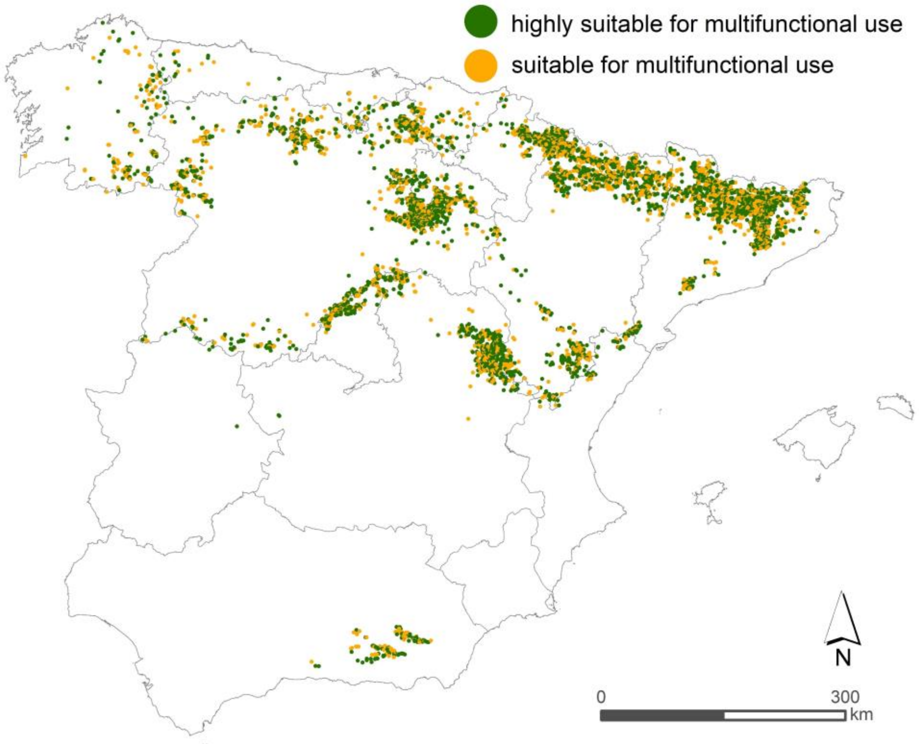


Figure 8. Map of the plots with potential multifunctional FUS based on 100-year simulation, assigned applying robustness analysis between primary and secondary FUS

4. Discussion

This study uses a novel methodological framework in assessing forest ESS for sustainable management. Our aim was to address the methodological and terminological limitations in ecosystem services assessment, with the goal of facilitating the integration of this framework into decision-making processes and management strategies [46]. Firstly, the intricate nature of the forest ESS concept presents challenges in conducting comprehensive studies [47]. Moreover, these challenges are compounded by the involvement of numerous stakeholders with diverse interests and objectives, which greatly hinders efforts to enhance environmental decision-making processes [48]. Secondly, the dynamic nature of forest ESS concepts demands strategic management actions that account for changes in forest characteristics [49] [50]. In such a scenario, decision-making processes can effectively adapt to environmental conditions and enhance the provision of ESS while considering the capacity of ecosystems to supply them [11]. We believe that solution-oriented research is the most effective approach to address these challenges. EES-related studies primarily focus on assessing the supply of ecosystem services, but they often do not succeed in providing actionable solutions to enhance the desired provision of services through effective management strategies [25]. We argue that defining appropriate management strategies can help address conflicting interests and significantly facilitate decision-making processes, minimizing potential conflicts and maximizing desired outcomes. For that reason, we recommend the adoption of the FUS approach as a foundational step towards achieving sustainable management of forest ESS. In this study, we present the FUS framework as a dynamic concept that utilizes simulations of forest characteristics over time, aiming to accurately define long-term planning strategies. We assume that the forest growth and dynamics can correctly represent the changes in the provision of certain forest ESS, while heterogeneous ESS metrics can be directly estimated from the forest's biogeophysical characteristics. Additionally, integrating different climate scenarios can contribute to generating more specific long-term strategic outcomes, narrowing down the range of management alternatives, and facilitating the identification of the most suitable approach [51]. While this study focuses on introducing a novel methodological approach and implementing dynamic variables, the application of climate projections in the model is left for future research. In addition, specific actions resulting from the FUS assignment are not specifically defined in this study. Instead, FUS categories are identified solely by their descriptive names (productive, protective, conservation-oriented, social, and multifunctional), serving as a guide for potential management directions.

The results of this study show heterogeneous characteristics of Spanish *Pinus sylverstis* forests, prioritizing protective and productive use suitability. While the FUS alternatives are clearly distinguishable in the maps (considering apparent overlaps due to the extent of the study area and map resolution), their interpretation is not straightforward. It is important to note that the primary FUS map alone may not always represent the most suitable option, so we recommend taking into account the presence of secondary FUS alternative, as well as carefully assessing the trade-offs associated with each option. The management implications differ based on the magnitude of the difference between the primary and secondary FUS scores. When there is a significant gap between these scores, it suggests that the secondary alternative may not require strong consideration when selecting a suitable management strategy. On the other hand, when the gap is small, the secondary FUS alternative could be also considered. Such an approach can help identify potential multifunctional characteristics of the forest and help to spatially identify potential multifunctional FUS. While we did not include the multifunctional FUS in the modelling process nor specific rules applied to define it, we decided to identify it simply by application of the robustness analysis on the primary and the secondary alternative. Nevertheless, apart from the difference scores, it is very useful to consider the patterns of FUS alternatives when identifying multifunctional uses. Namely, the presence of specific combinations of FUS alternatives presents challenges when selecting appropriate management strategies, such as primary productive-secondary protective and primary protective-secondary productive, hindering the definition of compatible joint management options. As a result, it is important to view the FUS maps as flexible alternatives that can be adjusted to accommodate specific circumstances, rather than fixed outcomes. By doing so, we increase our flexibility in adjusting the distribution of FUS alternatives across the region, enabling a more balanced representation, taking into account all available alternatives.

The outcomes of the study and their implications are highly influenced by the metrics employed to define each individual ecosystem service. Therefore, at the moment of results interpretation, it is necessary to recall which metrics represent each of the FUS alternatives [52], [53]. At the same time, data availability represents one of the main constraints of the simulation-based FUS assessment. While integrating forest dynamics into ESS assessment enhances the research outcomes by introducing a multi-temporal perspective and facilitating more accurate long-term management planning, it also poses a significant limitation due to data availability constraints. Validating a dynamic assessment requires the prevalence of dynamic metrics over static ones. However, conducting such an analysis relies on empirical-based simulations to forecast forest dynamics, which typically require specific datasets. Consequently, the available data selection can be considerably limited. Forest inventories, which serve as the primary source of data, often offer an insufficient range of variables for a comprehensive ESS assessment. An inventory-based approach can appropriately assess forest ESS that can be defined and quantified by metrics that contain forest's biogeophysical characteristics (such as timber production, climate regulation, soil protection, etc.), but considerably hinders an exhaustive assessment of ESS indicators that depend, at least in part, on non-material and intangible characteristics (e.g., most of the cultural ESS). The challenges related to quantifying cultural ecosystem services, caused by lack of variable standardization or methodological limitations, are further exacerbated in this study due to the limited incorporation of dynamic metrics in defining cultural services and, consequently, the social FUS [54], [55]. Unlike other FUS alternatives that are comprehensively defined by dynamic metrics, the social FUS relies on only two dynamic variables. Moreover, the extensive study area and corresponding geographical scale result in significantly more restricted spatial distribution of available non-inventory-based data. These factors contribute to the notable underrepresentation of the social FUS in our study results. Thus, we want to emphasise the importance of data selection in order to conduct comprehensive analysis and obtain objective and comparable results.

Application of the EMDS system enabled successful incorporation of the results obtained within the participatory analysis in spatial assessment of the FUS. Namely, the system shows several strengths regarding the multi-criteria spatial analysis satisfying the requirements needed to accomplish our objectives. Firstly, the transparent and user-friendly approach of EMDS simplifies the representation of geospatial reality, assisting in comprehending the complexity of the subject matter. These aspects of EMDS promote interactive collaboration between scientists and end-users, making it suitable for participatory planning. Additionally, EMDS facilitates the integration of expert knowledge and scientific methods, particularly through the weighting processes and evaluation of criteria and network relations [56], [57]. In this study, the weights and parameters were assigned through the participatory process, based on previously gathered datasets. It is important to acknowledge, however, that all decision processes inherently involve some degree of subjectivity, influenced by the choice of weighs in decision models, parameters in logic models, and choices regarding model structures. At the same time, all the factors are strongly influenced by possible, previously discussed, data availability limitations. Despite these caveats, and given that different user groups often bring varying perspectives, we consider that the inclusion of participatory planning is a crucial step to mitigate potential sources of bias and interest-driven decision-making and, therefore, should be implemented in environmental multi-criteria assessments [58].

5. Conclusions

This study demonstrates the successful application of the EMDS system, a decision-support framework with spatial capabilities, enabling the exploration of innovative approaches in the field. We incorporated simulation-based metrics to assess the dynamics of forest ESS, aiming to define appropriate forest use suitability and establish the basis for long-term forest management planning. We also addressed methodological constraints regarding forest management strategies, as well as strengths and weaknesses of implementing dynamic metrics. The assignment of FUS alternatives followed similar spatial patterns, but with different spatial density, with protective FUS being the prevalent primary alternative in this study. The level of multifunctionality was relatively high, but with questionable compatibility between dominant FUS alternatives. Additionally, social FUS was underrepresented due to unequal spatial presence of input data.

Endnotes [1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Funding: This work was funded by the Catalan government predoctoral scholarship (AGAUR-FSE 2020 FI_B2 00147), SuFoRun Marie Sklodowska-Curie Research and Innovation Staff Exchange (RISE) Program (Grant agreement No: 691149) and the Spanish Ministry of Science and Innovation (PID2020-120355RB-IOO).

Acknowledgments: We thank Steve Paplanus for his technological help with EMDS, Philip Murphy for his CDP model support and Irina Cristal for her support regarding dataset organisation.

Author contributions: J.R.G.O., B.M.Y. and G.K. participated on the conceptualization of the project. G.K. and B.M.Y. implemented the data preparation, N.A. simulated the data, G. K. implemented the analysis and wrote an initial draft. K.M.R. supervised the

development and implementation of EMDS framework. G.K., J.R.G.O. and J.G.G. analysed the results. All authors participated in in editing process of the manuscript. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflicts of interest in the preparation of this work.

References

[1] J. Ananda and G. Herath, “A critical review of multi-criteria decision making methods with special reference to forest management and planning,” *Ecological Economics*, vol. 68, no. 10, pp. 2535–2548, 2009, doi: 10.1016/j.ecolecon.2009.05.010.

[2] A. Kangas, K. T. Korhonen, T. Packalen, and J. Vauhkonen, “Sources and types of uncertainties in the information on forest-related ecosystem services,” *For Ecol Manage*, vol. 427, no. March, pp. 7–16, 2018, doi: 10.1016/j.foreco.2018.05.056.

[3] M. C. Dade, M. G. E. Mitchell, C. A. McAlpine, and J. R. Rhodes, “Assessing ecosystem service trade-offs and synergies: The need for a more mechanistic approach,” *Ambio*, vol. 48, no. 10, pp. 1116–1128, 2019, doi: 10.1007/s13280-018-1127-7.

[4] J. V. Roces-Díaz *et al.*, “Assessing the distribution of forest ecosystem services in a highly populated Mediterranean region,” *Ecol Indic*, vol. 93, no. October 2016, pp. 986–997, 2018, doi: 10.1016/j.ecolind.2018.05.076.

[5] S. Wang and B. Fu, “Trade-offs between forest ecosystem services,” *For Policy Econ*, vol. 26, pp. 145–146, 2013, doi: 10.1016/j.forpol.2012.07.014.

[6] B. Martín-López, E. Gómez-Baggethun, M. García-Llorente, and C. Montes, “Trade-offs across value-domains in ecosystem services assessment,” *Ecol Indic*, vol. 37, no. PART A, pp. 220–228, 2014, doi: 10.1016/j.ecolind.2013.03.003.

[7] J. Kangas, A. Kangas, P. Leskinen, and J. Pykäläinen, “MCDM methods in strategic planning of forestry on state-owned lands in finland: Applications and experiences,” *Journal of Multi-Criteria Decision Analysis*, vol. 10, no. 5, pp. 257–271, 2001, doi: 10.1002/mcda.306.

[8] I. B. Huang, J. Keisler, and I. Linkov, “Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends,” *Science of the Total Environment*, vol. 409, no. 19, pp. 3578–3594, 2011, doi: 10.1016/j.scitotenv.2011.06.022.

[9] R. Yousefpour, J. Bredahl Jacobsen, B. J. Thorsen, H. Meilby, M. Hanewinkel, and K. Oehler, “A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change,” *Ann For Sci*, vol. 69, no. 1, pp. 1–15, 2012, doi: 10.1007/s13595-011-0153-4.

[10] N. Naudiyal and J. Schmerbeck, “The changing Himalayan landscape: pine-oak forest dynamics and the supply of ecosystem services,” *J For Res (Harbin)*, vol. 28, no. 3, pp. 431–443, 2017, doi: 10.1007/s11676-016-0338-7.

[11] S. R. Shifley *et al.*, “The past and future of modeling forest dynamics: from growth and yield curves to forest landscape models,” *Landsc Ecol*, vol. 32, no. 7, pp. 1307–1325, 2017, doi: 10.1007/s10980-017-0540-9.

[12] M. Albert, J. Hansen, J. Nagel, M. Schmidt, and H. Spellmann, “Assessing risks and uncertainties in forest dynamics under different management scenarios and climate change,” *For Ecosyst*, vol. 2, no. 1, 2015, doi: 10.1186/s40663-015-0036-5.

[13] Y. Chang, H. S. He, Y. Hu, R. Bu, and X. Li, “Historic and current fire regimes in the Great Xing’an Mountains, northeastern China: Implications for long-term forest management,” *For Ecol Manage*, vol. 254, no. 3, pp. 445–453, 2008, doi: 10.1016/j.foreco.2007.04.050.

[14] Y. Haila, “Preserving ecological diversity in boreal forests: ecological background, research, and management,” *Ann Zool Fennici*, vol. 31, no. 1, pp. 203–217, 1994.

[15] J. Ananda and G. Herath, “A critical review of multi-criteria decision making methods with special reference to forest management and planning,” *Ecological Economics*, vol. 68, no. 10, pp. 2535–2548, 2009, doi: 10.1016/j.ecolecon.2009.05.010.

[16] B. Harvey, T. Nguyen-Xuan, Y. Bergeron, S. Gauthier, and A. Leduc, “Forest management planning based on natural disturbance and forest dynamics,” *Towards Sustainable Management of the Boreal Forest*, no. January, pp. 395–432, 2003.

[17] M. Kallio, D. Dykstra, and C. Binkley, *The Global Forest Sector: an Analytical Perspective*. John Wiley & Sons, 1987.

[18] P. Reed and G. Brown, “Values suitability analysis: A methodology for identifying and integrating public perceptions of ecosystem values in forest planning,” *Journal of Environmental Planning and Management*, vol. 46, no. 5, pp. 643–658, 2003, doi: 10.1080/0964056032000138418.

[19] D. B. Botkin *et al.*, “Forecasting the effects of global warming on biodiversity,” *Bioscience*, vol. 57, no. 3, pp. 227–236, 2007, doi: 10.1641/B570306.

[20] M. Uriarte *et al.*, “Natural disturbance and human land use as determinants of tropical forest dynamics: Results from a forest simulator,” *Ecol Monogr*, vol. 79, no. 3, pp. 423–443, 2009, doi: 10.1890/08-0707.1.

[21] G. W. Luck *et al.*, “Quantifying the contribution of organisms to the provision of ecosystem services,” *Bioscience*, vol. 59, no. 3, pp. 223–235, 2009, doi: 10.1525/bio.2009.59.3.7.

[22] Z. G. Siyum, “Tropical dry forest dynamics in the context of climate change: syntheses of drivers, gaps, and management perspectives,” *Ecol Process*, vol. 9, no. 1, 2020, doi: 10.1186/s13717-020-00229-6.

[23] S. Wang, B. Fu, Y. Wei, and C. Lyle, “Ecosystem services management: An integrated approach,” *Curr Opin Environ Sustain*, vol. 5, no. 1, pp. 11–15, 2013, doi: 10.1016/j.cosust.2013.01.003.

[24] K. McDonough, S. Hutchinson, T. Moore, and J. M. S. Hutchinson, “Analysis of publication trends in ecosystem services research,” *Ecosyst Serv*, vol. 25, pp. 82–88, 2017, doi: 10.1016/j.ecoser.2017.03.022.

[25] G. C. Daily *et al.*, “Ecosystem services in decision making: Time to deliver,” *Front Ecol Environ*, vol. 7, no. 1, pp. 21–28, 2009, doi: 10.1890/080025.

[26] G. Zanchi and M. V. Brady, “Evaluating the contribution of forest ecosystem services to societal welfare through linking dynamic ecosystem modelling with economic valuation,” *Ecosyst Serv*, vol. 39, no. September, p. 101011, 2019, doi: 10.1016/j.ecoser.2019.101011.

[27] P. Lamarque, F. Quétier, and S. Lavorel, “The diversity of the ecosystem services concept and its implications for their assessment and management,” *C R Biol*, vol. 334, no. 5–6, pp. 441–449, 2011, doi: 10.1016/j.crvi.2010.11.007.

[28] M. J. Martnez-Harms and P. Balvanera, “Methods for mapping ecosystem service supply: A review,” *Int J Biodivers Sci Ecosyst Serv Manag*, vol. 8, no. 1–2, pp. 17–25, 2012, doi: 10.1080/21513732.2012.663792.

[29] K. J. Bagstad, D. J. Semmens, S. Waage, and R. Winthrop, “A comparative assessment of decision-support tools for ecosystem services quantification and valuation,” *Ecosyst Serv*, vol. 5, pp. 27–39, 2013, doi: 10.1016/j.ecoser.2013.07.004.

[30] K. M. Reynolds and P. F. Hessburg, “An Overview of the Ecosystem Management Decision-Support System,” *Environmental Science and Engineering*, pp. 3–22, 2014, doi: 10.1007/978-3-642-32000-2_1.

[31] K. Reynolds, S. Paplanus, B. Miller, and P. Murphy, “Design features behind success of the ecosystem management decision support system and future development,” *Forests*, vol. 6, no. 1, pp. 27–46, 2015, doi: 10.3390/f6010027.

[32] “The 3rd Spanish National Forest Inventory.” https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/ifn3.aspx (accessed Apr. 26, 2023).

[33] Ministerio para la Transición Ecológica y el Reto Demográfico, *Anuario de Estadística Forestal de España 2019*. 2021. [Online]. Available: www.miteco.es

[34] L. Coll, J. R. González-Olabarria, B. Mola-Yudego, T. Pukkala, and C. Messier, “Predicting understory maximum shrubs cover using altitude and overstory basal area in different Mediterranean forests,” *Eur J For Res*, vol. 130, no. 1, pp. 55–65, 2011, doi: 10.1007/s10342-010-0395-y.

[35] Millennium Ecosystem Assessment, *Ecosystems and Human Well-being : Current State and Trends , Volume 1*. 2005.

[36] “The Catalan Government Spatial Dataset (Hipermapa).” https://sig.gencat.cat/visors/hipermapa.html (accessed May 01, 2023).

[37] M. Selkimäki, J. R. González-Olabarria, A. Trasobares, and T. Pukkala, “Trade-offs between economic profitability, erosion risk mitigation and biodiversity in the management of uneven-aged Abies alba Mill. stands,” *Ann For Sci*, vol. 77, no. 1, 2020, doi: 10.1007/s13595-019-0914-z.

[38] J. R. González, A. Trasobares, M. Palahí, and T. Pukkala, “Predicting stand damage and tree survival in burned forests in Catalonia (North-East Spain),” *Ann For Sci*, vol. 64, no. 7, pp. 733–742, 2007, doi: 10.1051/forest:2007053.

[39] “Federación española de senderismo.” https://fedme.es/ (accessed May 01, 2023).

[40] E. Blasco, J. R. González-Olabarria, P. Rodriguéz-Veiga, T. Pukkala, O. Kolehmainen, and M. Palahí, “Predicting scenic beauty of forest stands in Catalonia (North-east Spain),” *J For Res (Harbin)*, vol. 20, no. 1, pp. 73–78, 2009, doi: 10.1007/s11676-009-0013-3.

[41] A. Trasobares *et al.*, “Nationwide climate-sensitive models for stand dynamics and forest scenario simulation,” *For Ecol Manage*, vol. 505, 2022, doi: 10.1016/j.foreco.2021.119909.

[42] G. Rowe and G. Wright, “The Delphi technique as a forecasting tool: Issues and analysis,” *Int J Forecast*, vol. 15, no. 4, pp. 353–375, 1999, doi: 10.1016/S0169-2070(99)00018-7.

[43] O. S. Vaidya and S. Kumar, “Analytic hierarchy process: An overview of applications,” *Eur J Oper Res*, vol. 169, no. 1, pp. 1–29, 2006, doi: 10.1016/j.ejor.2004.04.028.

[44] B. Miller and M. Saunders, “NetWeaver Reference Manual,” no. September 2002, p. 127, 2006.

[45] P. Murphy and J. Solan, “Infoharvest.” http://www.infoharvest.com/ihroot/index.asp (accessed Feb. 21, 2023).

[46] B. Fisher, R. K. Turner, and P. Morling, “Defining and classifying ecosystem services for decision making,” *Ecological Economics*, vol. 68, no. 3, pp. 643–653, 2009, doi: 10.1016/j.ecolecon.2008.09.014.

[47] Y. Laurans, A. Rankovic, R. Billé, R. Pirard, and L. Mermet, “Use of ecosystem services economic valuation for decision making: Questioning a literature blindspot,” *J Environ Manage*, vol. 119, pp. 208–219, 2013, doi: 10.1016/j.jenvman.2013.01.008.

[48] J. Hauck, C. Görg, R. Varjopuro, O. Ratamäki, and K. Jax, “Benefits and limitations of the ecosystem services concept in environmental policy and decision making: Some stakeholder perspectives,” *Environ Sci Policy*, vol. 25, pp. 13–21, 2013, doi: 10.1016/j.envsci.2012.08.001.

[49] T. Li, Y. Cui, and A. Liu, “Spatiotemporal dynamic analysis of forest ecosystem services using ‘big data’: A case study of Anhui province, central-eastern China,” *J Clean Prod*, vol. 142, pp. 589–599, Jan. 2017, doi: 10.1016/j.jclepro.2016.09.118.

[50] N. Naudiyal and J. Schmerbeck, “The changing Himalayan landscape: pine-oak forest dynamics and the supply of ecosystem services,” *J For Res (Harbin)*, vol. 28, no. 3, pp. 431–443, May 2017, doi: 10.1007/s11676-016-0338-7.

[51] M. Lindner *et al.*, “Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management?,” *Journal of Environmental Management*, vol. 146. Academic Press, pp. 69–83, Dec. 15, 2014. doi: 10.1016/j.jenvman.2014.07.030.

[52] B. Czúcz *et al.*, “Where concepts meet the real world: A systematic review of ecosystem service indicators and their classification using CICES,” *Ecosystem Services*, vol. 29. Elsevier B.V., pp. 145–157, Feb. 01, 2018. doi: 10.1016/j.ecoser.2017.11.018.

[53] C. Albert, C. Galler, J. Hermes, F. Neuendorf, C. Von Haaren, and A. Lovett, “Applying ecosystem services indicators in landscape planning and management: The ES-in-Planning framework,” *Ecol Indic*, vol. 61, pp. 100–113, Feb. 2016, doi: 10.1016/j.ecolind.2015.03.029.

[54] M. M. Pleasant, S. A. Gray, C. Lepczyk, A. Fernandes, N. Hunter, and D. Ford, “Managing cultural ecosystem services,” *Ecosyst Serv*, vol. 8, pp. 141–147, 2014, doi: 10.1016/j.ecoser.2014.03.006.

[55] T. Plieninger, S. Dijks, E. Oteros-Rozas, and C. Bieling, “Assessing, mapping, and quantifying cultural ecosystem services at community level,” *Land use policy*, vol. 33, pp. 118–129, 2013, doi: 10.1016/j.landusepol.2012.12.013.

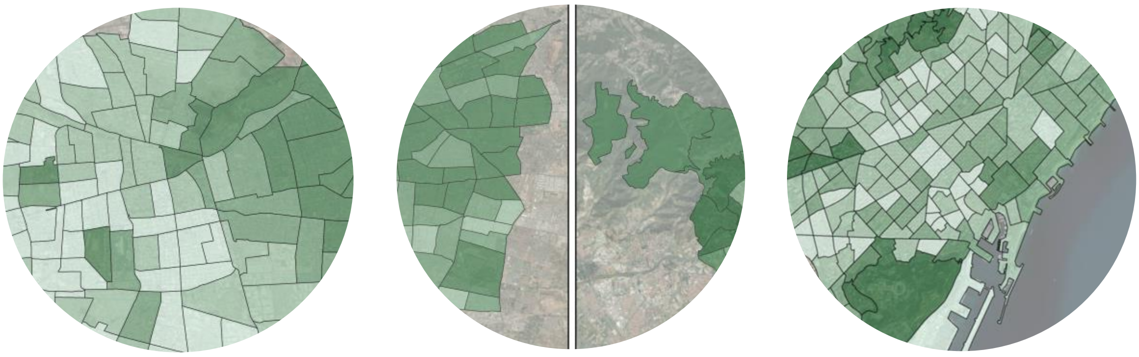
[56] M. Marques, K. M. Reynolds, S. Marques, M. Marto, S. Paplanus, and J. G. Borges, “A participatory and spatial multicriteria decision approach to prioritize the allocation of ecosystem services to management units,” *Land (Basel)*, vol. 10, no. 7, 2021, doi: 10.3390/land10070747.

[57] M. Acosta and S. Corral, “Multicriteria decision analysis and participatory decision support systems in forest management,” *Forests*, vol. 8, no. 4, pp. 215–216, 2017, doi: 10.3390/f8040116.

[58] S. Menzel, E. M. Nordström, M. Buchecker, A. Marques, H. Saarikoski, and A. Kangas, “Decision support systems in forest management: Requirements from a participatory planning perspective,” *Eur J For Res*, vol. 131, no. 5, pp. 1367–1379, 2012, doi: 10.1007/s10342-012-0604-y.

Article 3

ASSESSING RELATIVENESS IN PROVISION OF URBAN ECOSYSTEM SERVICES: BETTER COMPARISON METHODS FOR IMPROVED WELL-BEING



Published in *Land* (2023) DOI: doi.org/10.3390/land12051088

Krsnik G.; Reyes-Paecke, S.; Reynolds, M.K.; Garcia-Gonzalo, J.; González Olabarria, J.R.

Assessing Relativeness in the Provision of Urban Ecosystem Services: Better Comparison Methods for Improved Well-Being

Abstract: In this study, we evaluate alternative methods for comparing the provision of ecosystem services among urban areas, stressing how the choice of comparison method affects the ability to compare ecosystem service outcomes for improving management actions in urban green areas, reducing environmental inequality, and ensuring satisfactory levels of human well-being. For the analysis, ten spatial indicators were quantified to assess the provision of urban ecosystem services in Barcelona, Spain and Santiago, Chile. Two comparison methods were applied in both cities to evaluate differences in provision scores. The analysis was done using the Ecosystem Management Decision Support (EMDS) system, a spatially enabled decision support framework for environmental management. Results depict changes in values in provisioning of ecosystem services depending on the methodological approach applied. When data were analysed separately for each city, both cities register a wide range of provision values across city districts, varying from very low to very high values. However, when the analysis was based on the data for both cities, provision scores in Santiago decreased, while they increased in Barcelona, showing relativeness and discrepancy in provision, and hindering appropriate planning definition. Our results emphasise the importance of the choice of comparison approach in analyses of urban ecosystem services and the need for further study of comparison methods.

Keywords: urban ecosystem services, spatial modelling, urban green infrastructure, human well-being, urban planning

1. Introduction

Human wellbeing can be considerably increased by numerous services provided by ecosystems [1]. In urban areas, demand for ecosystem services is significantly higher than in rural environment due to limited natural recourses and high concentration of population in a relatively small area [2]. It is expected that the world's urban population will continue growing, and, therefore, an increased demand for urban ecosystem services (UES) in rapidly expanding urbanized areas can be expected, causing high pressures on urban green infrastructure [3] [4]. In such an environment, urban green areas (UGA), including parks, urban forests, and street trees, are multifunctional sources of benefits, such as recreation, air purification, water drainage or psychological relief [5] [6]. The importance of their management is crucial because they are heavily influenced by humans and can be modified relatively quickly according to the potential demand [7] [8]. Therefore, incorporation of ecosystem services-based strategies into urban planning and management affords an opportunity to promote a more sustainable society and simultaneously enhance human well-being [4]. Consequently, to promote the development of more sustainable cities, it is important to understand how UES are related to the structure of the urban landscape and how they spatially vary within the city [9] [4].

Spatial management of UES supply helps to define appropriate urban strategies to achieve ecologically sustainable cities [9]. In such a scenario, different planning methods can be applied, based on the stage of urbanization that the city is passing through [10]. Analysis of current UES features can help anticipate future urban processes in some parts of the world [10] and enhance practices relevant to maintaining or improving ecological [11] [12], social [13] and climate mitigation outcomes [14]. Often, spatial comparison methods are used to achieve these goals, such as comparison between different cities [3] [15] [16] or between city districts within the same city [17]. These methods provide good feedback concerning the UES assessment and address needed management actions regarding UGA.

Spatial patterns of UES supply are the result of both physical and socioeconomic features of the urban environment in which all the components are complexly intercorrelated [18]. Therefore, mapping and quantifying UES is a powerful tool in detection of spatial heterogeneity in provision of ecosystem services, and it is recommended as a first step towards a comprehensive management plan of green infrastructure, including comparison-based studies [6] [19] [20]. However, the lack of standardization in comparison methods and of comparable availability of spatial data significantly hinders ecosystem services modelling and quantification due to numerous datasets requirements [10] [21]. Moreover, open-source, remotely sensed images considerably limit comprehensive analysis in urban areas primary due to their spatial resolution requirements [6]. These limitations substantially impede cartography-based comparison and detection of hotspots that could be used as examples of good or bad UES management. Namely, benefits are usually not equally provided within or between cities, due to unequal access to green infrastructure, causing environmental injustice in the distribution of environmental goods and well-being [22] [23]. Differences on the distribution of environmental goods are mostly visible within the cities of emerging countries, with obvious socio-economical polarisation between city districts, or when comparing cities between more or less economically developed countries [24]. Due to continuing trends in urbanisation and, therefore, an increased pressure on UGA, reaching a desirable level of access to safe, inclusive, and accessible green space at the end of this decade, is considered a global policy objective [25]. Nevertheless, due to different data scales, absolute values of provision are usually not directly comparable among cities, and lack of consensus on a possible reference scale that would define how high provision should be to be considered optimal, deters improvements in management of UES [26]. This raises the question of relativeness in provision of UES, because the perception of satisfying provision can be significantly changed depending on whether the values are analysed independently, or are being compared to other urban areas. Therefore, an improvement in methods for assessing and comparing UES is needed, allowing comparison between different indicators and data sources though standardization processes, resulting in better and comparable planning.. Also, having information at the neighbourhood level and knowing the characteristics of all the relevant components implied, can promote improved human well-being, caused by increase in provision of UES, and inspired by strategies applied in areas with similar geographical characteristics [27] [28]. In such processes, spatial decision support tools are of great interest to assist in decision making and supporting relevant conclusions [29].

In this study, we apply the Ecosystem Management Decision Support (EMDS) system, a spatially enabled decision support framework for analysis and planning [30], to compare the provision of UES in Barcelona, Spain and Santiago, Chile. For that purpose, we follow the Millennium Ecosystem Assessment (MEA) framework for quantifying regulating and cultural ecosystem services provided by green urban areas [31]. Our objective is to test the utility of EMDS in comparison of urban environments, and make first steps towards a more standardised assessment in comparison of UES at the local level. We apply different comparison methods to detect differences in results regarding the supply of benefits, pointing out the relativeness of UES provision.

2. Materials and Methods

2.1. Study area

The study was conducted in the cities of Santiago, Chile and Barcelona, Spain. Santiago and Barcelona are characterised by different socioeconomic and geospatial features. While Santiago is representative of rapid urbanisation processes, urban sprawl, and demographic transition, and reliably representing socio-ecological-spatial patterns of Latin American cities, Barcelona is a dense, but planned, Mediterranean city with dominant post-transitional processes and limited space for expansion [32] [33]. Ecosystem services-based urban greening policy and sustainable strategies represent the main pillars of Barcelona's plan for the future development [34]. In contrast, awareness of green infrastructure and its incorporation in urban planning have distinct applications in Santiago, depending on the commune (an administrative subdivision of the city), although needed sustainable policies of urban development have generally not been applied [35]. Both cities lack adequate green infrastructure within the city boundary, but have continuous suburban forests in the city outskirts. In this study, we analyse UES within municipal limits of the city of Barcelona and northern communes of the continuously urbanised part of Santiago province. Only northern communes in Santiago (continuously urbanised parts of 20 communes) were chosen due to the large spatial extent of the city which encompasses a large variety of urban morphological patterns. We used division on statistical sections to conduct our UES analysis because this division in both cities was detailed enough and comparable between our study areas. As a result, Santiago was divided into 179 districts, and Barcelona was divided into 233 statistical areas. Regarding population, Barcelona has 1.6 million inhabitants, and covers an area of 101.9 km2 (population density is about 16,000 people/km2 [36]. Northern communes of Santiago have 3.1 million inhabitants, and cover a total area of 256.2 km2 (population density is approximately 12,100 people/km2 [37]. The climate of both cities is “Mediterranean hot summer climatic type” (CSa), but with stronger maritime influence in Barcelona due to its coastal location [38].

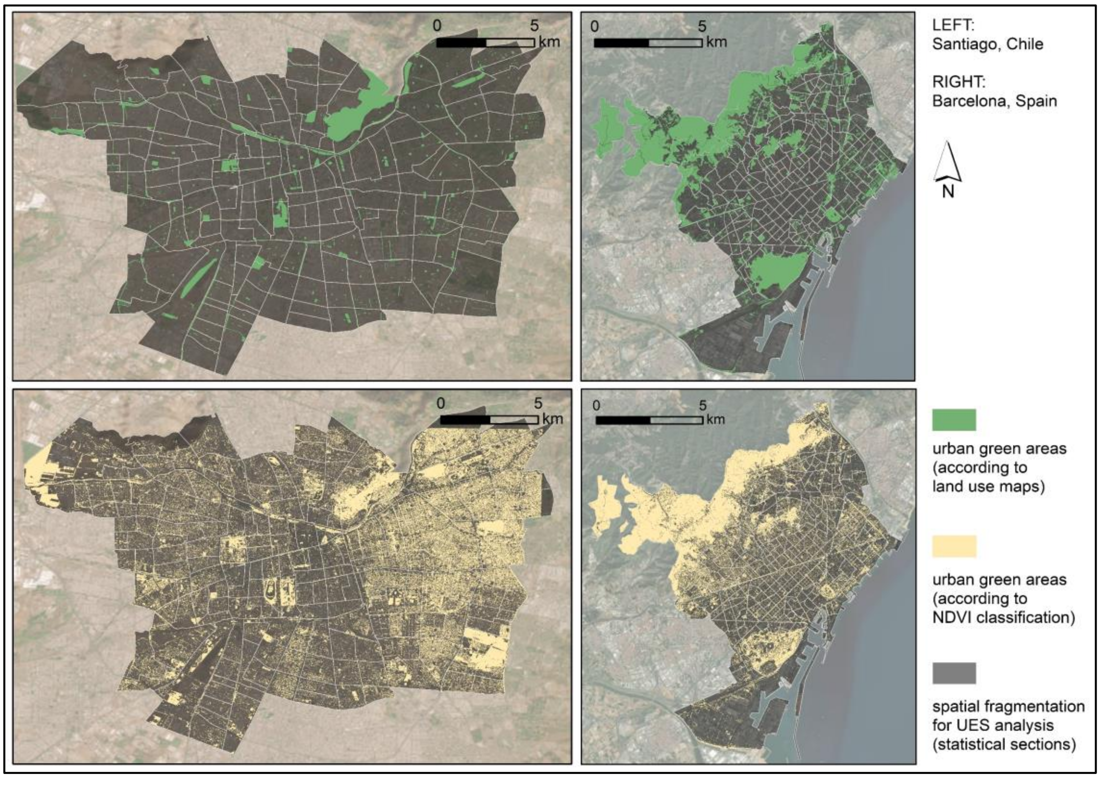


Figure 1. Study areas and relevant data layers

2.2. Conceptual design

The main objective of this study is to quantify, and spatially assign, the provision of urban ecosystem services at the district level in the cities of Barcelona and Santiago, and, by use of different standardization methods, examine the applicability of the EMDS system in comparison and quantification of urban ecosystem services provision at local the level. To meet this goal, the project was organized in four steps:

1. Define indicators for urban ecosystem services in terms of sets of metrics. An analysis of data availability was done at this first step to identify the metrics that could be used in assessment in both cities for accurate comparisons. Metrics are variables that collectively quantify each ecosystem service indicator. In total, the provision of 10 urban ecosystem services was defined in each city, with each UES represented by one metric.
2. Analyse the provision of urban ecosystem services at the district level. In this step we designed the model to quantify the provision of each of the 10 UES defined in the first step. The same model, created in a logic-based geospatial modelling system, was applied in each city.
3. Apply different normalization methods to compare provision between Barcelona and Santiago. In this step, we tested how different normalization methods affect interpretation of UES provision and comparison, and tested the utility of EMDS in this analysis. For that purpose, we used two different normalization methods. As a result, UES provision maps were obtained.
4. Spatial aggregation and variation analysis. In this final step, we analysed differences in spatial aggregation and variation of provisioning between the results obtained by the two normalization methods.

2.2.1. Definition of urban ecosystem services

The first step in ecosystem services analysis was the definition of UES indicators. An analysis of data availability was performed to identify spatial data that could be used to define and quantify the UES indicators. Because the goal of the study was to compare UES provision in the two cities, it was necessary to use at least approximately similar metrics in both cities, and this requirement substantially reduced data choices. Finally, one dataset of metrics, was used to define each UES indicator in both cities. Therefore, 20 metrics in total were used in this study to define and quantity the 10 UES (Table 1).

Geoprocessing operations in ArcMap 10.8 were applied to produce the desired metrics for each landscape unit of each city. Once calculated, all metrics were attributed to the relevant spatial units. We used the MEA methodological framework [31] to model the data (Table 1) and, consequently, categories of regulating and cultural ecosystem services were used as the basis for the analysis.

Table 1. Metrics selected to evaluate each of the 10 UES data inputs.

UES groups and UES indicators	UES metrics	Units	Format	Metrics references
REGULATING				
Micro-climate regulation	Intensity of urban heat island based on land surface temperature	°C	Raster	[39]
Air quality regulation	CO_2 storage by urban trees	Kg/m^2	Raster	[40]
Drainage	Extension of impermeable surfaces or areas covered by vegetation	%	Raster	[41], [42]
Noise reduction	Presence of green infrastructure along traffic axis	%	Polygon	[43], [44]
Habitat provision	Continuity of green urban areas	m^2	Raster	[45]
CULTURAL				
Recreation	Distance to the closest green urban area suitable for recreational activities	m	Point	[46], [47]
Social value	Quantity of sites within urban green areas serving as a meeting point with other citizens	$num./km^2$	Point	[48]
Psychological or health-related value	Abundance of urban green areas within neighbourhoods	$m^2/inh.$	Polygon	[49][50]
Cultural or historical value	Quantity of urban green sites relevant to local culture or history	$num./km^2$	Point	[51]
Aesthetics	Presence of green urban areas on the streets	%	Polygon	[52]

Regulating services are the benefits people obtain from the regulation of ecosystem processes [31]. We used five metrics to quantify the provision of five ecosystem services in each city (Table 1). To assess micro-climate regulation, an urban heat island intensity was calculated. The calculation was done using Landsat 8 imagery, band 10 from the TIRS sensor, and bands 4 and 5 from the OLI sensor. The list of images is shown in Table 2. All selected images correspond to the summer months, have minimum cloudiness in the scene and were adjusted by an atmospheric correction process [53]. The Jiménez-Muñoz and Sobrino method [54] was used to calculate land-surface temperature and approximate urban heat island intensity. Emissivity values, needed for the land-surface temperature calculation, were obtained using the Normalised Difference Vegetation Index (NDVI) thresholds approach for emissivity analysis [55], with NDVI values modified according to local imagery characteristics and established as shown in Table 3. Given the land-surface temperature calculations, a mean temperature for each district was calculated.

Table 2. Landsat 8 images used in urban heat island calculation.

Barcelona		**Santiago**	
Date	*Resolution*	*Date*	*Resolution*
12/07/2013	30 m multispectral, 100 m thermal pixel	09/01/2014	30 m multispectral, 100 m thermal pixel
14/08/2016	30 m multispectral, 100 m thermal pixel	15/01/2016	30 m multispectral, 100 m thermal pixel
22/07/2019	30 m multispectral, 100 m thermal pixel	23/01/2019	30 m multispectral, 100 m thermal pixel

Table 3. NDVI thresholds applied in emissivity calculation.

Land use type	**NDVI thresholds**	**Emissivity values**
Vegetation	> 0.4	0.99
Water	< 0	0.98
Built-up areas	0 <= NDVI < 0.1	0.95
Bare ground	0.1 <= NDVI < 0.2	0.94
Mixed pixels	0.2 <= NDVI < 0.4	Equation by Valor and Caselles [55]

We used CO2 storage in urban trees to quantify regulation of air quality. A remote sensing-based method using NDVI values was implemented with the formula adjusted to our image resolution [40]. Rapid-Eye images from the Catholic University of Chile, from 11/10/2013, were used to calculate NDVI values in Santiago. On the other hand, open-source NDVI data from 2017, provided by the City Council, was applied in the analysis in Barcelona [56]. Mean values were calculated for each city district. The same data sources were used in assessment of drainage. We identified pixels corresponding to impermeable surfaces and areas with vegetation cover, and calculated the percentage these areas occupy within the city district area. Urban green continuity was used as a proxy for habitat provision [57] [58]. Continuous areas of pixels with vegetation cover were detected and a mean value for each city district was calculated. Finally, noise reduction was assessed as the share of green area along streets using a buffer of 20 metres on either side of the street.

Cultural services are “nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, recreation, reflection, and aesthetic experiences” [31]. Due to their intangible characteristics, they are usually difficult to quantify, often being a subject of controversy, because their definitions are typically vague, and indicators for these are not well established [48][59]. In this study we used five metrics to quantify the provision of five cultural ecosystem services (Table 1).

Recreation was assessed by the proximity of the UGA to an analysis unit suitable for recreational activities (UGA > 2 ha) [56] [60]. A dot map, with the separation between dots of 30 m, was created over the urbanised areas of both cities. Distance from each point to the nearest UGA was measured and a mean value calculated for each district. Social value was measured by quantification of urban amenities for social activities located within an UGA, such as parks for children, open air gyms, barbecue areas, parks with registered social activities, etc. A density per square kilometre was calculated in each city district. The same unit was used to quantify cultural or historical value. Here, only protected urban green areas, such as historical parks, monumental trees, areas or trees of local interest, etc., were taken into account. The psychological and health-related value was assessed as the quantity of green areas within the city district (parks, urban forests or green squares) per number of inhabitants [56] [60]. Finally, we analysed the presence of UGA within the 20-m street buffers to assess the aesthetics. Values of a share of a green area out of the buffer zone were represented as a mean value at the city district level.

2.2.2. Analysis of the provision of urban ecosystem services

After quantifying the UES indicators with the metrics in the previous step, we proceeded to quantify their provision to districts. A geospatially based logic model was built in NetWeaver Developer [61], a component of the EMDS spatial decision support framework [30]. Provision of each metric in a district was quantified by use of a specific measure of the strength of evidence obtained from the model. The UES provision was quantified by application of unique rules applied to each metric that approximated relations between the metrics and the UES. These rules define type of relationship and interdependency between the metrics, as well as degree of consideration of each metric in indicator's quantification process.

The logic models in NetWeaver are built as networks of networks organised in a logical dependency structure. The strength of evidence of dependent networks is logically derived from evidence provided by antecedent networks [61]. Elementary networks, whose only antecedents are data (e.g., metrics), are located at the lowest level of the model structure, and are the origin of the strength of evidence measures. Each elementary network uses a fuzzy membership function to express the degree of support for a logical proposition provided by an observed data value. The evidence measures at the bottom of the network structure are propagated upward through the antecedent and dependent networks, connected by logic operators that specify how the evidence measures should be combined. In this study, we built two structurally equivalent logic models, one for each study area.

We used NetWeaver's graphical method of model design to build the model. The full model is documented in HTML (Archive 1), and we show a graphic representation of regulating services in Barcelona in Figure 2. The evaluation of regulating services considers five metrics (Table 1), each evaluated by a fuzzy membership function. In Figure 2, we show how the observed data relative to climate regulation are converted into the strength of evidence values. These range from -1 (meaning no evidence, or no provision of UES) to 1 (full evidence, or full provision of UES). Each of the other four metrics were similarly evaluated by definition of specific thresholds on the observed data, used to define the strength of evidence (Table 4). The U operator (Union in NetWeaver) specifies that the measures of strength of evidence for all metrics in our model are logically combined as an average, meaning that the lines of evidence are additive and compensatory, so that low evidence values on one metric can be compensated by high values on others. Although NetWeaver allows for weighting the evidence of antecedent networks, our models use NetWeaver's default value of 1 so all networks contribute equally to a conclusion of provisioning.

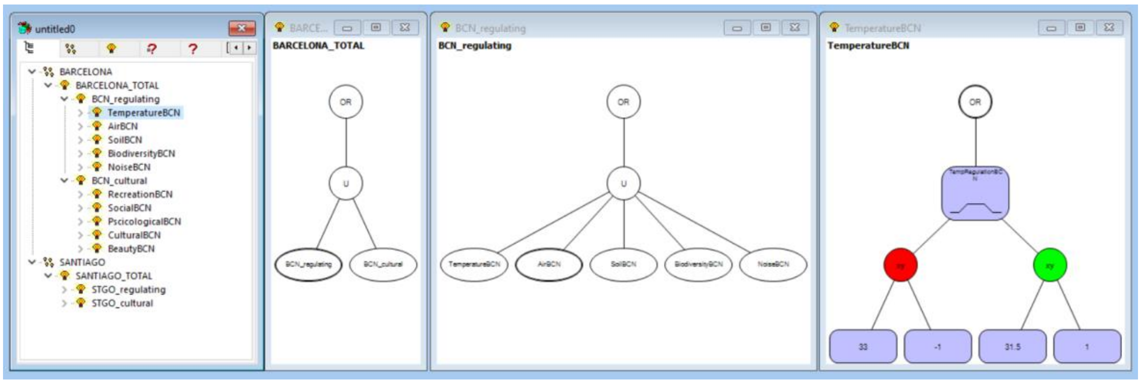


Figure 2. Graphic representation of NetWeaver model regarding the provision of regulating services in Barcelona

2.2.3. Comparison of urban ecosystem services between the two cities

Given the model construction described in the previous section, we compared the provision of UES within districts of a city and between cities. Because the metrics we implemented had different absolute ranges between the two cities, resulting in distinct scales for provision of a metric, they are not directly comparable. Therefore, we tested two different methods to analyse UES provision and, subsequently, compare provisioning outcomes between Santiago and Barcelona. The difference between the two methods is based on the assignment of thresholds used to define the fuzzy membership functions, described in the previous section. In the first method, which we refer to as the *separated thresholds approach*, observed data values were analysed independently for each city and unique thresholds were calculated separately for Santiago and Barcelona. Maximum and minimum thresholds values for defining the fuzzy membership functions in each city were assigned based on literature review, for recreation and noise reduction, or based on the 15th and the 85th percentile for other UES indicators (Table 4). On the other hand, in the second method, the *joint thresholds approach*, the analysis was run with the unique threshold values for defining the fuzzy membership functions determined based on both study areas (Figure 3). In particular, the threshold values of the fuzzy membership functions in the joint threshold approach are calculated as the mean threshold values from the separated thresholds approach (Table 4).

The spatial analysis was done using ArcGIS 10.8 software, as well as the EMDS 8.7 ArcMap Add-Inn. After running the NetWeaver model in EMDS, maps showing the provision of each UES indicator, UES groups, and total UES provision were generated. Lastly, we note that the strength of evidence measure computed in NetWeaver is a continuous variable, but the map values were classified in five categories using equal intervals, from very low to very high, for display purposes.

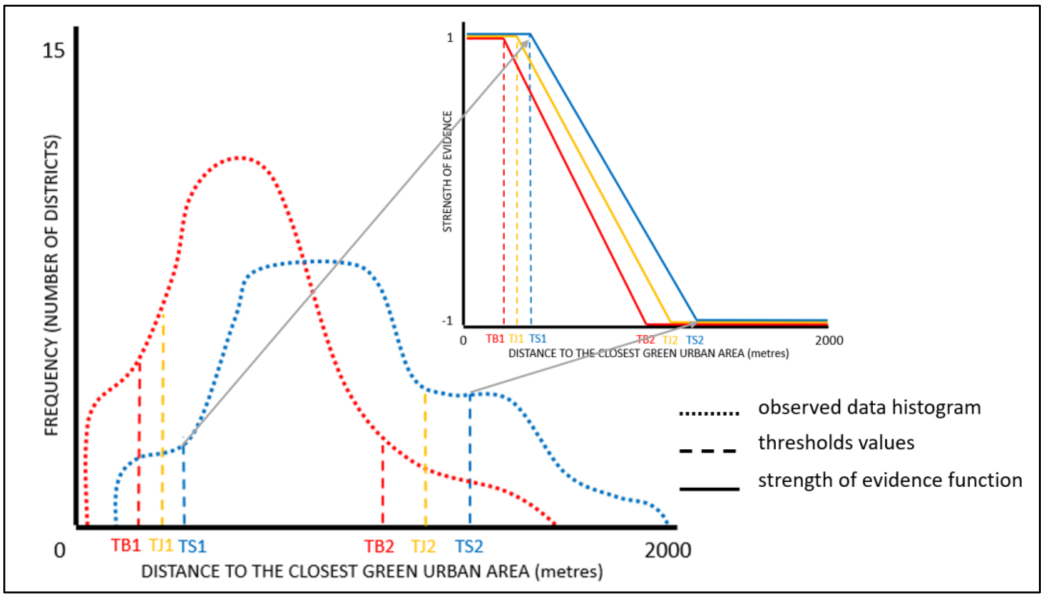


Figure 3. Schematic representation of threshold assignments for the strength of evidence function using recreation UES as an example. Red lines represent Barcelona

(using separated thresholds approach), blue lines represent Santiago (using separated thresholds approach) and orange lines represent joint thresholds approach

Table 4. Observed values thresholds to define strength of evidence values.

UES metrics	**Metrics units**	**Separated thresholds approach**				**Joint thresholds approach**	
		BARCELONA		SANTIAGO			
		No evidence	Full evidence	No evidence	Full evidence	No evidence	Full evidence
Micro-climate regulation	°C	33	31.5	35	32	34	31.75
Air quality regulation	Kg/m^2	1.25	1.7	1	1.45	1.35	1.57
Drainage	%	12	40	12	50	12	45
Habitat provision	m^2	900	80000	2000	4000000	1450	2000000
Noise reduction	%	20	40	10	35	15	37.5
Recreation	m	700	150	1000	300	850	225
Social value	num./km^2	0	15	0	2	0	1.5
Psychological or health-related value	m^2/inh.	1	23	0.1	1.2	0.55	12.1
Cultural or historical value	num./km^2	0	10	0	1.3	0	5.65
Aesthetics	%	10	35	5	35	7.5	35

2.2.4. Spatial aggregation and variation analysis

In this final step, total provision scores resulting from the two different methods were compared and analysed. For this purpose, the strength of evidence values (ranging from -1 to 1), were normalized to a [0-1] scale to simplify interpretation. Normalized provision scores obtained with the separated thresholds approach were deducted from the value obtained using the joint thresholds approach. The results depict the degree (0-1, or 0 % - 100 %) and direction (positive or negative) of change in provision resulting from application of the two different methods. Additionally, changes in spatial aggregation of provision per districts were analysed applying global Moran's I statistics, a spatial autocorrelation tool that assesses both spatial location and changes in values of features [62]. Applying Moran's I, we are aiming to assess the equality in provision of UESs and, therefore, urban well-being. Lack of spatial correlation (negative I values) means lower aggregation and greater equality in provision, and vice versa [63]. We aim to compare the results obtained by two different methods to identify the gap between provision between the cities and to study the relativeness regarding optimal provision of UES.

3. Results

The spatial distribution of provision of UES in Santiago calculated using separated thresholds approach is shown on Figure 4. The provision of cultural and regulating UES did not follow a common spatial pattern. Provision of cultural services is generally low within the entire study area, with the exception of a few specific districts where higher provision can be noticed. On the other hand, provision of regulating services shows clear east – west spatial polarization. While very low strength of evidence dominates the central and western districts of the city, with several low and medium values, eastern districts display continuous areas of very high provision. With respect to the total provision of UES in Santiago, a more irregular spatial pattern is evident, maintaining high strength of evidence values on the east, but with less distinctive difference towards the west.

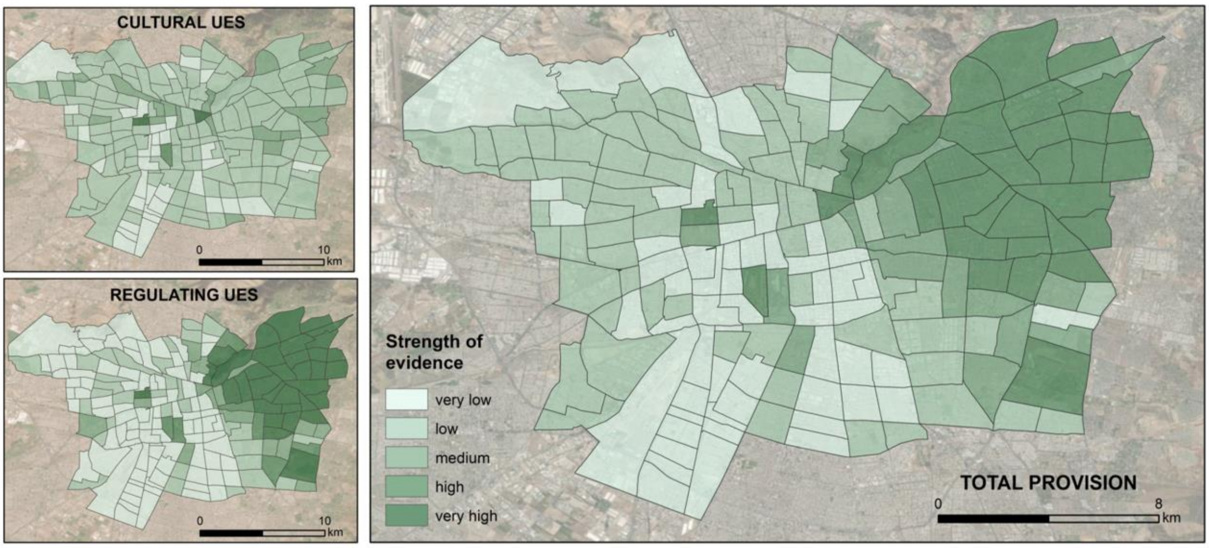


Figure 4. Maps of provision of UES in Santiago using separated thresholds approach

Figure 5 shows the spatial distribution of UES in Barcelona calculated using separated thresholds approach. In comparison to Santiago, the spatial distribution of both cultural and regulating services was more irregular. Generally, higher values are observed in the marginal districts of the city, leaving the central districts characterised by lower strength of evidence. Regulating services show greater polarisation in values within the study area, while score differences of cultural services are smoother. Total provision of UES in Barcelona has an uneven spatial distribution. In general terms, very high provision values are observed in the districts where parks or urban forests are situated, located in the mountainous parts of the city; coastal districts have medium values, while irregular representativeness of very low, low and medium scores can be noticed in the central portion of the study area.

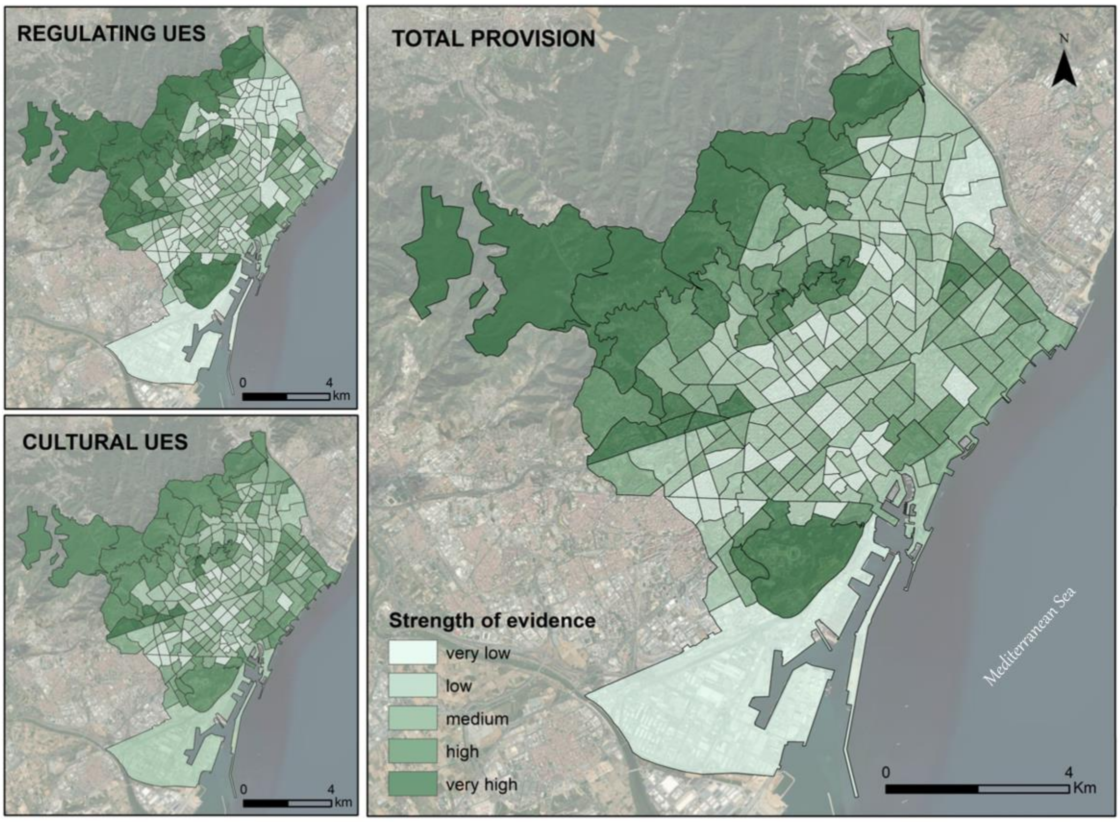


Figure 5. Maps of provision of UES in Barcelona using separated thresholds approach

Figure 6 shows the total provision of UES in Santiago and Barcelona when applying joint threshold approach. Spatial distribution of provisioning values follows a similar spatial pattern in both cities as in the previous method. However, changes in provision values can be noticed in both study areas. In Santiago, about 50% of city districts show an increase, while in other 50% of districts lower provision values were observed. Nevertheless, negative variations are more frequent (mean decrease value is -0.04, while mean increase value is 0.02), indicated by the predominance of lighter shades in the Figure 6. Most of the districts registered changes in values passing from high to medium, on the east, or low to very low in the western part of the city. Only a few city districts had a significant increase in provision after applying joint thresholds approach compared to the separated thresholds approach (Figure 4). On the contrary, most districts of Barcelona showed an increase of UES provision scores, about 80% of the total number. At the same time, mean variation values are equal in both positive and negative records. Most coastal districts passed from medium to high strength of evidence. The provision increased from very low to low, and from low to medium in several central city areas, while the increment from medium to high, and high to very high was observed in the mountain districts. Significant decrease in provision was only registered in a few suburban areas, mostly passing from very high to high.

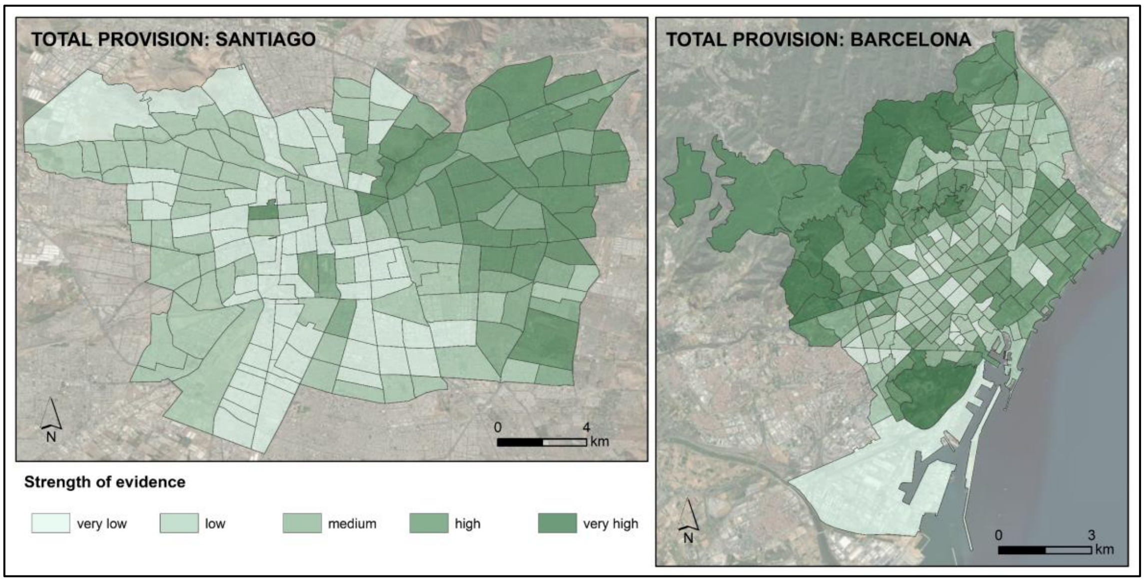


Figure 6. Maps of provision of UES in Santiago and Barcelona using joint thresholds approach

Variations in provisioning values between the two methods are much higher in Barcelona than in Santiago, both in positive and in negative changes. After using the joint thresholds approach, the provision values in Barcelona predominantly increased, with the scores up to 20 % higher. On the other hand, when provision scores in Santiago were directly compared to the absolute provision values in Barcelona, smoother variations were noticed, but with greater decrease tendency, reaching up to -10 %.

Regarding spatial aggregation of UES provision values, positive Moran's I values were obtained in both the separated and joint thresholds approaches in both cities, indicating some degree of aggregation. However, significant differences were observed between Santiago and Barcelona. First, spatial aggregation of total UES provision is higher in Santiago than in Barcelona. Moran's I in Santiago is 0.53 both in the separated thresholds approach and in the joint thresholds approach, while respective values in Barcelona are 0.19 and 0.15 so the aggregation of total provision varies more in Barcelona than in Santiago, when comparing the two thresholds approaches. Differences in spatial aggregation were also observed in provision of regulating UES using the joint thresholds approach, in which Santiago had a high index value (0.63), whereas Barcelona had a low value (0.12).

4. Discussion

In this study we conducted two different comparison methods to evaluate the provision of UES in the cities of Santiago and Barcelona. In both cases, an innovative spatial decision support framework, EMDS, was applied toallow the analysis of single and combined UES provision.. We used the same data in both approaches, only changing the threshold values to define low and high evidence of UES provision, which were primarily derived from evaluation of histograms of data distributions. After the application of the different threshold approaches, clearly distinct results were obtained in both cities, resulting in changed provision evidence values. Because the identification of needed interventions on the green infrastructure, and specification of actions required to improve urban green and human well-being are directly conditioned by characteristics of UES supply, it is crucial to know their current state and manage them appropriately [64]. Our approach also attempts to develop standardised comparison methods to reduce ambiguities in results, as well as provide a spatial solution for analysing UES to support urban planning policies that, in turn, provide a basis for less ambiguous definition of good urban strategy [65].

Provision of ecosystem services including UES depends primarily on the capacity of the ecosystem to deliver them [31]. While in rural environments, it might be a challenging task to change the ecosystem capacity in the short-term, urban environments are characterised by more dynamic geospatial features that are amenable to implementing changes. Namely, by land-use changes or interventions on urban facilities, environmental settings can be substantially changed in a relatively short time, enabling new scenarios for UES provision [66]. Ideally, these changes should be induced by prior analyses of current UES characteristics, aiming to improve them [2]. The comparison analyses presented in this study can substantially help to define the actions needed to initiate these changes and, therefore, act as a useful tool in UES management. These types of analyses also can improve awareness of the need to continue improving urban ecosystems and increase UES provision. Our results illustrate how perception of provision values in a certain city can change by considering alternative comparison methods. Such perception can result in obtaining a wrong image of UES-related processes and their provision, and can lead to taking inappropriate decision regarding urban planning. For example, generally high provision values were observed in the eastern part of Santiago when the data were analysed independently, but, after observing results in the broader context of the joint comparison method that included data from Barcelona, the provision in Santiago decreased, whereas the opposite outcome was observed in Barcelona. In other words, when using the separated thresholds approach, high values in Santiago and Barcelona were not equally high, which emphasizes the relativeness in provision of UES in this approach. This can easily cause difficulties with defining an appropriate urban planning strategy that attempts to improve the distribution of environmental goods and well-being. This also raises questions about the methodology for such comparison studies and which scores the provision should register to be considered as high enough. Until now, UES comparison between different cities has only been conducted in a limited number of studies with a clear lack of coherent comparison methods [3], [16], and these have been based on what we refer to as the separated thresholds method, in which each dataset, before being compared, was analysed and normalised independently. As demonstrated in this study, such methods can provide misleading results, because the provision scales are based on different absolute values. While there is an objective at the global level focused on urgent mitigation of inequality of environmental goods, development of research methodology does not follow the same path [25]. It is evident that each urban area has a unique geospatial reality defined by specific sets of features, including urban green infrastructure, and that the capacity of UES provision strongly depends on these characteristics, but effective improvements cannot be achieved at a broader global scale if each urban landscape is analysed independently. Thus, in this study, we emphasize the need to improve UES comparison methods in order to obtain more comparable results that would help to achieve more equal distribution of urban well-being across cities by establishing more standardised comparison methods, such as definition of UES thresholds that could be applicable over broad spatial extents.

Regarding the provision values, the literature usually strives for an increase of UES supply, but there is no consensus on how high the provision should be to satisfactorily supply all the benefits. In rural environments, the goal is to achieve the maximum provision that the environment can provide according to its capacity, without putting it at environmental risk [67]. In urban environments, the capacity can easily be increased, but the environmental pressure on UGA can also fluctuate drastically depending on geographical circumstances [68]. The joint thresholds method that was demonstrated in this study can help to evaluate UES provision over broader spatial extents, and can give a better perception of the comparability UES characteristics (or lack thereof), but it cannot a complete solution of the actions needed to manage UGA. At the same time, we recognize that, in some cases, absolute values of provision of UES can be so different that it may not make sense to adjust their interpretation to a common data scale. However, using the separated thresholds approach in the latter case would give even more problematic as discussed above. For that reason, this study also emphasizes the methodological constraints regarding UES comparison, although it represents a first step towards more complete comparison methods, while also emphasising the need for more developed and elaborated methodological approaches.

The EMDS system that was used in this study enables the application of geospatial modelling to assess the complexity of the urban environment. Although EMDS had not been applied in UES related studies previously, the system shows several strengths in resolving complex spatial problems. Apart from well-established terminology that facilitates the interpretation of results, a user-friendly interface enables consideration of spatial complexities in a relatively simple way [69]. The latter features help to strengthen collaboration between scientists and end-users, facilitating EMDS application in participatory planning. The possibility of implementation of such methodology, by combination of expert knowledge and scientific methods, is of great interest in the UES related decision-making processes [70].

The spatial analysis of UES provision as illustrated in this study is a useful foundation for decision makers in setting policies and developing strategies for improving provisioning of ES in urban landscapes insofar as it spatially quantifies the current state of the urban environment with respect to its current status. However, to effectively support decision making in this context, additional decision tools are needed to 1) identify which urban districts are the best targets for improvements in UES provision (e.g., strategic planning), and 2) what specific actions in those districts would produce the biggest gain in provisioning (e.g., tactical planning). Whereas the spatial analysis of UES provisioning is relatively objective, the subsequent decision analyses are relatively subjective, but can be assisted by tools for multi-criteria decision analysis (MCDA, [71]) that help decision makers to organize decision criteria into models, decide on the relative importance of those criteria, and document the decision models in order to facilitate stakeholder participation. While the current study only addresses the foundational spatial analysis of UES provisioning, the EMDS system includes a variety of MCDA methods that can be applied to extend the current EMDS application to the strategic and tactical phases of decision support for UES provisioning.

5. Conclusions

In this study, we assessed the provision of UES in Barcelona, Spain and Santiago, Chile, implementing two different comparison methods. The EMDS spatial decision support framework was applied in data modelling and results interpretation. The results demonstrate different levels of provisioning of UES, depending on the methodological approach, and reflect the relativeness in UES provision which presents difficulties in developing effective strategic and tactical solutions for urban planning. Therefore, we suggest UES comparison methods as a useful tool to detect environmental injustice in urban areas and to support better UGA management. Still, it has to be considered that standardization processes required for comparisons between urban entities, may neglect the use of highly specific but relevant information.

Endnotes: The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Author Contributions: All authors participated on the conceptualization of the project. G.K. and S.R.P. implemented the data preparation. G.K. did the analysis and wrote an initial draft. K.M.R supervised the development and implementation of EMDS framework. G.K., J.R.G.O. and J.G.G. analysed the results. All authors participated in in editing process of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Catalan government predoctoral scholarship (AGAUR-FSE 2020 FI_B2 00147) and SuFoRun Marie Sklodowska-Curie Research and Innovation Staff Exchange (RISE) Program (Grant agreement No: 691149).

Data Availability Statement: Archive 1, containing data used in the analysis, is elaborated and available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] P. Bolund and S. Hunhammar, "Ecosystem services in urban areas," Ecological Economics, vol. 29, no. 2, pp. 293–301, 1999, doi: 10.1016/S0921-8009(99)00013-0.

[2] E. Gómez-Baggethun and D. N. Barton, "Classifying and valuing ecosystem services for urban planning," Ecological Economics, vol. 86, pp. 235–245, 2013, doi: 10.1016/j.ecolecon.2012.08.019.

[3] C. Kourdounouli and A. M. Jönsson, "Urban ecosystem conditions and ecosystem services–a comparison between large urban zones and city cores in the EU," Journal of Environmental Planning and Management, vol. 63, no. 5, pp. 798–817, 2020, doi: 10.1080/09640568.2019.1613966.

[4] C. Dobbs, D. Kendal, and C. R. Nitschke, "Multiple ecosystem services and disservices of the urban forest establishing their connections with landscape structure and sociodemographics," Ecol Indic, vol. 43, pp. 44–55, 2014, doi: 10.1016/j.ecolind.2014.02.007.

[5] R. Kraemer and N. Kabisch, "Parks in context: Advancing citywide spatial quality assessments of urban green spaces using fine-scaled indicators," Ecology and Society, vol. 26, no. 2, 2021, doi: 10.5751/ES-12485-260245.

[6] M. L. Derkzen, A. J. A. van Teeffelen, and P. H. Verburg, "REVIEW: Quantifying urban ecosystem services based on high-resolution data of urban green space: An assessment for Rotterdam, the Netherlands," Journal of Applied Ecology, vol. 52, no. 4, pp. 1020–1032, 2015, doi: 10.1111/1365-2664.12469.

[7] M. L. Wilkerson et al., "The role of socio-economic factors in planning and managing urban ecosystem services," Ecosyst Serv, vol. 31, pp. 102–110, 2018, doi: 10.1016/j.ecoser.2018.02.017.

[8] J. Niemelä et al., "Using the ecosystem services approach for better planning and conservation of urban green spaces: A Finland case study," Biodivers Conserv, vol. 19, no. 11, pp. 3225–3243, 2010, doi: 10.1007/s10531-010-9888-8.

[9] A. R. Holt, M. Mears, L. Maltby, and P. Warren, "Understanding spatial patterns in the production of multiple urban ecosystem services," Ecosyst Serv, vol. 16, pp. 33–46, 2015, doi: 10.1016/j.ecoser.2015.08.007.

[10] C. Dobbs, Á. Hernández-Moreno, S. Reyes-Paecke, and M. D. Miranda, "Exploring temporal dynamics of urban ecosystem services in Latin America: The case of Bogota (Colombia) and Santiago (Chile)," Ecol Indic, vol. 85, no. December 2017, pp. 1068–1080, 2018, doi: 10.1016/j.ecolind.2017.11.062.

[11] C. Dobbs, F. J. Escobedo, and W. C. Zipperer, "A framework for developing urban forest ecosystem services and goods indicators," Landsc Urban Plan, vol. 99, no. 3–4, pp. 196–206, 2011, doi: 10.1016/j.landurbplan.2010.11.004.

[12] F. Li, S. Guo, D. Li, X. Li, J. Li, and S. Xie, "A multi-criteria spatial approach for mapping urban ecosystem services demand," Ecol Indic, vol. 112, no. January, 2020, doi: 10.1016/j.ecolind.2020.106119.

[13] S. M. Gold, "Social benefits of trees in urban environmentst," International Journal of Environmental Studies, vol. 10, no. 1, pp. 85–90, 1976, doi: 10.1080/00207237608737297.

[14] V. Amini Parsa, E. Salehi, A. R. Yavari, and P. M. van Bodegom, “Evaluating the potential contribution of urban ecosystem service to climate change mitigation,” Urban Ecosyst, vol. 22, no. 5, pp. 989–1006, 2019, doi: 10.1007/s11252-019-00870-w.

[15] C. Xu, W. Jiang, Q. Huang, and Y. Wang, “Ecosystem services response to rural-urban transitions in coastal and island cities: A comparison between Shenzhen and Hong Kong, China,” J Clean Prod, vol. 260, p. 121033, 2020, doi: 10.1016/j.jclepro.2020.121033.

[16] A. Gret-Regamey, A. Gret-Regamey, A. Gret-Regamey, M. Galleguillos-Torres, A. Dissegna, and B. Weibel, “How urban densification influences ecosystem services - A comparison between a temperate and a tropical city,” Environmental Research Letters, vol. 15, no. 7, 2020, doi: 10.1088/1748-9326/ab7acf.

[17] M. Subiza-pérez, L. Vozmediano, and C. San, “Landscape and Urban Planning Green and blue settings as providers of mental health ecosystem services : Comparing urban beaches and parks and building a predictive model of psychological restoration,” Landsc Urban Plan, vol. 204, no. March, p. 103926, 2020, doi: 10.1016/j.landurbplan.2020.103926.

[18] Z. Bing, Y. Qiu, H. Huang, T. Chen, W. Zhong, and H. Jiang, “Spatial distribution of cultural ecosystem services demand and supply in urban and suburban areas: A case study from Shanghai, China,” Ecol Indic, vol. 127, p. 107720, 2021, doi: 10.1016/j.ecolind.2021.107720.

[19] R. Remme, T. de Nijs, and M. Paulin, “Natural Capital Model - Technical documentation of the quantification, mapping and monetary valuation of urban ecosystem services,” RIVM report 2017-0040, p. 76, 2018, [Online]. Available: www.rivm.nl/en

[20] P. A. Tavares, N. Beltrão, U. S. Guimarães, A. Teodoro, and P. Gonçalves, “Urban ecosystem services quantification through remote sensing approach: A systematic review,” Environments - MDPI, vol. 6, no. 5, pp. 9–11, 2019, doi: 10.3390/environments6050051.

[21] J. B. Alemu I, D. R. Richards, L. Y. F. Gaw, M. Masoudi, Y. Nathan, and D. A. Friess, “Identifying spatial patterns and interactions among multiple ecosystem services in an urban mangrove landscape,” Ecol Indic, vol. 121, p. 107042, 2021, doi: 10.1016/j.ecolind.2020.107042.

[22] K. Shiraishi, “The inequity of distribution of urban forest and ecosystem services in Cali, Colombia,” Urban For Urban Green, vol. 67, no. September 2021, p. 127446, 2022, doi: 10.1016/j.ufug.2021.127446.

[23] S. L. Watkins and E. Gerrish, “The relationship between urban forests and race: A meta-analysis,” J Environ Manage, vol. 209, pp. 152–168, 2018, doi: 10.1016/j.jenvman.2017.12.021.

[24] F. J. Escobedo, N. Clerici, C. L. Staudhammer, and G. T. Corzo, “Socio-ecological dynamics and inequality in Bogotá, Colombia’s public urban forests and their ecosystem services,” Urban For Urban Green, vol. 14, no. 4, pp. 1040–1053, 2015, doi: 10.1016/j.ufug.2015.09.011.

[25] C. C. Konijnendijk, “Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: Introducing the 3–30–300 rule,” J For Res (Harbin), 2022, doi: 10.1007/s11676-022-01523-z.

[26] A. M. Nahlik, M. E. Kentula, M. S. Fennessy, and D. H. Landers, "Where is the consensus? A proposed foundation for moving ecosystem service concepts into practice," Ecological Economics, vol. 77, pp. 27–35, 2012, doi: 10.1016/j.ecolecon.2012.01.001.

[27] E. Blanco, K. Raskin, and P. Clergeau, "Towards regenerative neighbourhoods: An international survey on urban strategies promoting the production of ecosystem services," Sustain Cities Soc, vol. 80, no. January, p. 103784, 2022, doi: 10.1016/j.scs.2022.103784.

[28] D. Haase et al., "A quantitative review of urban ecosystem service assessments: Concepts, models, and implementation," Ambio, vol. 43, no. 4, pp. 413–433, 2014, doi: 10.1007/s13280-014-0504-0.

[29] A. Grêt-Regamey, E. Sirén, S. H. Brunner, and B. Weibel, "Review of decision support tools to operationalize the ecosystem services concept," Ecosyst Serv, vol. 26, no. April 2016, pp. 306–315, 2017, doi: 10.1016/j.ecoser.2016.10.012.

[30] K. M. Reynolds and P. F. Hessburg, "An Overview of the Ecosystem Management Decision-Support System," Environmental Science and Engineering, pp. 3–22, 2014, doi: 10.1007/978-3-642-32000-2_1.

[31] Millennium Ecosystem Assessment., "Ecosystems and Human Well-Being.," Washington DC, 2005.

[32] C. Montoya-Tangarife, F. de La Barrera, A. Salazar, and L. Inostroza, "Monitoring the effects of land cover change on the supply of ecosystem services in an urban region: A study of Santiago-Valparaíso, Chile," PLoS One, vol. 12, no. 11, pp. 1–22, 2017, doi: 10.1371/journal.pone.0188117.

[33] S. Zhang and F. M. Ramírez, "Assessing and mapping ecosystem services to support urban green infrastructure : The case of Barcelona , Spain," Cities, vol. 92, no. May 2018, pp. 59–70, 2019, doi: 10.1016/j.cities.2019.03.016.

[34] F. Baró, I. Palomo, G. Zulian, P. Vizcaino, D. Haase, and E. Gómez-Baggethun, "Mapping ecosystem service capacity, flow and demand for landscape and urban planning: A case study in the Barcelona metropolitan region," Land use policy, vol. 57, no. November 2017, pp. 405–417, 2016, doi: 10.1016/j.landusepol.2016.06.006.

[35] C. Dobbs et al., "Urban ecosystem Services in Latin America: mismatch between global concepts and regional realities?," Urban Ecosyst, vol. 22, no. 1, pp. 173–187, 2019, doi: 10.1007/s11252-018-0805-3.

[36] "National Statistics Institute. Residents in Spain 2022." https://www.ine.es/index.htm (accessed Jan. 30, 2023).

[37] "National Statistics Institute. Census 2017." https://www.ine.gob.cl/censo (accessed Jan. 30, 2023).

[38] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World map of the Köppen-Geiger climate classification updated," Meteorologische Zeitschrift, vol. 15, no. 3, pp. 259–263, 2006, doi: 10.1127/0941-2948/2006/0130.

[39] F. Cui et al., "Quantifying the response of surface urban heat island to urban greening in global north megacities," Science of the Total Environment, vol. 801, 2021, doi: 10.1016/j.scitotenv.2021.149553.

[40] S. Myeong, D. J. Nowak, and M. J. Duggin, "A temporal analysis of urban forest carbon storage using remote sensing," Remote Sens Environ, vol. 101, no. 2, pp. 277–282, 2006, doi: 10.1016/j.rse.2005.12.001.

[41] D. Armson, P. Stringer, and A. R. Ennos, “The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK,” Urban For Urban Green, vol. 12, no. 3, pp. 282–286, 2013, doi: 10.1016/j.ufug.2013.04.001.

[42] E. Kuehler, J. Hathaway, and A. Tirpak, “Quantifying the benefits of urban forest systems as a component of the green infrastructure stormwater treatment network,” Ecohydrology, vol. 10, no. 3, pp. 1–10, 2017, doi: 10.1002/eco.1813.

[43] A. Dzhambov and D. Dimitrova, “Urban green spaces′ effectiveness as a psychological buffer for the negative health impact of noise pollution: A systematic review,” Noise Health, vol. 16, no. 70, pp. 157–165, 2014, doi: 10.4103/1463-1741.134916.

[44] G. Rey Gozalo, J. M. Barrigón Morillas, D. Montes González, and P. Atanasio Moraga, “Relationships among satisfaction, noise perception, and use of urban green spaces,” Science of the Total Environment, vol. 624, pp. 438–450, 2018, doi: 10.1016/j.scitotenv.2017.12.148.

[45] H. Rudd, J. Vala, and V. Schaefer, “Importance of backyard habitat in a comprehensive biodiversity conservation strategy: A connectivity analysis of urban green spaces,” Restor Ecol, vol. 10, no. 2, pp. 368–375, 2002, doi: 10.1046/j.1526-100X.2002.02041.x.

[46] K. Grunewald, B. Richter, G. Meinel, H. Herold, and R. U. Syrbe, “Proposal of indicators regarding the provision and accessibility of green spaces for assessing the ecosystem service ‘recreation in the city’ in Germany,” Int J Biodivers Sci Ecosyst Serv Manag, vol. 13, no. 2, pp. 26–39, 2017, doi: 10.1080/21513732.2017.1283361.

[47] H. Zhang, B. Chen, Z. Sun, and Z. Bao, “Landscape perception and recreation needs in urban green space in Fuyang, Hangzhou, China,” Urban For Urban Green, vol. 12, no. 1, pp. 44–52, 2013, doi: 10.1016/j.ufug.2012.11.001.

[48] T. Plieninger, S. Dijks, E. Oteros-Rozas, and C. Bieling, “Assessing, mapping, and quantifying cultural ecosystem services at community level,” Land use policy, vol. 33, pp. 118–129, 2013, doi: 10.1016/j.landusepol.2012.12.013.

[49] J. M. Ulmer et al., “Health & Place Multiple health bene fi ts of urban tree canopy : The mounting evidence for a green prescription,” vol. 42, pp. 54–62, 2016, doi: 10.1016/j.healthplace.2016.08.011.

[50] K. L. Wolf, S. T. Lam, J. K. Mckeen, G. R. A. Richardson, M. van den Bosch, and A. C. Bardekjian, “Urban Trees and Human Health : A Scoping Review,” 2020.

[51] R. Maraja, J. Barkmann, and T. Tscharntke, “Perceptions of cultural ecosystem services from urban green,” Ecosyst Serv, vol. 17, pp. 33–39, 2016, doi: 10.1016/j.ecoser.2015.11.007.

[52] T. Hu et al., “Quantifying the shape of urban street trees and evaluating its influence on their aesthetic functions based mobile lidar data,” ISPRS Journal of Photogrammetry and Remote Sensing, vol. 184, no. November 2021, pp. 203–214, 2022, doi: 10.1016/j.isprsjprs.2022.01.002.

[53] E. Chuvieco, Teledetección ambiental. Barcelona, Spain: Ariel, 2010.

[54] J. C. Jime, “A generalized single-channel method for retrieving land surface temperature from remote sensing data,” vol. 108, no. April, 2004, doi: 10.1029/2003JD003480.

[55] E. Valor and V. Caselles, “Mapping land surface emissivity from NDVI: Application to European, African, and South American areas,” Remote Sens Environ, vol. 57, no. 3, pp. 167–184, 1996, doi: 10.1016/0034-4257(96)00039-9.

[56] "Barcelona's City Hall Open Data Service." https://opendata-ajuntament.barcelona.cat/en (accessed Jan. 31, 2023).

[57] V. Dormidontova and A. Belkin, "The Continuity of Open Greened Spaces-Basic Principle of Urboecology," IOP Conf Ser Mater Sci Eng, vol. 753, no. 2, 2020, doi: 10.1088/1757-899X/753/2/022048.

[58] J. Puigdollers et al., "Barcelona green infrastructure and biodiversity plan 2020," Barcelona, Spain (in Spanish, English summary), p. 111, 2013, [Online]. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Barcelona+green+infrastructure+and+biodiversity+plan+2020.#0

[59] M. Hernández-Morcillo, T. Plieninger, and C. Bieling, "An empirical review of cultural ecosystem service indicators," Ecol Indic, vol. 29, pp. 434–444, 2013, doi: 10.1016/j.ecolind.2013.01.013.

[60] "Geospatial Data Infrastructure." https://www.ide.cl/ (accessed Jan. 31, 2023).

[61] B. Miller and M. Saunders, "NetWeaver Reference Manual," no. September 2002, p. 127, 2006.

[62] A. Getis and J. K. Ord, "The Analysis of Spatial Association by Use of Distance Statistics," Geogr Anal, vol. 24, no. 3, pp. 189–206, 1992, doi: 10.1111/j.1538-4632.1992.tb00261.x.

[63] M. Goodchild and D. Janelle, Spatially Integrated Social Science. Spatial Information Systems, 2004.

[64] L. LIU and J. WU, "Scenario analysis in urban ecosystem services research: Progress, prospects, and implications for urban planning and management," Landsc Urban Plan, vol. 224, no. October 2021, p. 104433, 2022, doi: 10.1016/j.landurbplan.2022.104433.

[65] L. P. Romero-Duque, J. M. Trilleras, F. Castellarini, and S. Quijas, "Ecosystem services in urban ecological infrastructure of Latin America and the Caribbean: How do they contribute to urban planning?," Science of the Total Environment, vol. 728, p. 138780, 2020, doi: 10.1016/j.scitotenv.2020.138780.

[66] T. McPhearson, E. Andersson, T. Elmqvist, and N. Frantzeskaki, "Resilience of and through urban ecosystem services," Ecosyst Serv, vol. 12, pp. 152–156, 2015, doi: 10.1016/j.ecoser.2014.07.012.

[67] S. Polasky, D. J. Lewis, A. J. Plantinga, and E. Nelson, "Implementing the optimal provision of ecosystem services," Proc Natl Acad Sci U S A, vol. 111, no. 17, pp. 6248–6253, 2014, doi: 10.1073/pnas.1404484111.

[68] J. H. Spangenberg, C. Görg, D. T. Truong, V. Tekken, J. V. Bustamante, and J. Settele, "Provision of ecosystem services is determined by human agency, not ecosystem functions. Four case studies," Int J Biodivers Sci Ecosyst Serv Manag, vol. 10, no. 1, pp. 40–53, 2014, doi: 10.1080/21513732.2014.884166.

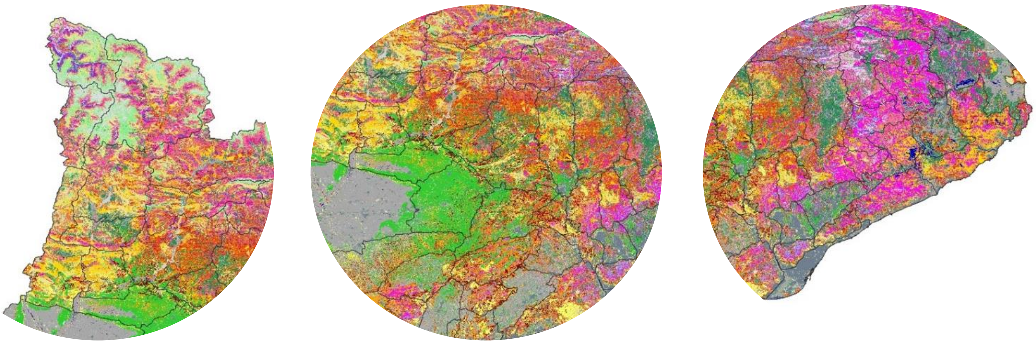
[69] K. M. Reynolds, "EMDS 3.0: A modeling framework for coping with complexity in environmental assessment and planning," Science in China, Series E: Technological Sciences, vol. 49, no. SUPPL. 1, pp. 63–75, 2006, doi: 10.1007/s11431-006-8108-y.

[70] T. Elliot, A. Bertrand, J. Babí Almenar, C. Petucco, V. Proença, and B. Rugani, "Spatial optimisation of urban ecosystem services through integrated participatory and multi-objective integer linear programming," Ecol Modell, vol. 409, no. May, p. 108774, 2019, doi: 10.1016/j.ecolmodel.2019.108774.

[71] I. B. Huang, J. Keisler, and I. Linkov, “Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends,” Science of the Total Environment, vol. 409, no. 19, pp. 3578–3594, 2011, doi: 10.1016/j.scitotenv.2011.06.022.

Article 4

REGIONAL LEVEL DATA SERVER FOR FIRE HAZARD EVALUATION AND FUEL TREATMENTS PLANNING



Published in *Remote Sensing* (2020) DOI: doi.org/10.3390/rs12244124

Krsnik G.; Busquets Olivé, E.; Piqué Nicolau M.; Larrañaga, A.; Cardil, A.; Garcia-Gonzalo, J.; González Olabarria, J.R.

Regional Level Data Server for Fire Hazard Evaluation and Fuel Treatments Planning

Abstract: Both fire risk assessment and management of wildfire prevention strategies require different sources of data to represent the complex geospatial interaction that exists between environmental variables in the most accurate way possible. In this sense, geospatial analysis tools and remote sensing data offer new opportunities for estimating fire risk and optimizing wildfire prevention planning. Herein, we presented a conceptual design of a server that contained most variables required for predicting fire behavior at a regional level. For that purpose, an innovative and elaborated fuel modelling process and parameterization of all needed environmental and climatic variables were implemented in order to enable to more precisely define fuel characteristics and potential fire behaviors under different meteorological scenarios. The server, open to be used by scientists and technicians, is expected to be the steppingstone for an integrated tool to support decision-making regarding prevention and management of forest fires in Catalonia.

Keywords: forest fire prevention; fire hazard; fire simulation; open access server; fuel modelling; weather scenarios modelling; geospatial dataset

1. Introduction

The use of spatial explicit tools that support management decisions is becoming a common practice to mitigate the negative impact of wildfires [1–4]. As in any type of decision, when planning fire prevention strategies and assessing fire risk, a set of criteria and their importance has to be set in accordance with the problem's specific requirements. The risk values, potential post-fire recovery of the ecosystem, and the candidate management options are basic information sources that usually are considered when planning preventive measure. Still, there is a criterion that always requires consideration when planning mitigation actions, i.e., the potential behavior of fire. The probability of fire occurrence over a period of time, the expected spread and intensity of single events, or the accompanying severity, defines how prone an area is to be affected by fires. Moreover, it helps anticipate the impact of those fires on the natural resources and human made infrastructures. Therefore, having at the disposition of researchers and technicians a server with all the information required to evaluate fuel hazards and fire behaviors should be used to decide and apply management actions that aim to mitigate the negative impact of wildfires on human and environmental resources [5].

New remote sensing tools have provided a new capacity to assess the state of the forest over large areas. The use of satellite multispectral images and airborne LIDAR

(Laser Imaging Detection and Ranging) has implemented an important step ahead to gather spatial information on the structure of vegetation [63], [64] and canopy characteristics [64]–[68], distribution of fuel types [64], and their temporal changes due to forest management and forest disturbances [69], [70]. Fire risk evaluation has taken advantage of these tools, both to support decisions at strategic [71], [72] and tactical level [73], especially if the data precision/resolution is appropriate. In this sense, [74] proposed a methodology for determining operational priorities for fire prevention and suppression activities, [75] modelled the effects of fuel treatments on the potential fire spread and behavior. [76], [77] analyzed the fire exposure of highly valued resources and assets. [78] suggested a model-based framework to evaluate alternative wildfire suppression strategies. González-Olabarría et al. [25] identified areas where fuel management had to be implemented to support suppression efforts.

Fire simulation and modelling allows for the estimation of fire behavior and spread in complex fire environments [79]–[81], considering different inputs such as ignition location, elevation, fuels, canopy characteristics, weather, and fuel moisture. Different modelling approaches allow for the application of outputs in many ways. This allows one to plan and conduct prescribed fires by analyzing temporal windows to reach specific purposes depending on fire behavior [82], assess the effectiveness of fuel treatments [75], [83], [84], evaluate fire behavior for all the cells in a landscape [85]–[87], asses direct hazard and risk [88], [89], estimate burn probabilities [90], [91], or analyze fire exposure [77]. Although fire simulations can be focused on specific fires, either in the past or happening in real-time [92], the use of simulation outputs for tactical or strategic management planning requires fuel moisture and weather scenarios adjusted to the historical data of areas with an homogenous fire regime [33,38–41].

Fires are the main cause of forest damage in the Mediterranean region. Apart from ending up with serious environmental and ecologic damage, they generate an important economic loss. Therefore, in these regions, they are perceived by the public as the main environmental problem, especially amid climate change. Having available actualized data on forest fuel characteristics and evaluation of potential fire risk via simulation of fire behavior are required steps on the way towards successful decision-making regarding fire prevention and suppression. Moreover, developing an open server, where maps of all variables are required to simulate fires, including elevation, fuels, canopy characteristics, and weather scenarios. Further, they provide a harmonized and easy to apply framework for many technicians and researchers working on fire-related topics, with the additional advantage of comparability between results that can hardly be achieved if the baseline information is generated independently and based on different methodologies. In this sense, the LANDFIRE (LF) Program in the United States began the process of providing consistent national biological/ecological inventory data [93] with an increased concern about the number, severity, and size of wildfires. LF provides the current state of vegetation, fuels, and fire regimes at a national scale, and the data have become a critical piece of wildfire modelling, research, planning, and operational support for fire management [93].

Although several studies on forest fires characterization and modelling have been implemented across Southern Europe, and specifically in Catalonia [43–48], an exhaustive research with a strong geospatial component that could define fuel models and fire behavior, has not yet been conducted. For this purpose, two methodologically different datasets have been developed: (1) data related to the biophysical environmental characteristics and (2) data related to potential fire weather conditions. The first dataset provides a set of georeferenced variables from different datasets, on the state and arrangement of fuels, that helps to simulate forest fires, its behavior. It also evaluates fire hazard across landscapes even if fires are not simulated. The second dataset corresponds to the climatic conditions required to simulate relevant historical fires or fires under extreme weather conditions. In this manuscript, we presented the methodology to generate all information required to assess fire hazards and simulate fire behavior, combining multiple datasets from biophysical variables to allometric functions, meteorological records, and readjustments based on expert knowledge. The resulting database is presented as an evolving server that will be further developed to explore preventive measures at a regional level.

2. Materials and Methods

2.1. Study Site and Methodological Approach

Our study was performed in the autonomous community of Catalonia, which is located in the northeastern part of Spain. According to the Land Cover Map of Catalonia, 42% of the approximate 32,000 km^2 of the Catalan territory is classified as wooded forest area [49]. Around 75% of forests is privately owned, and due to high level of fragmentation of the land holdings, developing and implementing adequate forest management plans is still a challenge in the region [50]. The most dominant species regarding stocking are *Pinus sylvestris*, *Pinus halepensis,* and *Quercus ilex* [51]. According to the Köppen climate classification [52], the biggest part of Catalonia corresponds to the temperate climate type (C climates); Csa (Hot-summer Mediterranean climate) is the dominant one. Nevertheless, in the northernmost part of the study area (the Pyrenees and Pre-Pyrenees zones), D climates (mostly Dsb and Dsc) are also common. Finally, in the western part of the study area, dry climates (BSk) can be found [53].

During the last 33 years, 21,686 forest fires have been detected across Catalonia, with about 265,000 ha of forest area burned [54]. Thus, forest fire risk management is crucial in order to find efficient ways of minimizing fire damages [55]. Therefore, it is necessary to dispose of an accurate and continuous spatial database, bearing in mind all specific parameters that have a strong influence on fire behavior modelling (Figure 1). However, oversimplifications regarding the compositional variability of Mediterranean forests should be avoided. For example, forest type classification data and species is crucial as it frames relations between structural features that are captured through remote sensing means and others that need to be defined through allometric parametrization. Furthermore, the combination of forest typologies and fuel arrangement also frames the potential forest management alternatives that can be implemented.

Variables representing the landscape and meteorological scenario data represents the base for each fire simulation; therefore, the initial aim was to unite and organize these datasets in order to be used by fire simulators and evaluate fire behavior characteristics. Generation process of both datasets encompasses the workflow where data, obtained from different databases, underwent several transformations, parametrizations, and geospatial analysis, depending on the nature of the data, initial data type, and data characteristics required by the simulators. A certain amount of data was already freely available and ready to be used. Other datasets, nevertheless, needed to be parameterized and estimated by implementing different spatial modelling processes.

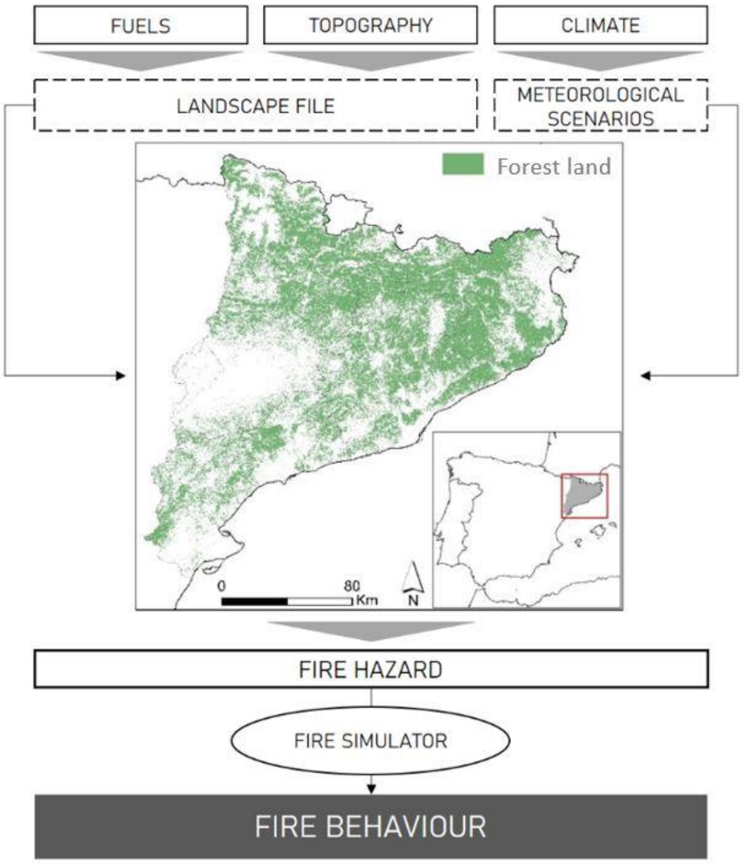


Figure 1. Schematic diagram of the conceptual design of the project.

2.2. Fire Hazard Evaluation

2.2.1. Fuel Mapping and Landscape File Generation

By defining a set of georeferenced variables—such as elevation, slope, aspect, fuel model, canopy cover, canopy height, canopy base height, and canopy bulk density—it is possible to anticipate fire behavior once the weather conditions are set. Those georeferenced variables can be compiled into a landscape file (LCP) and used as an input in the most commonly used fire simulation software packages [56]. Therefore, to create the spatial frame of our server, it was required to estimate the 8 variables that conform into a LCP (Table 1).

Table 1. List of variables used to generate the landscape file (LCP).

Variable	Unit	Data Processing
Forest canopy cover (FCC)	%	Original data, not processed
Standard height (SH)	meters	Original data, not processed
Canopy base height (CBH)	meters	Parameterized and (geospatially) modelled
Canopy bulk density (CBD)	kg/m^3	Parameterized and (geospatially) modelled
Fuel models (FM)	Categories	Parameterized and (geospatially) modelled
Digital Terrain Model (DTM)	meters	Original data, not processed
Slope (SL)	%	Geospatially transformed
Aspect (ASP)	degrees	Geospatially transformed

With the aim to define fuel models and parameters that describe forest fire hazards, a forest typology analysis was conducted. This was done in order to improve the modelling process of the variables representing the landscape file, according to each of the tree species presented in the study area. Secondly, it facilitated the forest management decision-making process, as management prescriptions should adapt to the ecological and operational requirements of each species and typology. For this purpose, we used the Forest Formation Map of Catalonia [57] to represent stands with at least 20% of forest coverage and the Land Cover Map of Catalonia [49] to represent areas without a significant forest cover, such as urban/agricultural areas, meadows, or shrub lands.

Apart from that, for the generation of the LCP, four main data sources were used: (I) Map of Biophysical Variables of Catalonia (MBVC) obtained with LiDAR-based technology [58], (II) the 4th National Forest Inventory (NFI4) [59], (III) the Forest Typology Guide of Catalonia (FTGC) [60] (IV), and Digital Terrain Model (DTM) [61]. MBVC is a dataset consisting of 8 rasters containing modelled information on structural characteristics of Catalan forests. Two of these variables (i.e., Forest Canopy Cover and Standard Height) were implemented into the LCP, with minor corrections but without any significant transformation needed. Three other data rasters (i.e., foliar biomass, basal area, and aerial biomass) were used in calculations to obtain other LCP variables. Canopy base height (CBH), canopy bulk density (CBD), and fuel models (FM) were parameterized and calculated, employing different combinations of available data. The last one also requires the Understory Shrub Cover Model to be implemented. All of the allometric parametrizations made for wooded forest areas were applied on a sp. composition basis based on the indications from the Forest Formation Map of Catalonia and the FTGC; the models were defined and implemented separately for each tree species including parameters obtained from the NFI4, where needed. Finally, a raster Digital Terrain Model was directly included into the LCP; it was employed into the Understory Shrub Cover

Model calculation and used to obtain Slope and Aspect variables of the LCP using geospatial processing tools. The workflow and complete parameterization model is shown in Figure 2.

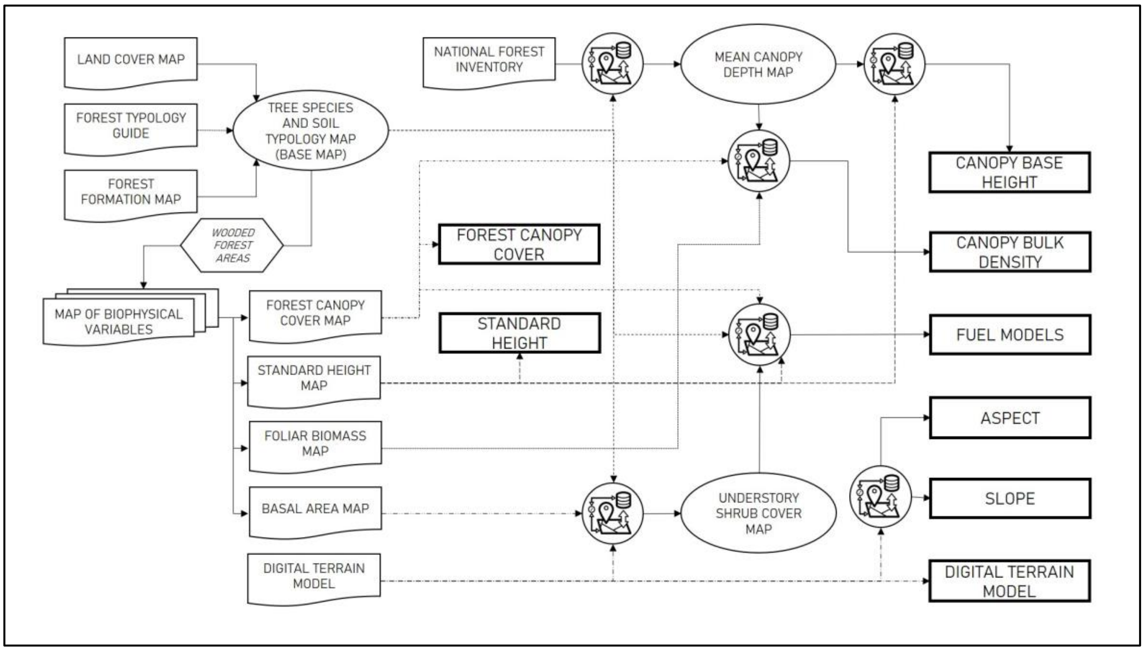


Figure 2. Schematic diagram of the landscape file (LCP) generation workflow.

Calculation of Canopy Base Height Variable

CBH is an indicator for the vertical fuel continuity and refers to the lowest height above the ground at which there is sufficient canopy fuel to vertically propagate fire [62]. We have calculated CBH for each of the species contained in the FTGC within the study area using the following formula:

$$CBH = Hm - Hc \tag{1}$$

where: Hm is LiDAR based standard height; Hc is mean canopy depth obtained based on two models:

$$\begin{gathered} \text{if } Hm > 5\text{ m: } Hc = \beta_0 + (\beta_1 \times Hm) \\ \text{if } Hm <= 5\text{ m: } Hc = \beta_1 \times Hm \end{gathered} \tag{2}$$

values for β_0 *and* β_1 were constant varying depending on dominant tree species (Appendix A).

Calculation of Canopy Bulk Density Variable

CBD is the canopy biomass fuel load available in each unit of canopy volume [62]. In order to compute CBD, we consider that the available canopy fuel equals to the foliar load provided by LiDAR estimates; therefore, the formula we used is:

$$CBD = FB/V \tag{3}$$

where: FB is foliar biomass; V is canopy volume.

Canopy volume data was computed on a pixel level considering that each pixel represents one tree. In order to make the model more realistic, we assumed that each tree crown has a spheroidal shape which leads to equation:

$$V_{spheroid} = \frac{4\pi r^2 Hc}{6} \tag{4}$$

where: Hc is canopy depth ($Hc = Hm - CBH$); r is radius of the crown in horizontal projection.

Nevertheless, since each pixel does not represent the FCC of 100%, the value of this variable was introduced into the equation as a reducing factor in order to readjust the crown volume at pixel level. A tree representing the volume of one pixel has been denominated as a “super tree”. Therefore:

$$V_{super\ tree} = FCC \times \frac{4\pi}{24} \times V_{pixel} \tag{5}$$

$$V_{pixel} = c^2 \times Hc = 20^2 \times Hc \tag{6}$$

FCC = forest canopy cover; c = pixel size; $Hc = Hm - CBH$.

Fuel Models Assignation

Fuel models (FM) are a set of fuel bed inputs needed by a particular fire behavior [63]. They are used to denote physical fuel characteristics representing diverse fire environments. Several models have been used over the time to represent these spatial processes [26,63–65]. Mainly upgrading the algorithm sets, the Anderson’s 13 models [65] have been in extensive use until recently. Nevertheless, in agreement with the experts from the Forestry Action Group (GRAF, Fire Department of the Government of Catalonia), it was finally decided to use models created by Scott and Burgan [63] since they provide the most accurate results for our study purposes and better represent the compositional and climatic seasonal variability of the region.

The creation and denomination of the fuel models was conducted for each pixel of the study area after creating an algorithm highly dependent on tree species, mean vegetation height, forest canopy cover, understory shrub cover, and climatic zones. These were supervised and adjusted by experts in order to match both the description of fuel model [63] and the experience from the GRAF experts regarding representability and observed fire behavior.

To estimate the understory shrub cover needed for the fuel model generation, models created by Coll et al. [50] were implemented. They permitted us to calculate a maximum shrub cover per stand based on dominant tree species, topographic elevation, and basal area. Nevertheless, since the number of species contained in the Forest Typology Guide of Catalonia exceeded the number of models, all species were grouped based on their resemblance.

Regarding humidity, Scott and Burgan's [63] methodology differed fuel models as follows: (a) dry areas, with a water deficit in summer months; and (b) humid areas, without a water deficit. According to the local climatic features, it was decided that areas with more than 150 mm of accumulated precipitation during the summer season are considered as humid areas, while zones with less than 150 mm of precipitation are considered as dry areas [66]. This zonification, consequently, has a strong influence on algorithm generation.

In order to facilitate fuel model assignation, vegetation types were organized into 5 groups according to the fuel load characteristics. One or more fuel types were assigned to each group (Table 2). Each fuel type is defined by the vegetation kind that is to be considered as the primary fire carrier in the area, and contains several fuel models based on detailed fuel load features. Fuel models are differentiated by code and number, and are defined by the unique algorithm [63].

Table 2. Correspondence between vegetation type (basic fuel models) and Scott and Burgan's models [63].

Vegetation Types	Fuel Type by Scott and Burgan [63]
Wooded forest area	Slash-Blowdown (SB), Timber Litter (TL), Timber Litter (TL)
Regenerated forest	Shrub (SH)
Scrubland	Grass-Shrub (GS), Shrub (SH)
Grassland	Grass (GR)
Non-burnable	Non-burnable (NB)

Furthermore, tree stratum fuel models were generated following the Forest Typology Guide of Catalonia classification by aggregating tree species present in the study area in 11 groups, according to their spatial representativeness and similarity, and in terms of their ecological and structural features. For each of the 11 forest types, a set of fuel models were assigned depending on the observed and predicted forest canopy and understory shrub coverage values, aiming to reach the maximum similarity to the Scott and Burgan [63] models, both in terms of structural description and potential fire behavior. For this purpose, thresholds were set with the participation of the experts from the GRAF. An example of the algorithm applied for *Pinus halepensis* is shown in Figure 3, while all other used models are shown in Supplementary Materials.

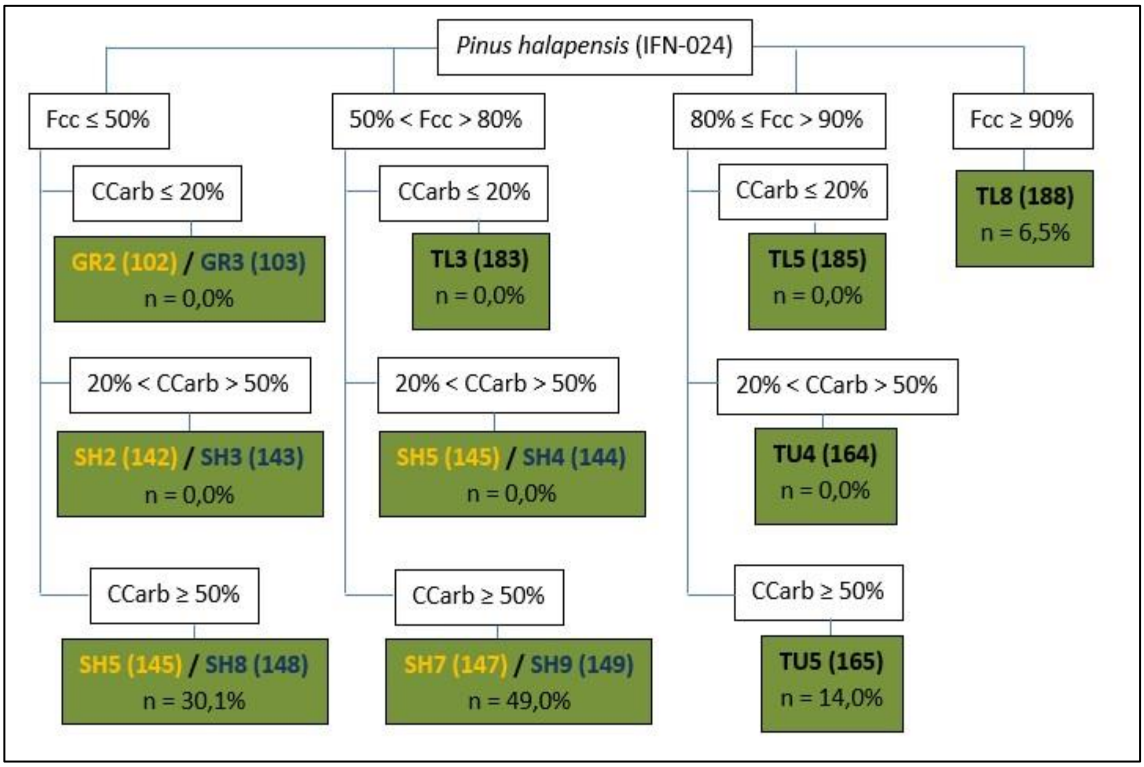


Figure 3. Algorithm used for assignation of the Scott and Burgan [63] model to stand populated by *Pinus halepensis*; Fcc = Forest Canopy Cover; CCarb = Understory Shrub Cover; yellow color = model assigned if the pixel is located within the dry area; blue color = model assigned if the pixel is located within the humid area; black color = model assigned regardless of the area; n = representativeness of the model (% in the total area covered by species).

2.2.2. Generation of Meteorological Scenarios

Meteorological scenarios were generated using 20 years of historical climatic data (until 2018) for the study area, using statistical analysis and combining expert knowledge from the Forest Fire Prevention Service, SPIF (Government of Catalonia) and the GRAF [67]. In order to generate meteorological scenarios, the historical climate datasets were analyzed for each of 15 meteorological regions (Figure 4) that were defined based on homogeneous synoptic characteristics and Zones of Homogeneous Fire Regime (ZHR). The ZHR are parts of the territory that present homogeneity in terms of orography, vegetation, wind regime, fire rotation, and fire type characteristics [47,60].

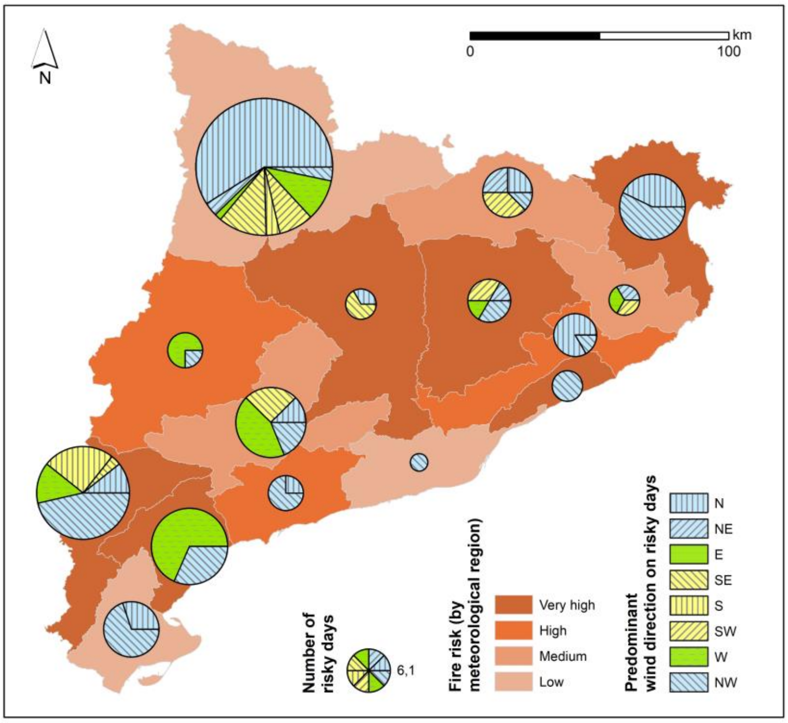


Figure 4. Meteorological regions of Catalonia and characteristic synoptic situations, defined by the frequency of the predominant wind directions during high risk days. The spatial frame of these regions being the basis for the assessment of meteorological data.

Within the meteorological scenarios dataset, two types of scenarios can be defined: (1) those based on data for the worst fire weather conditions and (2) those based on a reference fire that occurred in the past, which represents a large fire prototypical of an ZHR, according to its propagation patterns and synoptic conditions [47,68].

The methodological base for the generation of the worst weather condition scenarios was a designation of the critical days for forest fire risk based on a combination of percentiles from different meteorological variables: (1) relative humidity (RH), (2) temperature (T), and (3) wind speed (WS). Four different combinations of percentiles (p) were established to define critical days: (1) $p < 5$ RH + $p > 95$ T; (2) $p < 5$ RH + $p > 95$ WS; (3) $p < 10$ RH + $p > 90$ T + $p > 90$ WS; (4) $p < 10$ RH + $p > 99$ WS. Once identified, all synoptic situations and their occurrence probabilities based on meteorological records from days that met previously mentioned requirements, and meteorological scenarios were created.

For each of the 15 meteorological regions, one reference fire was chosen by the GRAF experts and data on the registered weather conditions was provided. However, this was only if the fire occurred more than 20 years ago, due to data availability for some of the meteorological stations.

3. Results

3.1. Geodatabase and Modelled Maps

Georeferenced data on biophysical environmental characteristics (FCC, SH, CBD, CBH), topographic features (DTM, SL, ASP), and fuel models were obtained as the first step of the project (Figures 5 and 6). These variables are available in georaster format with a spatial resolution of 20 m. Moreover, the meteorological scenarios dataset, contained in data tables and associated spatially to each meteorological region, was generated.

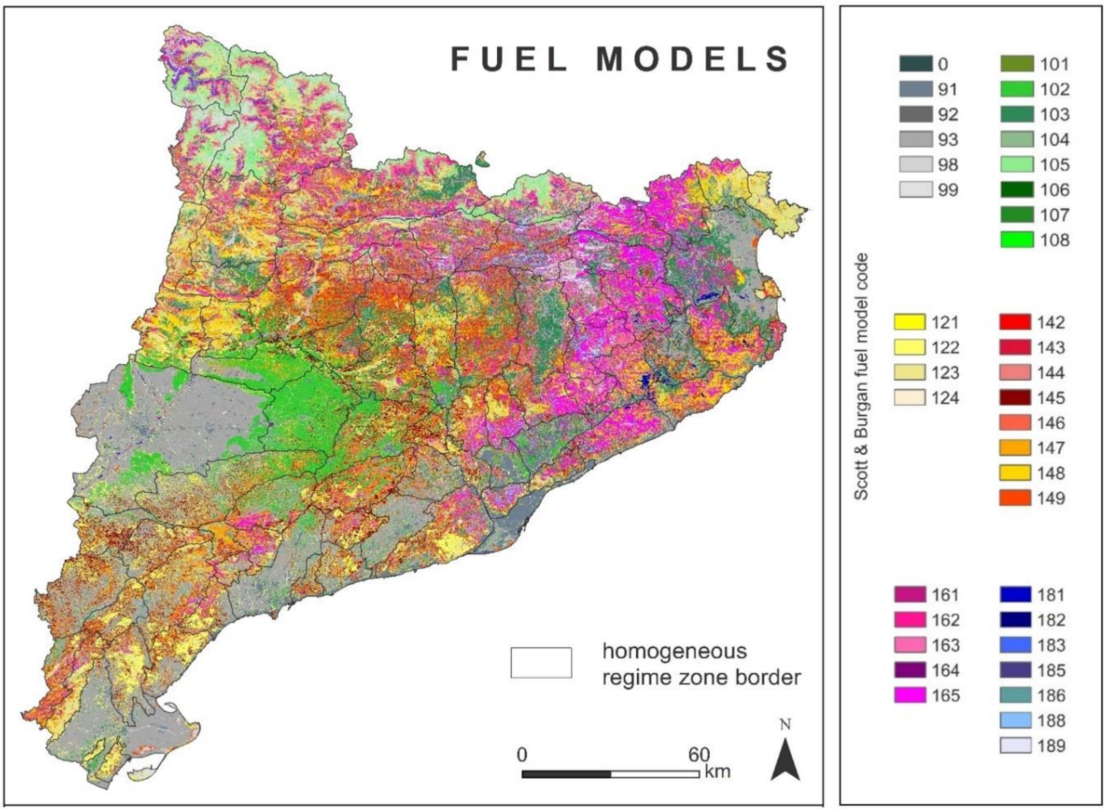


Figure 5. Fuel models map of Catalonia, according to Scott and Burgan [63].

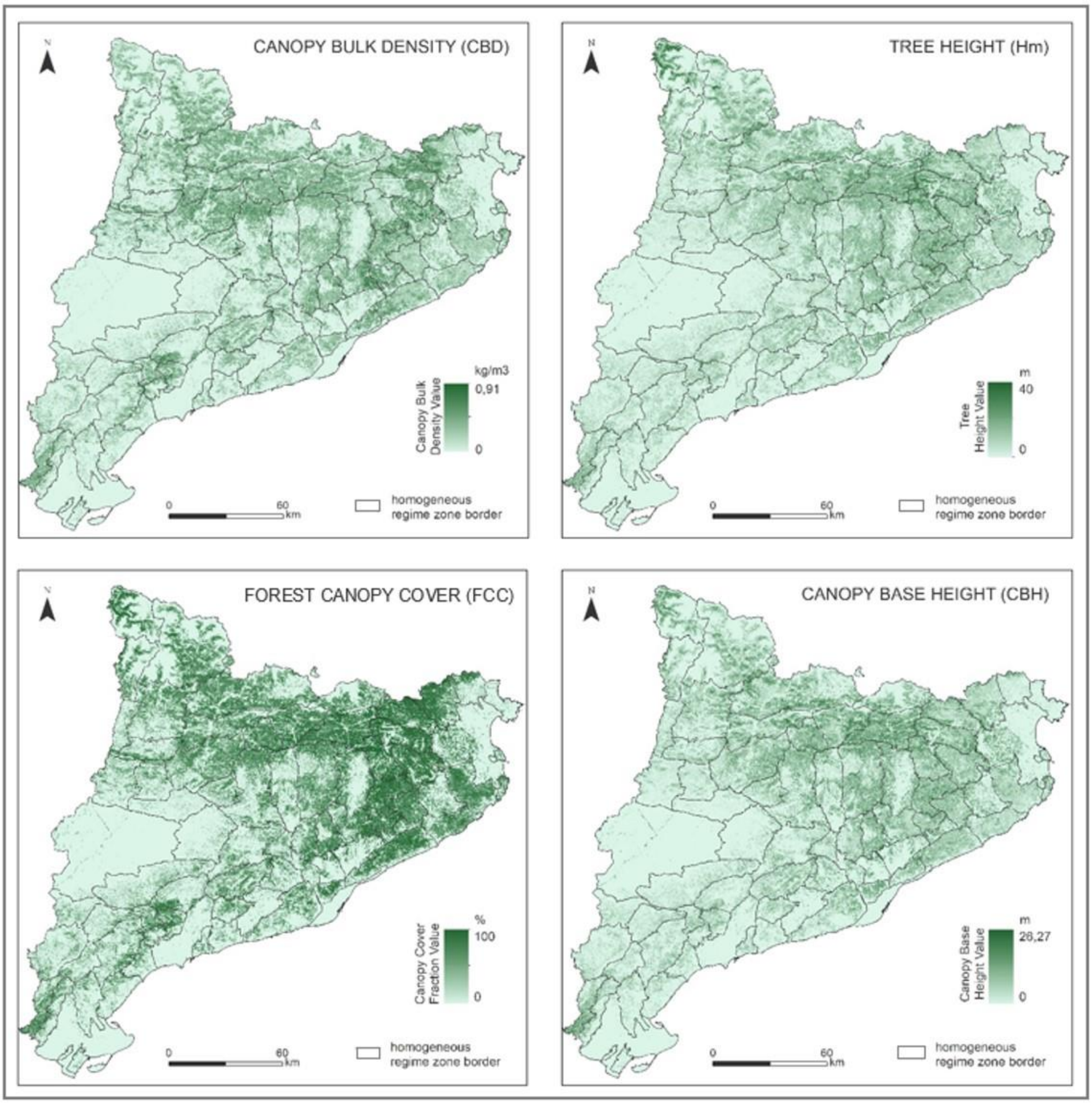
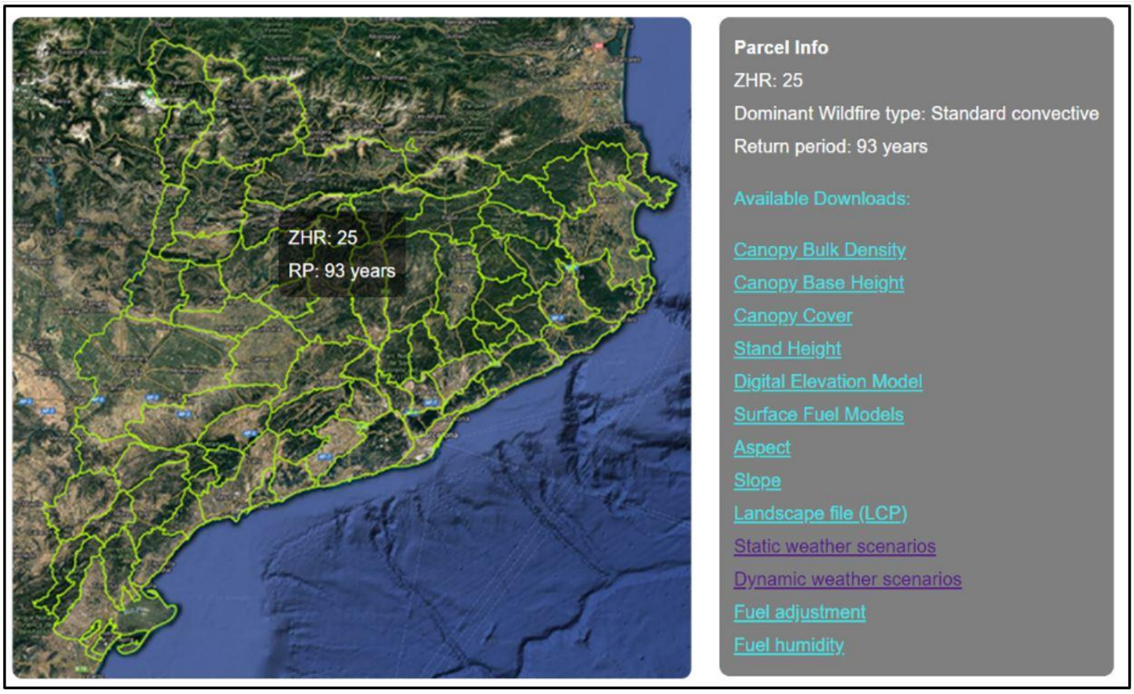


Figure 6. Biophysical variables of wooded forest areas in Catalonia contained in the landscape file of PREVINCAT.cat.

3.2. Data Server

In order to make these data freely accessible to all potential users, an open data server called PREVINCAT.cat was created (Figure 7), which contains all required variables for fire modelling at the regional level. This allows one to run fire simulations across any forest landscape in Catalonia. Therefore, the server compiles maps and information on: (1) LCP variables needed for the forest fire simulation (Table 1; Figures 5 and 6) that are downloadable separately, as well as a precompiled LCP consisted of a multi-layer raster file containing descriptive information about terrain and fuels in order to be used as a base to run spatial explicit fire simulations; (2) data on meteorological scenarios, the worst weather condition data, and the reference forest fire data, both of which are available in two different formats: static meteorological scenarios data (average of an hourly data of the days identified as risky) and dynamic meteorological scenarios data (hour by hour data from the risky days that can be used in dynamic fire spread simulators); (3) fuel adjustment data needed for an simulator functionality and precise results obtaining [69]; (4) fuel humidity models according to Scott and Burgan's [63] methodology.



Parcel Info
ZHR: 25
Dominant Wildfire type: Standard convective
Return period: 93 years

Available Downloads:

- Canopy Bulk Density
- Canopy Base Height
- Canopy Cover
- Stand Height
- Digital Elevation Model
- Surface Fuel Models
- Aspect
- Slope
- Landscape file (LCP)
- Static weather scenarios
- Dynamic weather scenarios
- Fuel adjustment
- Fuel humidity

Figure 7. Interface of PREVINCAT server with all available data layers spatially structured by 77 Zones of Homogeneous Fire Regime (ZHR) [70].

All the cartography contained on the server can be downloaded in ASCII format, UTM 31N ETRS89 Datum coordinate system. Data is spatially fragmented and available for download based on ZHR regionalization. By pairing biophysical and climatic data at the same spatial level and using a relevant regionalization frame, we wanted to represent how fire behaves according to the specific regime defined by unique interrelation of spatial variables in certain areas. This type of data provision enables an implementation of different climate scenarios in forest fire behavior simulation for each zone, obtaining better analysis adjustment according to the local geographic and biophysical characteristics.

4. Data Use and Future Development

Data provided on the server can be used in different stages and on different levels of forest management. First of all, biophysical and topographic variables can be directly used to analyze and evaluate potential fire hazards at a regional level.

Secondly, data on the PREVINCAT.cat server is provided and organized to be used in different fire simulation tools. These simulators can provide complete information on potential fire behavior, such as spread rate, fire line intensity, or flame length. Moreover, fire growth and spread under constant weather and fuel moisture conditions can be simulated. Depending on software capabilities, temporal variations in fire behaviors according to different weather scenarios provided within the server dataset can be incorporated in simulations, too. For example, static meteorological scenario data can be used in static fire spread simulators, such as FlamMap [56], with the objective to foresee the potential fire behavior across the whole landscape. However, dynamic meteorological scenario data can be used in dynamic fire spread simulators such as FARSITE [71] or WildfireAnalyst [72], with the objective to predict the fire spread pattern given a single or multiple fire initiation points (Figure 8).

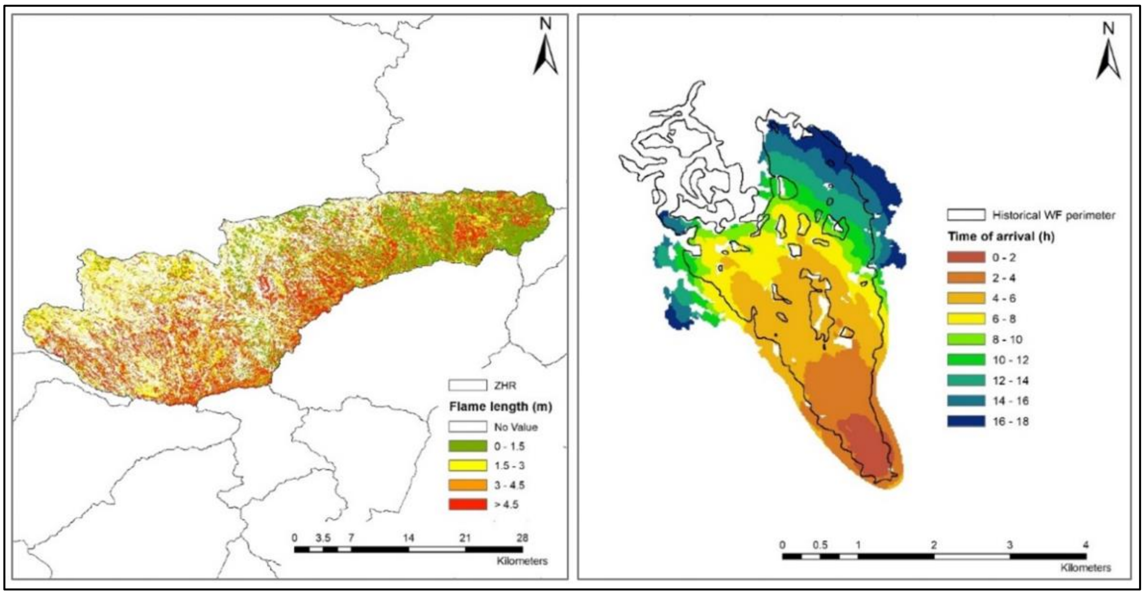


Figure 8. Examples of fire behavior outputs from fire simulation tools (left: flame length obtained from FlamMap; right: reconstruction of an historical fire and time of arrival using FARSITE) in two different areas of Catalonia using the PREVINCAT.cat database.

The fact that all the data is organized and available on ZHR level permits one to run simulations, design theoretical fires, create virtual extreme conditions, or recreate historical fires at a regional level, while also taking into account the spatial variability on weather conditions to attain better predictions.

Finally, both data and the server are meant to be used by firefighters and other professionals working in the field of fire prevention and suppression. We were guided by the idea of providing relevant information on all the variables needed, both in the case of an occurring fire and management options to reduce fire risk.

Therefore, the server and information that it encloses is part of an evolving project aimed at providing data and information that would help professionals manage fire prevention and suppression strategies. Following this line, plans and ideas for future development of the server are already defined. From a theoretical point of view, the server is divided into different modules (Figure 9). Module 1 and Module 2 are finished and available to be used. They represent the data and functionalities presented in this paper. On the other hand, Module 3 and Module 4 are currently under development. Module 3 focuses on defining where fuel management actions should be prioritized according to various decision criteria. For this purpose, additional data on selected criteria (exposure, accessibility, etc.) will be uploaded into the server and, through a participatory process, their influence on the defined goal will be parametrized, and their relative importance provided. Finally, the priority across the region will be estimated through multi-criteria decision analysis methods. Once the priorities are defined, Module 4 will select areas, generally forest stands, and forest management actions that better reduce priority levels, considering economic and surface constrains. This goal will be achieved by using mathematical optimization methods.

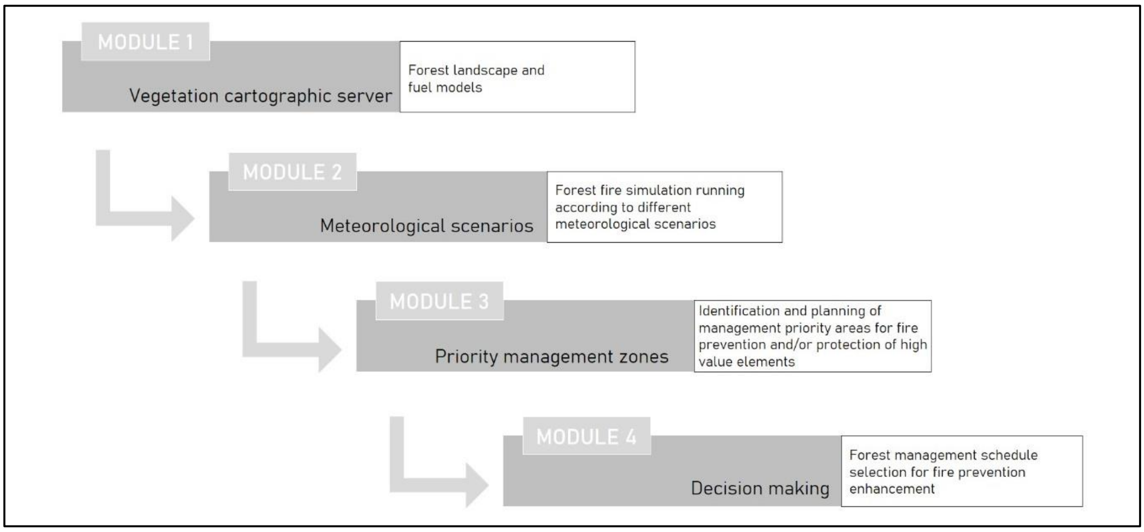


Figure 9. Theoretical organization of the PREVINCAT.cat server.

It should be mentioned that the project and its results have a strong multidisciplinary component, and not only due to the necessity of compiling and managing heterogeneous data sources. Participatory processes and expert modelling play a major role in this project, i.e., the final users of the server strongly participated in its creation, goal definition, and modelling from the early beginning. Since the original idea was to create a server that could be used both by scientists and professionals working in the field of fire suppression and prevention, and in order to get to know all the needs and, consequently, the benefits that the server would provide to the potential users, we wanted to establish a functional collaboration between these two ambits. The methodology and the nature of the resulting data was defined according to the needs of the professionals from the field, mostly firefighters from the regional governing institutions that are highly familiarized with the topic. We ensured that the methodological approach was valid and results were accordingly applicable to our study area, successfully accomplishing the main objective of the project.

5. Conclusions

This study presents an innovative and elaborated fuel modelling process to define fuel characteristics and potential fire behavior under different meteorological scenarios. In order to store all the data and models developed, as well as all required variables to run fire simulations at a regional scale in Catalonia, an open free server (i.e., PREVINCAT.cat) was developed. It offers three products: landscape files, meteorological scenarios, and some fire perimeters of historical wildfires. This data is primarily destined to be used to assess potential fire behavior with different fire spread simulators. The server is logically structured in order to meet the user requirements and can be used both by scientists and fire management practitioners. All the data is subdivided according to the Zones of Homogeneous Fire Regime, which are considered as a relevant planning frames to guide the forestry policy regarding fire prevention and suppression. The presented results are part of an ongoing project that considers a strategic plan to set management priority areas, through MCDA means, and a tactical plan where specific management actions will be selected using mathematical optimization methods.

Author Contributions: J.R.G.O., M.P.N., J.G.G., and E.B.O. participated on the conceptualization of the project; G.K. and E.B.O. implemented most of the data management; A.L. supervised and selected the rules for fuel model identification; G.K., A.C., and J.R.G.O. wrote the initial draft. All authors participated in the editing process of the manuscript.

Funding: This research was funded by the Departament d’Agricultura, Ramaderia, Pesca i Alimentació, of the Generalitat de Catalunya. Goran Krsnik acknowledges funding from AGAUR though the scholarship FI_B2 00147. J Garcia Gonzalo and JR Gonzalez Olabarria received funding from Spanish Ministry of Economy and Business (MINECO) and from Agency for the Research Centre of Catalonia (CERCA Programme/Generalitat de Catalunya).

Acknowledgments: We would like to thank to all if the collaborators and experts who participated in this project: Marc Castellnou (UT-GRAF, DGPEISGRAF, Generalitat de Catalunya), Carlos San Román (Servei de Gestió Forestal, Generalitat de Catalunya), Carles Furriol (Servei de Gestió Forestal, Generalitat de Catalunya), Esteve Canyameres and José A. Terés (Servei de Prevenció d'Incendis Forestals, Generalitat de Catalunya), and Irina Cristal (FBS).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Equations for Mean Canopy Depth (*Hc*) calculation for each species in the study area.

IFN4 Code	Tree Specie	Mean Canopy Depth (*Hc*, m)	
024	*Pinus halepensis*	$Hm > 5$ m $\rightarrow Hc = 1.106 + (0.421 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.421 \times Hm$
021	*Pinus sylvestris*	$Hm > 5$ m $\rightarrow Hc = 1.201 + (0.391 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.391 \times Hm$
045	*Quercus ilex ilex*	$Hm > 5$ m $\rightarrow Hc = -0.328 + (0.640 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.640 \times Hm$
025	*Pinus nigra*	$Hm > 5$ m $\rightarrow Hc = 0.432 + (0.426 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.426 \times Hm$
049	*Quercus ilex ballota*	$Hm > 5$ m $\rightarrow Hc = -0.328 + (0.640 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.640 \times Hm$
022	*Pinus uncinata*	$Hm > 5$ m $\rightarrow Hc = 1.401 + (0.476 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.476 \times Hm$
046	*Quercus suber*	$Hm > 5$ m $\rightarrow Hc = -0.328 + (0.640 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.640 \times Hm$
243	*Quercus humilis*	$Hm > 5$ m $\rightarrow Hc = -0.429 + (0.629 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.629 \times Hm$
050	*Riverbank forests*	$Hm > 5$ m $\rightarrow Hc = 2.121 + (0.375 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.375 \times Hm$
044	*Quercus faginea*	$Hm > 5$ m $\rightarrow Hc = 0.348 + (0.326 \times Hm)$	$Hm < 5$ m $\rightarrow Hc = 0.326 \times Hm$

023	*Pinus pinea*	$Hm > 5\ \text{m} \rightarrow Hc = 0.265 + (0.465 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.465 \times Hm$
071	*Fagus sylvatica*	$Hm > 5\ \text{m} \rightarrow Hc = -0.428 + (0.667 \times Hm)$	$Hm < 5\ \text{m} \rightarrow \text{Hc} = 0.667 \times Hm$
042	*Quercus petraea*	$Hm > 5\ \text{m} \rightarrow Hc = -0.688 + (0.624 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.624 \times Hm$
026	*Pinus pinaster*	$Hm > 5\ \text{m} \rightarrow Hc = 1.750 + (0.321 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.321 \times Hm$
031	*Abies alba*	$Hm > 5\ \text{m} \rightarrow Hc = -0.040 + (0.708 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.708 \times Hm$
072	*Castanea Sativa*	$Hm > 5\ \text{m} \rightarrow Hc = -0.131 + (0.592 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.592 \times Hm$
051	*Populus sp.*	$Hm > 5\ \text{m} \rightarrow Hc = -1.609 + (0.769 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.769 \times Hm$
373	*Betula pendula*	$Hm > 5\ \text{m} \rightarrow Hc = -0.455 + (0.653 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.653 \times Hm$
041	*Quercus robur*	$Hm > 5\ \text{m} \rightarrow Hc = -0.688 + (0.624 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.624 \times Hm$
255	*Fraxinus excelsior*	$Hm > 5\ \text{m} \rightarrow Hc = 2.121 + (0{,}375 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.375 \times Hm$
061	*Eucalyptus sp.*	$Hm > 5\ \text{m} \rightarrow Hc = -0.131 + (0{,}592 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.592 \times Hm$
079	*Platanus x hybrida*	$Hm > 5\ \text{m} \rightarrow Hc = 1.391 + (0{,}443 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.443 \times Hm$
028	*Pinus radiata*	$Hm > 10\ \text{m} \rightarrow Hc = 3.279 + (0{,}444 \times Hm)$	$Hm < 10\ \text{m} \rightarrow Hc = 0.444 \times Hm$
034	*Pseudotsuga menziesii*	$Hm > 10\ \text{m} \rightarrow Hc = 6.247 + (0{,}250 \times Hm)$	$Hm < 10\ \text{m} \rightarrow Hc = 0.250 \times Hm$
047	*Quercus canariensis*	$Hm > 5\ \text{m} \rightarrow Hc = -1.166 + (0{,}885 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.885 \times Hm$
043	*Quercus pyrenaica*	$Hm > 5\ \text{m} \rightarrow Hc = -1.166 + (0{,}885 \times Hm)$	$Hm < 5\ \text{m} \rightarrow Hc = 0.885 \times Hm$
035	*Larix sp.*	$Hm > 10\ \text{m} \rightarrow Hc = 6.247 + (0{,}250 \times Hm)$	$Hm < 10\ \text{m} \rightarrow Hc = 0.250 \times Hm$
917	*Cedrus sp.*	$Hm > 10\ \text{m} \rightarrow Hc = 6.247 + (0{,}250 \times Hm)$	$Hm < 10\ \text{m} \rightarrow Hc = 0.250 \times Hm$
033	*Picea sp.*	$Hm > 10\ \text{m} \rightarrow Hc = 6.247 + (0{,}250 \times Hm)$	$Hm < 10\ \text{m} \rightarrow Hc = 0.250 \times Hm$

References

1. Calkin, D.E.; Thompson, M.P.; Finney, M.A.; Hyde, K.D. A real-time risk-assessment tool supporting wildland fire decision-making. *J. For.* **2011**, *109*, 274–280, doi:10.1093/jof/109.5.274.
2. Thompson, M.P.; Calkin, D.E.; Finney, MA.; Gebert, K.M.; Hand, M.S. A Risk-Based Approach to Wildland Fire Budgetary Planning. *For. Sci.* **2013**, *59*, 63–77, doi:10.5849/forsci.09-124.
3. González-Olabarría, J.R.; Rodríguez, F.; Fernández-Landa, A.; Mola-Yudego, B. Mapping fire risk in the Model Forest of Urbión (Spain) based on airborne LiDAR measurements. *For. Ecol. Manag.* **2012**, *282*, 149–156, doi:10.1016/j.foreco.2012.06.056.

4. Ramirez, J.; Monedero, S.; Silva, C.A.; Cardil, A. Stochastic decision trigger modelling to assess the probability of wildland fire impact. *Sci. Total Environ.* **2019**, *694*, 133505.
5. Price, O.F.; Gordon, C.E. The potential for LiDAR technology to map fire fuel hazard over large areas of Australian forest. *J. Environ. Manag.* **2016**, *181*, 663–673, doi:10.1016/j.jenvman.2016.08.042.
6. Riaño, D.; Chuvieco, E.; Ustin, S.L.; Salas, J.; Rodríguez-Pérez, J.R.; Ribeiro, L.M.; Viegas, D.X.; Moreno, J.M.; Fernández, H. Estimation of shrub height for fuel-type mapping combining airborne LiDAR and simultaneous color infrared ortho imaging. *Int. J. Wildland Fire* **2007**, *16*, 341–348, doi:10.1071/WF06003.
7. Arellano-Pérez, S.; Castedo-Dorado, F.; López-Sánchez, C.; González-Ferreiro, E.; Yang, Z.; Díaz-Varela, R.; Álvarez-González, J.; Vega, J.; Ruiz-González, A. Potential of Sentinel-2A Data to Model Surface and Canopy Fuel Characteristics in Relation to Crown Fire Hazard. *Remote Sens.* **2018**, *10*, 1645 doi:10.3390/RS10101645.
8. González-Olabarria, J.R.; Rodríguez, F.; Fernández-Landa, A.; Mola-Yudego, B. Mapping fire risk in the Model Forest of Urbión (Spain) based on airborne LiDAR measurements. *For. Ecol. Manag.* **2012**, *282*, 149–156, doi:10.1016/j.foreco.2012.06.056.
9. Bottalico, F.; Chirici, G.; Giannini, R.; Mele, S.; Mura, M.; Puxeddu, M.; McRoberts, R.E.; Valbuena, R.; Travaglini, D. Modeling Mediterranean forest structure using airborne laser scanning data. *Int. J. Appl. Earth Obs. Geoinf.* **2017**, *57*, 145–153, doi:10.1016/j.jag.2016.12.013.
10. Riaño, D.; Meier, E.; Allgöwer, B.; Chuvieco, E.; Ustin, S.L. Modeling airborne laser scanning data for the spatial generation of critical forest parameters in fire behavior modeling. *Remote Sens. Environ.* **2003**, *86*, 177–186, doi:10.1016/S0034-4257(03)00098-1.
11. Valbuena, R.; Maltamo, M.; Packalen, P. Classification of forest development stages from national low-density lidar datasets: A comparison of machine learning methods. *Revista Teledetección* **2016**, *S.I.,* 15–25, doi:10.4995/raet.2016.4029.
12. Riaño, D.; Chuvieco, E.; Condés, S.; González-Matesanz, J.; Ustin, S.L. Generation of crown bulk density for *Pinus sylvestris* L. from lidar. *Remote Sens. Environ*. **2004**, *92*, 345–352, doi:10.1016/j.rse.2003.12.014.
13. González-Olabarría, J.R.; Pukkala, T. Integrating fire risk considerations in landscape-level forest planning. *For. Ecol. Manag.* **2011**, *261*, 278–287, doi:10.1016/j.foreco.2010.10.017.
14. De Almeida, D.R.A.; Nelson, B.W.; Schietti, J.; Gorgens, E.B.; Resende, A.F.; Stark, S.C.; Valbuena, R. Contrasting fire damage and fire susceptibility between seasonally flooded forest and upland forest in the Central Amazon using portable profiling LiDAR. *Remote Sens. Environ*. **2016**, *184*, 153–160, doi:10.1016/j.rse.2016.06.017.
15. Miller, J.D.; Yool, S.R. Mapping forest post-fire canopy consumption in several overstory types using multi-temporal Landsat TM and ETM data. *Remote Sens. Environ.* **2002**, *82*, 481–496, doi:10.1016/s0034-4257(02)00071-8.
16. Peterson, D.L.; Littell, J.S. Appendix 2: Risk-Based Framework and Risk Case Studies. Risk Assessment for Wildfire in the Western United States. In *Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector*; Vose, J.M., Peterson, D.L., Patel-Weynand, T., Eds.; General Technical Report PNW-GTR-870; U.S. Department of Agriculture,

Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 2012; pp. 249–252.

17. Calkin, D.E.; Cohen, J.D.; Finney, M.A.; Thompson, M.P. How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 746–751, doi:10.1073/pnas.1315088111.
18. Thompson, M.; Lauer, C.; Calkin, D.; Rieck, J.; Stonesifer, C.; Hand, M. Wildfire Response Performance Measurement: Current and Future Directions. *Fire* **2018**, *1*, 21, doi:10.3390/fire1020021.
19. Scott, J.H.; Thompson, M.P.; Calkin, D.E. *A Wildfire Risk Assessment Framework for Land and Resource Management*; General Technical Report RMRS-GTR-315; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2013.
20. Rodríguez y Silva, F.; Molina Martínez, J.R.; González-Cabán, A. A methodology for determining operational priorities for prevention and suppression of wildland fires. *Int. J. Wildland Fire* **2014**, *23*, 544–554, doi:10.1071/WF13063.
21. Salis, M.; Del Giudice, L.; Arca, B.; Ager, A.A.; Alcasena-Urdiroz, F.; Lozano, O.; Bacciu, V.; Spano, D.; Duce, P. Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area. *J. Environ. Manag.* **2018**, *212*, 490–505, doi:10.1016/j.jenvman.2018.02.020.
22. Alcasena, F.J.; Salis, M.; Vega-García, C. A fire modeling approach to assess wildfire exposure of valued resources in central Navarra, Spain. *Eur. J. For. Res.* **2016**, *135*, 87–107, doi:10.1007/s10342-015-0919-6.
23. Salis, M.; Ager, A.A.; Arca, B.; Finney, M.A.; Bacciu, V.; Duce, P.; Spano, D. Assessing exposure of human and ecological values to wildfire in Sardinia, Italy. *Int. J. Wildland Fire* **2013**, *22*, 549–565, doi:10.1071/WF11060.
24. Riley, K.; Thompson, M.; Scott, J.; Gilbertson-Day, J. A Model-Based Framework to Evaluate Alternative Wildfire Suppression Strategies. *Resources* **2018**, *7*, 4, doi:10.3390/resources7010004.
25. Gonzalez-Olabarria, J.R.; Reynolds, K.M.; Larrañaga, A.; Garcia-Gonzalo, J.; Busquets, E.; Pique, M. Strategic and tactical planning to improve suppression efforts against large forest fires in the Catalonia region of Spain. *For. Ecol. Manag*. **2019**, *432*, 612–622, doi:10.1016/j.foreco.2018.09.039.
26. Albini, F. 1976. *Estimating Wildfire Behavior and Effects*; General Technical Report INT-30; USDA Forest Service, Intermountain Forest and Range Experiment Station: Ogden, UT, USA; 92p.
27. Finney, M. Fire growth using minimum travel time methods. *Can. J. For. Res.* **2002**, *32*, 1420–1424, doi:10.1139/X02-068.
28. Andrews, P. Current status and future needs of the BehavePlus Fire Modeling System. *Int. J. Wildland Fire* **2014**, *23*, 21–33.
29. Anderson, K.; Englefield, P.; Little, J.; Gerhard Reuter, M. An approach to operational forest fire growth predictions for Canada. *Int. J. Wildland Fire* **2009**, *18*, 893–905.
30. Pettinari, M.L.; Chuvieco, E. Fire Behavior Simulation from Global Fuel and Climatic Information. *Forests* **2017**, *8,* 179, doi:10.3390/f8060179.
31. Roccaforte, J.P.; Fulé, P.Z.; Covington, W.W. (2008) Landscape-scale changes in canopy fuels and potential fire behaviour following ponderosa pine restoration treatments. *Int J Wildland Fire*. **2008**, *17*, 293-303, doi: 10.1071/WF06120
32. Finney, M.A.; McHugh, C.W.; Grenfell, I.C.; Riley, K.L.; Short, K.C. A simulation of probabilistic wildfire risk components for the continental United States. *Stoch. Environ. Res. Risk Assess.* **2011**, *25*, 973–1000, doi:10.1007/s00477-011-0462-z.

33. Finney, M.A.; Grenfell, I.C.; McHugh, C.W.; Seli, R.C.; Trethewey, D.; Stratton, R.D.; Brittain, S.A Method for Ensemble Wildland Fire Simulation. *Environ. Model. Assess.* **2011**, *16*, 153–167, doi:10.1007/s10666-010-9241-3.
34. Finney, M.A.; Mchugh, C.W.; Grenfell, I.; Riley, K.L. Continental-scale simulation of burn probabilities, flame lengths, and fire size distribution for the United States. In Proceedings of the VI International Conference on Forest Fire Research, 15–18 November 2010, Coiambra, Portugal; Viegas, D.X., Ed.; Univeristy of Coiambra: Coiambra, Portugal, 2010; pp. 15–18.
35. Ye, T.; Wang, Y.; Guo, Z.; Li, Y. Factor contribution to fire occurrence, size, & burn probability in a subtropical coniferous forest in East China. *PLoS ONE* **2017**, *12*, 1–18, doi:10.1371/journal.pone.0172110.
36. Monedero, S.; Ramirez, J.; Molina-Terrén, D.; Cardil, A. Simulating wildfires backwards in time from the final fire perimeter in point-functional fire models. *Environ. Model. Softw.* **2017**, *92*, 163–168, doi:10.1016/j.envsoft.2017.02.023.
37. Ramirez, J.; Monedero, S.; Buckley, D. New approaches in fire simulations analysis with Wildfire Analyst. In Proceedings of the 5th International Wildland Fire Conference; Sun City, South Africa, 9–13 May 2011.
38. Duane, A.; Aquilué, N.; Gil-Tena, A.; Brotons, L. Integrating fire spread patterns in fire modelling at landscape scale. *Environ. Model. Softw.* **2016**, *86*, 219–231, doi:10.1016/j.envsoft.2016.10.001.
39. Cardil, A.; Merenciano, D.; Molina-Terrén, D. Wildland fire typologies and extreme temperatures in NE Spain. *iForest Biogeosci. For.* **2016**, *10*, 9–14, doi:10.3832/ifor1939-009.
40. Parisien, M.A.; Miller, C.; Parks, S.A.; DeLancey, E.R.; Robinne, F.N.; Flannigan, M.D. The spatially varying influence of humans on fire probability in North America. *Environ. Res. Lett.* **2016**, *11*, 075005, doi:10.1088/1748-9326/11/7/075005.
41. Garcia, M.; Riaño, D.; Yebra, M.; Salas, F.J.; Cardil, A.; Monedero, S.; Ramirez, J.; Martín, M.P.; Vilar, L.; Gajardo, J.; et al. A Live Fuel Moisture Content product from medium spatial resolution Landsat TM satellite time series ready for implementation in fire behavior models. *Remote Sens.* **2020**, *12*, 1714; doi:10.3390/rs12111714.
42. Rollins, M.G. LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. *Int. J. Wildland Fire* **2009**, *18*, 235–249, doi:10.1071/WF08088.
43. González, J.R.; Pukkala, T. Characterization of forest fires in Catalonia (north-east Spain). *Eur. J. For. Res.* **2007**, *126*, 421–429, doi:10.1007/s10342-006-0164-0.
44. González, J.R.; Palahí, M.; Trasobares, A.; Pukkala, T.A probability model for forest stands in Catalonia (north-east Spain). *Ann. For. Sci.* **2006**, *63*, 169–176, doi:10.1051/forest:2005109.
45. Díaz-Delgado, R.; Lloret, F.; Pons, X. Spatial patterns of fire occurrence in Catalonia, NE, Spain. *Landsc. Ecol.* **2004**, *19*, 731–745, doi:10.1007/s10980-005-0183-1.
46. Díaz-Delgado, R.; Pons, X. Spatial patterns of forest fires in Catalonia (NE of Spain) along the period 1975–1995: Analysis of vegetation recovery after fire. *For. Ecol. Manag.* **2001**, *147*, 67–74.
47. Castellnou, M.; Pagés, J.; Larrañaga, A.; Piqué, M. *Mapa de Risc D'incendi Tipus de Catalunya (Map of Wildfires in Catalonia Using Fire Types Concept)*; GRAF-Bombers; Ministry of Home Affairs, Generalitat of Catalonia and Forest Science and Technology Centre of Catalonia: Barcelona, Spain, 2010.
48. Badia-Perpinyà, A.; Pallares-Barbera, M. Spatial distribution of ignitions in Mediterranean periurban and rural areas: The case of Catalonia. *Int. J. Wildland Fire* **2006**, *15*, 187–196, doi:10.1071/WF04008.

49. Centre de Recerca Ecològica i Aplicacions Forestals. *Mapa de Cobertes del Sòl de Catalunya v4 (Land Cover Map of Catalonia v4)*; CREAF, Ministry of Agriculture, Livestock, Fisheries and Food, Ministry of Home Affairs and Ministry of Territory and Sustainibility, Generalitat of Catalonia: Barcelona, Spain, 2009.
50. Coll, L.; González-Olabarria, J.R.; Mola-Yudego, B.; Pukkala, T.; Messier, C. Predicting understory maximum shrubs cover using altitude and overstory basal area in different Mediterranean forests. *Eur. J. Forest Res*. **2011**, *130*, 55–65, doi:10.1007/s10342-010-0395-y.
51. MAGRAMA (Ministerio de Agricultura, Pesca y Alimentación). *Tercer Inventario Forestal Nacional (The Third National Forest Inventory)*; Ministry of Agriculture, Fisheries and Food: Madrid, Spain, 2007.
52. Köppen, W. *Das Geographische System der Klimate. Handbuch der Klimatologie*; Köppen, W., Geiger, R., Eds.; Verlag von Gebrüder Borntraeger: Berlin, Germany, 1936; Volume 1, Part C, pp. 1–44.
53. Iberian Climate Atlas. Available online: https://www.aemet.es/es/conocermas/recursos_en_linea/publicaciones_y_estudios/publicaciones/detalles/Atlas-climatologico (accessed on 2 August 2020).
54. SPIF (Servei de Prevenció d'Incendis Forestals). *Nombre D'incendis i Superficie Cremada per Anys. Període: 1986–2019 (Number of Fires and Burned Area per Years. Period: 1986–2019)*; Forest Fires Prevention Service, Ministry of Agriculture, Livestock, Fisheries and Food, Generalitat of Catalonia: Barcelona, Spain, 2020.
55. González Olabarría, J.R.; Pukkala, T.; Palahi, M. Optimising the management of Pinus sylvestris L. stand under risk of fire in Catalonia (north-east of Spain). *Ann. For. Sci.* **2005**, *62*, 493–501.
56. Finney, M.A. An Overview of FlamMap Fire Modeling Capabilities. In *Fuels Management—How to Measure Success: Conference Proceedings, 28–30 March 2006, Portland, OR, USA*; Andrews, P.L., Butler, B.W., Eds.; Proceedings RMRS-P-41; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2006; pp. 213–220.
57. Vericat, P.; Piqué, M.; Koua, O.; Pla, M. *Mapa de Formacions Forestals Pures i Mixtes de Catalunya a Partir del Mapa Forestal de España 1:50,000 Digitalitzat (Map of Pure and Mixed Forest Formations of Catalonia Based on the Digitalized Forest Map of Spain 1:50,000)*; Forest Science and Technology Centre of Catalonia(CTFC): Solsona, Spain, 2010.
58. ICGC (Institut Cartogràfic i Geològic de Catalunya). *Mapa de Variables Biofísiques de L'arbrat de Catalunya (Map of Biophysical Variables of Wooded Forest Areas of Catalonia)*; Cartographic and Geological Institut of Catalonia, Ministry of Agriculture, Livestock, Fisheries and Food and Ministry of Territory and Sustainibility, Generalitat of Catalonia: Barcelona, Spain, 2016.
59. MAGRAMA (Ministerio de Agricultura, Pesca y Alimentación). *Cuarto Inventario Forestal Nacional (The Fourth National Forest Inventory)*; Ministry of Agriculture, Fisheries and Food: Madrid, Spain, 2017.
60. Piqué, M.; Vericat, P.; Cervera, T.; Baiges, T.; Farriol, R. Tipologies Forestals Arbrades. In *Orientacions de Gestió Forestal Sostenible per a Catalunya (ORGEST) (Typologies of Wooded Forest Areas. Orientacions of Sustainable Forest Management in Catalonia)*; Ministry of Agriculture, Livestock, Fisheries and Food, Generalitat of Catalonia: Barcelona, Spain, 2011.
61. ICGC (Institut Cartogràfic i Geològic de Catalunya). Cartographic and Geological Institute of Catalonia, Ministry of Agriculture, Livestock, Fisheries and Food and

Ministry of Territory and Sustainability, Generalitat of Catalonia. Available online: https://www.icgc.cat/Descarregues/Elevacions (Accessed on 13 October 2020)

62. Scott, J.H.; Reinhardt, E.D. *Assessing Crown Fire Potential by Linking Models of Surface and Crown Fire Behavior*; USDA Forest Service: Fort Collins, CO, USA, 2001.
63. Scott, J.H.; Burgan, R.E. *Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model*; USDA Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2005.
64. Rothermel, R.C. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*; Research Paper INT-115; U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station: Ogden, UT, USA, 1972; 40p.
65. Anderson, H.E. *Aids to Determining Fuel Models for Estimating Fire Behavior*; General Technical Report INT-122; U.S.Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: Ogden, UT, USA, 1982; 22p.
66. Ninyerola, M.; Pons, X.; Roure, J.M. *Atlas Climático Digital de la Península Ibérica. Metodología y Aplicaciones en Bioclimatología y Geobotánica*; Universidad Autónoma de Barcelona: Cerdanyola del Vallès, Spain, 2005.
67. Servei Meteorològic de Catalunya (Meteorological Service of Catalonia). Available online: https://www.meteo.cat/observacions/xema (accessed on 24 March 2018).
68. Duane, A.; Piqué, M.; Castellnou, M.; Brotons, L. Predictive modelling of fire occurrences from different fire spread patterns in Mediterranean landscapes. *Int J Wildland Fire* **2005**, *24*, 407–418, doi:10.1071/WF14040.
69. Cardil, A.; Monedero, S.; Silva, C.A.; Ramirez, J. Adjusting the rate of spread of fire simulations in real-time. *Ecol. Model.* **2019**, *395*, 39–44, doi:10.1016/j.ecolmodel.2019.01.017.
70. PREVINCAT. Available online: http://previncat.ctfc.cat/ (accessed on 13 October 2020).
71. Finney, M.A. *FARSITE: Fire Area Simulator-Model Development and Evaluation*; Research Paper RMRS-RP-4, Revised 2004; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Ogden, UT, USA, 1998; 47p.
72. WildfireAnalyst. Available online: https://tecnosylva.es/wildfire-analyst (accessed on 13 October2020).

Chapter 4

GENERAL DISCUSSION

This thesis provides concrete methodological support on the application of spatial planning in management of forest ecosystem services and ecosystem-services-derived strategies. It deals with challenges related to the complex environmental modelling, incorporating multi-criteria-based approaches, decision support tools and geographical information technologies. It encourages objective approach to the ecosystem services assessment, potentiating forest multifunctionality and sustainable ecosystem development. We applied this framework in four different studies, each of them with different study area, geographical scale and objectives, but with similar general methodological approach and the aim to improve prioritization of spatial management strategies. Each of the studies addresses multiple strengths and some weaknesses of application of spatial-based technologies in management of forest ecosystem services, stressing the importance of such analyses, reporting existent methodological constraints and proposing solutions for better strategical spatial planning.

4.1. Constraints regarding spatial planning of forest ecosystem services

Spatial data availability represents one of the main problems and challenges in spatial planning studies [1]. While spatial planning relies on the models as a mean of approximation of geospatial reality, the high accuracy of the models and variables used to run them represent ones of the main requirements in spatial analyses [2]. Accuracy pertains to the extent of agreement between the outcomes of spatial modelling and the object or occurrence being modelled. In simpler terms, accuracy demonstrates the proficiency of a spatial model in approximating the actual arrangement and quantity of an environmental system at a resolution that adequately encompasses the relevant phenomena [3] [4]. Spatial data serve as a primary input for approximating the environmental condition, forming the foundation for subsequent modelling processes [5]. Consequently, their accessibility and ability to quantify spatial phenomena directly influence the accuracy of the model, which, in turn, impacts decision-making and the identification of suitable management options [6]. In addition to data accuracy, another crucial consideration in spatial modelling is assessing the complexity involved in achieving high accuracy when modelling spatial processes. This complexity is influenced by the spatial variability of environmental process distribution and the data's capacity to capture and simulate such variations [7]. Modelling spatial processes that involve movement or intangible spatial characteristics poses greater challenges as they are harder to capture accurately in static maps. In the context of ecosystem services, this primarily pertains to cultural ecosystem services and habitat-related regulating services [4].

In this thesis, four distinct spatial datasets were utilized in an attempt to approximate the geospatial reality and conduct analyses. Different levels of data limitations were encountered in each study. While Article 1 and Article 4 encountered minor temporal discrepancies within each dataset, mainly due to obtaining data from different sources but still allowing for easy comparison, Article 2 and Article 3 faced significant data availability issues. Article 2, which focused on forest dynamics, required specific datasets to enable spatial-temporal simulations, resulting in limited data availability. Moreover, the national-level representation of non-inventory data was hindered by the geographical scale, restricting the model's accuracy by limiting spatial variations and leading to a less comprehensive analysis. On the other hand, Article 3 observed limitations in the comparative analysis methods at the local level due to varying data availability across different countries. Due to differences in urban policies and levels of development, different cities often possess data inventories that are not directly comparable, thereby limiting the possibility of making direct comparisons. As a result, the reliance on remote sensing data becomes the primary alternative for analysis.

Related to that, geographical scale is another important factor to consider in spatial planning of environmental processes. With an increase in the size of the study area, the demand for data also increases. However, as the area expands, the likelihood of obtaining spatially representative data decreases [8]. While the applicability of spatial planning technologies allows for a detailed analysis independent of the geographical scale utilized, the data availability restrictions may cause inaccuracies in the models. The development, accomplishment, and administration of policies aimed at incorporating range of services offered by ecosystems rely on the presence of spatially detailed information, but the execution of management options and strategies directly depends on the corresponding authorities [9]. For that reason, it is crucial to consider the scale of applicability for the obtained results. While the studies' objectives are primarily practical, organized, and intended for real-world application, the geographical scale should also facilitate the practicality of the findings [10]. In this regard, broader scales may offer more generalized environmental solutions, but they are geared towards larger areas and higher-level policymakers, and vice versa [11]. As a result, the impact of spatial planning can vary significantly. In this thesis, three different geographical scales were implemented for environmental analysis. With similar objectives, we analysed ecosystem-services-related data at the local, regional, and national levels. We noticed less model accuracy problems at regional level, enabling to conduct comprehensive analyses. Nevertheless, we affirm that the outcomes obtained from all three geographical scales exhibit a high degree of applicability, provided that we carefully consider possible methodological constraints during the interpretation of the results.

"An indicator in environmental planning is a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions or changes or to set environmental goals" [2]. Therefore, indicators are essential tool for spatial modelling of ecosystem services to identify appropriate management strategies. Nevertheless, one of the major challenges in ecosystem services analyses is the standardization of indicators, which is caused by the diverse nature of ecosystems and the wide range of services they provide [12] [13]. One of the main problems is the lack of consensus among researchers, practitioners, and stakeholders regarding the selection and measurement of indicators. There are various approaches and methodologies available for assessing ecosystem services, and each may prioritize different indicators based on their specific objectives and priorities [14]. This lack of standardization can lead to inconsistencies and difficulties in comparing and integrating findings from different studies or across different regions [15]. Although the Millennium Ecosystem Assessment made significant progress in addressing some of the issues related to indicators standardization, the broadness of the ecosystem services concept hinders the establishment of more precise frameworks [16]. On one side, this provides more flexibility in the methodological approach for analysing forest ecosystem services. However, on the other side, it makes it more challenging to compare ecosystem services provision (Article 3), select appropriate metrics to quantify ecosystem services supply (Article 2 and Article 3), quantify less studied intangible indicators (Article 1, Article 2, and Article 3), and account for the underrepresentation of benefits supply caused by methodological constraints (Article 2). In this thesis, we aim to address the challenges related to the selection of indicators and quantification of cultural ecosystem services in both rural and urban areas. Unlike other ecosystem services, cultural forest ecosystem services often suffer from a lack of comprehensive data and standardized measurement methods [17] [18]. Gathering reliable data on cultural values, preferences, and practices associated with forests can be challenging. This limitation hampers the development of indicators and the effective assessment and monitoring of cultural forest ecosystem services. This is primarily due to their intangible and qualitative nature, which is not easily quantifiable [19]. As a result, in many cases, instead of utilizing actual provision data for cultural ecosystem services, a theoretical capacity of supply is employed, leading to discrepancies in methodology approaches [20]. For example, in Article 1, we adopted such an approach; however, additional difficulties were encountered in Article 3, and particularly in Article 2. In Article 3, we attempted to address these challenges by employing remote sensing data as an alternative when spatial dataset inventories were incomplete. Remote sensing data also facilitated improved comparison approaches. While not an ideal substitute for assessing cultural services, it allowed for a sufficiently precise spatial quantification of relevant indicators. In Article 2, we observed an underrepresentation of cultural services due to the broad geographical scale and the absence of indicators at the national level that could be compared with the detailed provision data of other ecosystem services, derived from forest inventories.

4.2. Contributions of the thesis

In addition to addressing the limitations associated with the spatial assessment of forest ecosystem services, which have had a partial impact on the analysis, we aim to highlight the main contributions of this thesis. Firstly, this thesis aims to enhance the terminological and methodological approach in the assessment of forest ecosystem services, with the goal of facilitating the identification of long-term forest management strategies. For that purpose, we introduced the term forest use suitability. The concept of forest use suitability contributes to a better assessment of forest ecosystem services by providing a systematic framework to evaluate the compatibility between different forest uses and maximisation of the provision of services. It helps identify optimal management options, consider trade-offs and synergies among services, incorporate stakeholder perspectives using participatory workshops, and support spatial planning efforts. By integrating these considerations, forest use suitability assessment enhances the sustainable management of forest ecosystems and the promotion of ecosystem services. The concept of forest use suitability can be utilized to assess the current and projected future supply of forest ecosystem services, enabling the identification of short-, mid-, and long-term management strategies. In addition, we view it as a flexible-solution approach that acknowledges the multifunctionality of forests, incorporates trade-off assessments, and provides multiple priority options based on the spatial and temporal characteristics of the territory. We consider this approach to be an effective means of achieving and maintaining ecosystem sustainability through its integration into forest management policies.

In this thesis, we also focus on the management of urban ecosystem services and specifically address the challenges associated with assessing urban green areas. We propose solutions by emphasizing the significance of employing ecosystem services comparison methods. While each urban unit possesses a distinctive geospatial reality that often varies significantly from others, we believe that there is a substantial need to enhance approaches for comparing urban ecosystem services. This improvement is crucial to mitigate environmental inequality and promote urban well-being. These approaches also enhance the understanding of the ongoing need to improve urban ecosystems. Our findings demonstrate how the perception of provision values in a specific city can be altered by comparing it to other urban areas. Such perception can potentially create a distorted view of urban-ecosystem-services-related processes and their provision, leading to the adoption of inappropriate decisions regarding urban planning.

Additionally, to reduce the fire risk and sustain the provision of forest ecosystem services, this thesis presents a geoprocessing-based conceptual design of a server that contains most spatial variables for predicting fire behaviour at regional level. In order to accurately define fuel characteristics and predict potential fire behaviours under various meteorological scenarios, we implemented an innovative and detailed fuel modelling process. This involved parameterizing all the necessary environmental and climatic variables, enabling a more precise analysis of fire dynamics. We assert that this open server overcomes heterogeneous methodological constraints regarding forest fire management and forest fire behaviour prediction and represents the first step towards a complete data inventory for the management of wildfire prevention.

Finally, in order to assess the various aspects of geospatial planning discussed earlier, we utilized the latest version of the Ecosystem Management Decision Support (EMDS) system [21]. The transparent and user-friendly nature of EMDS offers a simplified representation of geospatial reality, aiding in the understanding of complex subject matter. This characteristic promotes interactive collaboration between scientists and end-users, making it well-suited for participatory planning [22] [23]. Furthermore, EMDS facilitates the integration of expert knowledge and scientific methods, specifically through its weighting processes and evaluation of criteria and network relations [24]. Apart from that, several of the EMDS features employed in this thesis were specifically developed to achieve the objectives we set forth. These features focus on conducting multi-criteria spatial assessments, employing fuzzy-logic-based modelling of geospatial reality related to the provision of ecosystem services, and facilitating the hierarchical analysis of management prioritization alternatives. The incorporation of these novel features, alongside the existing ones, allowed us to explore spatial studies that had previously seen limited or no use within the EMDS. As a result, this thesis not only contributes to the further enhancement of the EMDS capabilities but also expands its applicability, demonstrating highly satisfactory results.

References

[1] S. Dühr and A. Müller, "The Role of Spatial Data and Spatial Information in Strategic Spatial Planning," *Reg Stud*, vol. 46, no. 4, pp. 423–428, 2012, doi: 10.1080/00343404.2012.669535.

[2] F. Müller and B. Burkhard, "The indicator side of ecosystem services," *Ecosyst Serv*, vol. 1, no. 1, pp. 26–30, 2012, doi: 10.1016/j.ecoser.2012.06.001.

[3] D. J. Peuquet, "A Conceptual Framework and Comparison of Spatial Data Models," *Classics in Cartography: Reflections on Influential Articles from Cartographica*, vol. 21, no. 4, pp. 147–195, 2011, doi: 10.1002/9780470669488.ch12.

[4] M. Schröter, R. P. Remme, E. Sumarga, D. N. Barton, and L. Hein, "Lessons learned for spatial modelling of ecosystem services in support of ecosystem accounting," *Ecosyst Serv*, vol. 13, pp. 64–69, 2015, doi: 10.1016/j.ecoser.2014.07.003.

[5] D. García-Álvarez, H. Van Delden, M. T. Camacho Olmedo, and M. Paegelow, *Uncertainty Challenge in Geospatial Analysis: An Approximation from the Land Use Cover Change Modelling Perspective*, no. December 2021. Springer International Publishing, 2019. doi: 10.1007/978-3-030-04750-4_15.

[6] H. Francis, *A Primer of GIS: Fundamental Geographic and Cartographic Concepts*. New York, USA: The Guildford Press, 2008.

[7] M. Schröter, D. N. Barton, R. P. Remme, and L. Hein, "Accounting for capacity and flow of ecosystem services: A conceptual model and a case study for Telemark, Norway," *Ecol Indic*, vol. 36, pp. 539–551, 2014, doi: 10.1016/j.ecolind.2013.09.018.

[8] M. G. Turner, R. V. O. Neill, R. H. Gardner, and B. T. Milne, "Turner and O´Neill 1989.pdf," *Landsc Ecol*, vol. 3, pp. 153–162, 1989.

[9] J. Maes *et al.*, "Mapping ecosystem services for policy support and decision making in the European Union," *Ecosyst Serv*, vol. 1, no. 1, pp. 31–39, 2012, doi: 10.1016/j.ecoser.2012.06.004.

[10] D. Martin, E. McCann, and M. Purcell, "Space, scale, governance, and representation: Contemporary geographical perspectives on urban politics and policy," *J Urban Aff*, vol. 25, no. 2, pp. 113–121, 2003, doi: 10.1111/1467-9906.t01-1-00001.

[11] S. M. Posner, E. McKenzie, and T. H. Ricketts, "Policy impacts of ecosystem services knowledge," *Proc Natl Acad Sci U S A*, vol. 113, no. 7, pp. 1760–1765, 2016, doi: 10.1073/pnas.1502452113.

[12] A. Tiemann and I. Ring, "Towards ecosystem service assessment: Developing biophysical indicators for forest ecosystem services," *Ecol Indic*, vol. 137, no. March, 2022, doi: 10.1016/j.ecolind.2022.108704.

[13] C. Dobbs, F. J. Escobedo, and W. C. Zipperer, “A framework for developing urban forest ecosystem services and goods indicators,” *Landsc Urban Plan*, vol. 99, no. 3–4, pp. 196–206, 2011, doi: 10.1016/j.landurbplan.2010.11.004.

[14] C. Blattert, R. Lemm, O. Thees, M. J. Lexer, and M. Hanewinkel, “Management of ecosystem services in mountain forests: Review of indicators and value functions for model based multi-criteria decision analysis,” *Ecol Indic*, vol. 79, no. February, pp. 391–409, 2017, doi: 10.1016/j.ecolind.2017.04.025.

[15] R. J. Keenan, G. Pozza, and J. A. Fitzsimons, “Ecosystem services in environmental policy: Barriers and opportunities for increased adoption,” *Ecosyst Serv*, vol. 38, no. May, p. 100943, 2019, doi: 10.1016/j.ecoser.2019.100943.

[16] Millennium Ecosystem Assessment., “Ecosystems and Human Well-Being.,” Washington DC, 2005.

[17] D. La Rosa, M. Spyra, and L. Inostroza, “Indicators of Cultural Ecosystem Services for urban planning: A review,” *Ecol Indic*, vol. 61, pp. 74–89, 2016, doi: 10.1016/j.ecolind.2015.04.028.

[18] M. Hernández-Morcillo, T. Plieninger, and C. Bieling, “An empirical review of cultural ecosystem service indicators,” *Ecol Indic*, vol. 29, pp. 434–444, 2013, doi: 10.1016/j.ecolind.2013.01.013.

[19] M. M. Pleasant, S. A. Gray, C. Lepczyk, A. Fernandes, N. Hunter, and D. Ford, “Managing cultural ecosystem services,” *Ecosyst Serv*, vol. 8, no. November, pp. 141–147, 2014, doi: 10.1016/j.ecoser.2014.03.006.

[20] R. Bryce, K. N. Irvine, A. Church, R. Fish, S. Ranger, and J. O. Kenter, “Subjective well-being indicators for large-scale assessment of cultural ecosystem services,” *Ecosyst Serv*, vol. 21, no. December 2015, pp. 258–269, 2016, doi: 10.1016/j.ecoser.2016.07.015.

[21] K. M. Reynolds, “EMDS 3.0: A modeling framework for coping with complexity in environmental assessment and planning,” *Science in China, Series E: Technological Sciences*, vol. 49, no. SUPPL. 1, pp. 63–75, 2006, doi: 10.1007/s11431-006-8108-y.

[22] M. Marques, K. M. Reynolds, S. Marques, M. Marto, S. Paplanus, and J. G. Borges, “A participatory and spatial multicriteria decision approach to prioritize the allocation of ecosystem services to management units,” *Land (Basel)*, vol. 10, no. 7, 2021, doi: 10.3390/land10070747.

[23] K. M. Reynolds and P. F. Hessburg, “An Overview of the Ecosystem Management Decision-Support System,” *Environmental Science and Engineering*, pp. 3–22, 2014, doi: 10.1007/978-3-642-32000-2_1.

[24] K. Reynolds, S. Paplanus, B. Miller, and P. Murphy, “Design features behind success of the ecosystem management decision support system and future development,” *Forests*, vol. 6, no. 1, pp. 27–46, 2015, doi: 10.3390/f6010027.

Chapter 5

CONCLUSIONS

This thesis utilized diverse spatially enabled methods to evaluate multi-criteria decision-making processes concerning the sustainable management of forest ecosystem services. Innovative methodological approaches were employed to assess the provision of both forest and urban ecosystem services, with the goal of enhancing the identification of suitable management and planning strategies. A novel forest use suitability approach was developed to address this objective. Additionally, comparison methods for urban ecosystem services were implemented to improve the assessment of urban green areas. Furthermore, spatial modelling techniques were employed to establish an open server for evaluating fire hazard and planning fuel treatments. While each study presented in Chapter 3 provides specific conclusions, the overall conclusion of this thesis can be summarized as follows:

1. Spatial planning of forest or urban ecosystem services, aimed at defining long-term management strategies based on forest biogeophysical characteristics, is crucial for obtaining a sustainable environment that maximizes the provision of the most suitable ecosystem services without causing environmental damage.
2. There are several methodological and terminological constraints within the framework of forest ecosystem services, caused by the lack of consensus and standardization, which impede the fully successful assessment of sustainable forest ecosystem services strategies.
3. The concept of forest use suitability substantially helps overcome current methodological constraints and improves the process of identifying appropriate forest management actions.
4. The major limitations in the comprehensive spatial analysis of environmental processes and solution-oriented spatial assessments are the spatial data availability and the insufficiently developed indicators framework for ecosystem services, especially related to cultural ecosystem services.
5. The application of the EMDS system, in combination with other geographical information technologies, is a powerful tool that facilitates spatial multi-criteria decision-making regarding forest-ecosystem-services-related topics.
6. Geospatial modeling and geographical information technologies approximate complex geospatial reality and environmental processes in a simplified way; therefore, they are a good means to enhance interactive collaboration between

scientists and end-users, encourage participatory planning, and contribute to the integration of expert knowledge and scientific methods.

7. There is a need for continued work on the topics assessed in this thesis to further improve the application of geospatial technologies in environmental planning, continue reducing methodological and terminological constraints, and achieve more comprehensive and fully applicable spatial assessments.