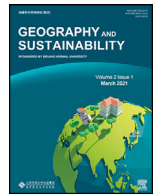




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Research Article

Forest use suitability: Towards decision-making-oriented sustainable management of forest ecosystem services

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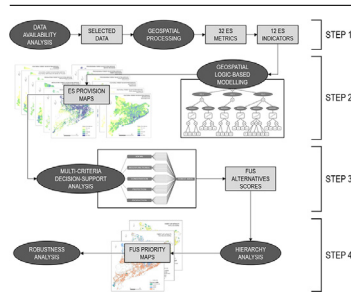
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HIGHLIGHTS

- Forest use suitability facilitates comprehensive management of forest ecosystem services.
- EMDS helps in forest ecosystem service's multi-objective spatial decision-making.
- Thirty two indicators of ecosystem services (ESs) features were mapped across Catalonia.
- ESs yield, their relative importance, and trade-offs, define forest use suitability.

GRAPHICAL ABSTRACT



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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 multi-functional) 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 multi-functional use. The assignment of forest use suitability aims to significantly improve the definition of the most adequate management strategy to be applied.

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1. Introduction

Ecosystem services (ESs) are benefits to society provided by ecosystems and are considered essential for human well-being (Castro et al., 2011). 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 (Millennium Ecosystem Assessment, 2005). 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 (García-Nieto et al., 2013). Several research groups have stressed the importance of a multi-disciplinary 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 (Anton et al., 2010; Bennett et al., 2015; Egoh et al., 2008). To maintain the flow of benefits to people while maintaining ecosystems, an appropriate management strategy needs to be considered (Egoh et al., 2008; van Jaarsveld et al., 2005). Up to the present, the role of ESs in decision-making for land governance has not received sufficient attention (Petz and van Oudenhoven, 2012). 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 (Daily et al., 2009; Ericksen et al., 2012; Schägner et al., 2013). Therefore, several authors have stressed the importance of developing ES-based approaches (Niemi et al., 2010; Tallis and Polasky, 2009), their application in spatial management of ecosystems (Guerry et al., 2012; Metzger et al., 2005), and effective implementation in national and regional governing policies (Bérbés-Blázquez et al., 2016; Bouwma et al., 2018).

Mapping the provision of ESs has been recommended as the first step towards a comprehensive management plan (Harrington et al., 2010; Luck et al., 2009). 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 (Bagstad et al., 2014). The modeling required to implement this type of spatial quantification is a challenging task (Crossman et al., 2012; Troy and Wilson, 2006; Wolff et al., 2015) due to the different nature and scale of factors influencing the provision of ESs and related methodological constraints (Eigenbrod et al., 2010; Hou et al., 2013; McDonough et al., 2017; Wang et al., 2013). Another relevant aspect to be considered when mapping ESs, with an intention of supporting decision making, is the diverse types of benefits provided (Simončič and Bončina, 2015), usually categorized according to the Millennium Ecosystem Assessment (MEA) as provisioning, regulating and cultural (Millennium Ecosystem Assessment, 2005). 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 (Roces-Díaz et al., 2018). Sayer et al. (1997) 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 multi-functional, due to trade-offs among the different services they provide, they usually cannot simultaneously deliver high levels of multiple services in a sustainable way (Wang and Fu, 2013). 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 min-

imize the negative impacts on provision of others (Martín-López et al., 2014).

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 (Ananda and Herath, 2009). 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 (Díaz-Balteiro and Romero, 2008). 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 (Selkimäki et al., 2020). 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 (Reed and Brown, 2003). 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 socioeconomic 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 (Bidegain et al., 2019; Maestre-Andrés et al., 2016; McDonough et al., 2017), 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 (Martnez-Harms and Balvanera, 2012), ranging from survey-based questionnaires (Simončič and Bončina, 2015), to mathematical or statistical models (Roces-Díaz et al., 2018), to explicit decision-making tools (Bagstad et al., 2013). 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 (Reynolds et al., 2015; Reynolds and Hessburg, 2014), 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.

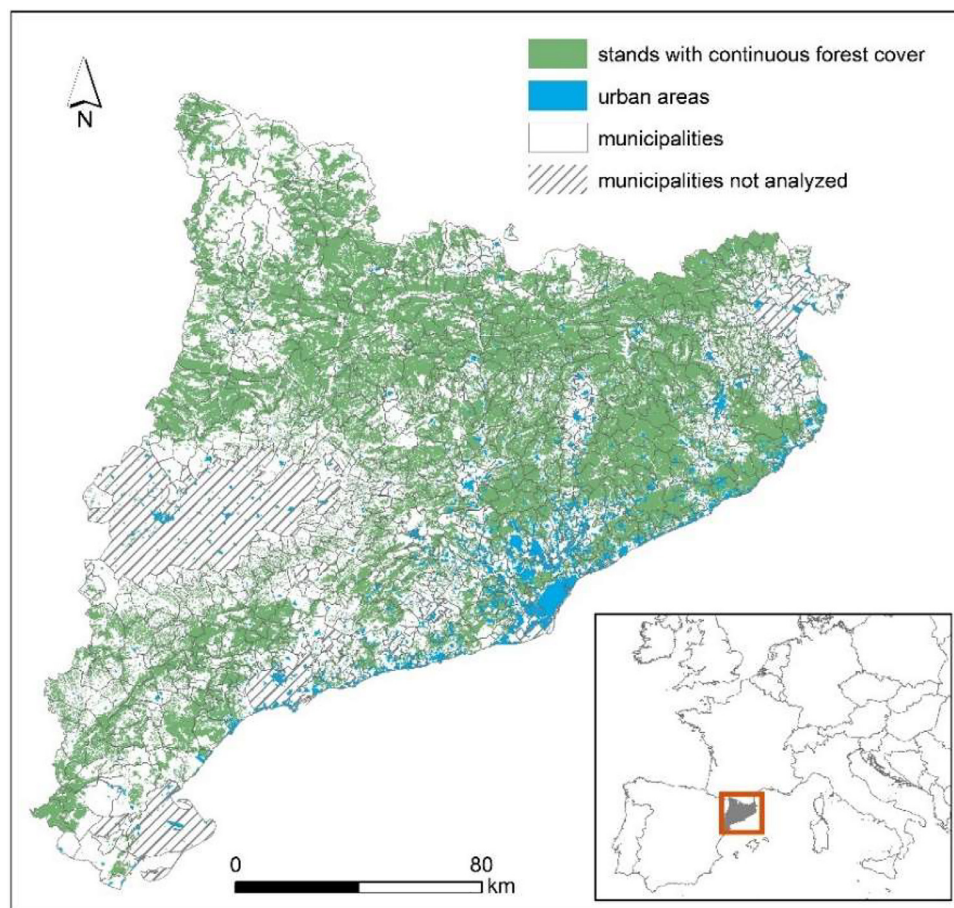


Fig. 1. Study area and relevant data layers.

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 km², and about 42% of the area is classified as forest and woodland (Centre de Recerca Ecològica i Aplicacions Forestals (CREAF), <https://www.mcsc.creaf.cat>). 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 (Coll et al., 2011). 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 (Roces-Díaz et al., 2018). 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 kilometer (Catalan Statistics Institute, 2015); 43% of its population is concentrated in the metropolitan area of Barcelona (Roces-Díaz et al., 2018). The area is orographically diverse, with elevations ranging from sea level to >3,000 m (Roces-Díaz et al., 2018) and with strong influences on climate, ranging from semi-arid to Mediterranean-influenced subarctic climates (Krsnik et al., 2020).

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 (MITECO, 2006). Based on these selection criteria, the study area included 25,408 forest stand polygons from the SFM and 779 of the 947 Catalan municipalities (Fig. 1). A

detailed list of data used to calculate the ES metrics are presented in Table 1.

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 (Fig. 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) *Analyze the provision of forest ecosystem services at the forest stand.* Once FES had been established, in the second step, by using geospatial logic-based modeling, their provision at each stand was quantified. Values of FES provision were used as input for FUS assignment.
- (3) *Assess 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) *Analyze robustness between suitability alternatives.* In this final step, the FUS performance scores obtained in the previous step were ranked

Table 1
Selected 32 metrics used to evaluate each of the 12 forest ecosystem services (FES) indicators.

FES groups and FES indicators ^a	FES metrics	Spatial scale	Units
<i>PROVISIONING</i>			
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
<i>REGULATING</i>			
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	%
<i>CULTURAL</i>			
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
	Monumental trees	Municipality	number
Cultural heritage or sense of place	Cultural sights	Municipality	number/km ²
	Rural accommodation	Municipality	number/km ²
Tourism	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 indicators are categorized by the three FES groups, which are indicated in italics and all upper case.

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.

2.2.1. Definition of forest ecosystem services indicators

Definition of FES indicators was the first step towards the complete ES analysis. A 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 indicator are presented in Section 2.2.2. The MEA methodological framework was used to process and organize data. There-

fore, three FES groups were established: provisioning, regulating and cultural.

Provisioning services are the products people obtain from the ecosystems (Millennium Ecosystem Assessment, 2005). 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 (Cartographic and Geological Institute of Catalonia, <https://www.icgc.cat/>).
- (2) Forest productivity values, on the other hand, were estimated by the MITECO and were spatially adapted to our scale (MITECO, <https://www.miteco.gob.es/>).
- (3) Density of roads suitable for wood extraction machinery was obtained from the road network map 1:5000 and topographic map of Catalonia 1:25,000 adapted by the Forestal Catalana (Generalitat of Catalonia) for PORF assessment purposes (Generalitat of Catalonia, <http://forestalcatalana.gencat.cat/es/>).
- (4) Time cost of access to each forest stand was adopted from the PORF study made by the Forestal Catalana (Generalitat of Catalonia, <http://forestalcatalana.gencat.cat/es/>).

We used three indicators to describe potential production of non-wood forest products in Catalan forests, defining food provision. The Bonet et al. (2014) model was used to estimate potential mushroom productivity by forest ecosystems in Catalonia. On the other hand, both

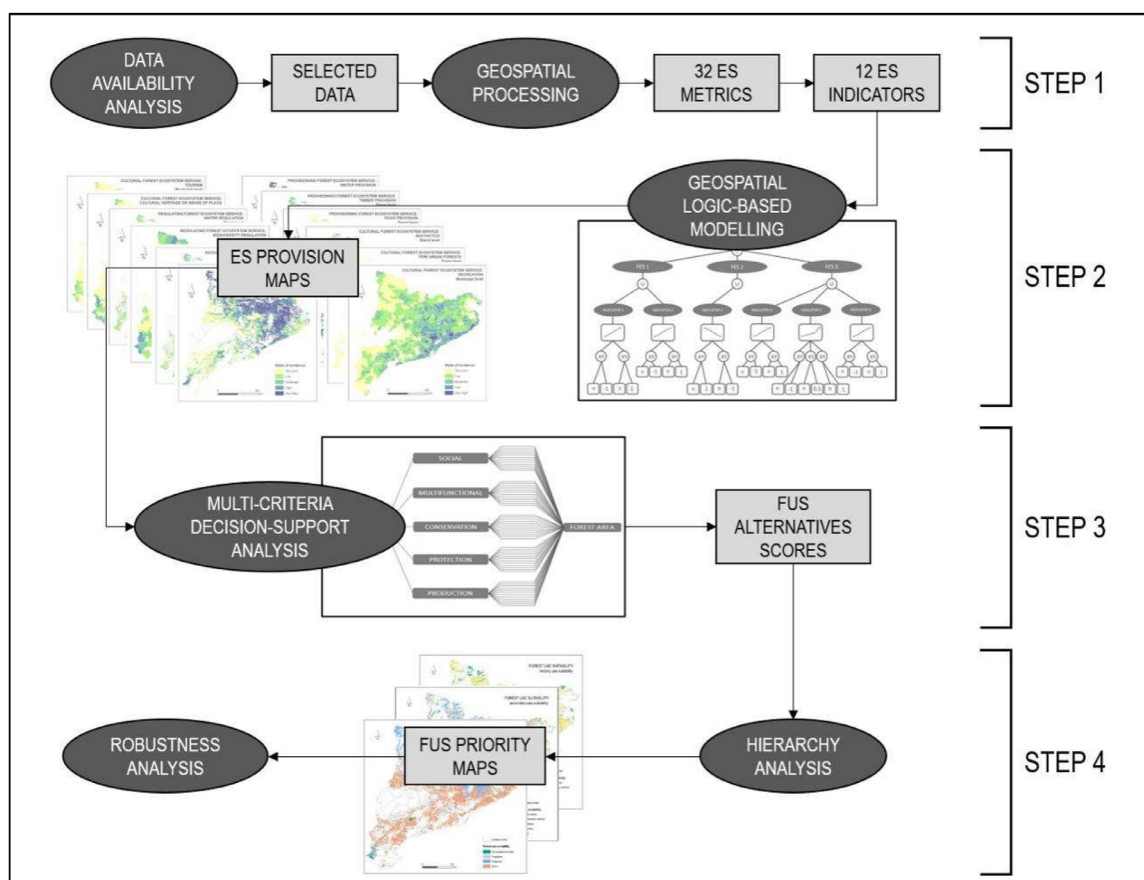


Fig. 2. Conceptual design of the study.

for pine nuts and cork, we used data from the SFM to define the potential production capability in the area (MITECO, 2006). To represent water provision, we used estimated data on total annual runoff provided by the national Ministry of Agriculture, Fisheries and Food (2005; <https://www.mapa.gob.es/es/>).

Regulating services are the benefits people obtain from the regulation of ecosystem processes (Millennium Ecosystem Assessment, 2005). 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; <http://mediambient.gencat.cat>), from the Catalan System of Natural Protected Areas (Department of Territory and Sustainability, <https://sig.gencat.cat/visors/hipermapa.html>) to assess the biodiversity regulation service. Additionally, we included the cartographic dataset of Natural Habitats of High Priority, and areas considered to have presence of threatened flora or fauna species (Department of Territory and Sustainability, <https://sig.gencat.cat/visors/hipermapa.html>). 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 (Cartographic and Geological Institute of Catalonia, 2016; MITECO, 2006). Carbon sequestration was used to represent climate regulation, based on LiDAR data (Cartographic and Geological Institute of Catalonia, 2016). 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 (Ministry of Agriculture, Fisheries and Food, <https://www.mapa.gob.es>). 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, recre-

ation, reflection, and esthetic experiences” (Millennium Ecosystem Assessment, 2005). 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 (Department of Agriculture, Stocking, Fisheries and Food, <http://agricultura.gencat.cat/ca/ambits/medi-natural/casa>). The availability and potential demand of recreation services was represented by the density of officially approved hiking trails, and statistics on population density (Catalan Excursionist Federation, <https://senders.feec.cat/>; Catalan Statistics Institute, <https://www.idescat.cat/>). 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 (Department of Territory and Sustainability, <https://sig.gencat.cat/visors/hipermapa.html>). 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 kilometer, which were used as proxies to estimate potential demand of forest-oriented touristic activities (Catalan Statistics Institute, 2015). Moreover, archeological and paleontological sites and cultural heritage monuments located within forests were used to represent potential touristic attractions (Generalitat of Catalonia, <https://sig.gencat.cat/portalsigcultural.html>). The latter two metrics, together with monumental trees (Department of Territory and Sustainability, <https://sig.gencat.cat/visors/hipermapa.html>) were considered to define a cultural heritage or sense-of-place indicator, aiming to designate historical, symbolic, and cultural significance of forests. An esthetic value of forest was obtained using a model developed by Blasco et al. (2009) that implements an index for scenic beauty. Ad-

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

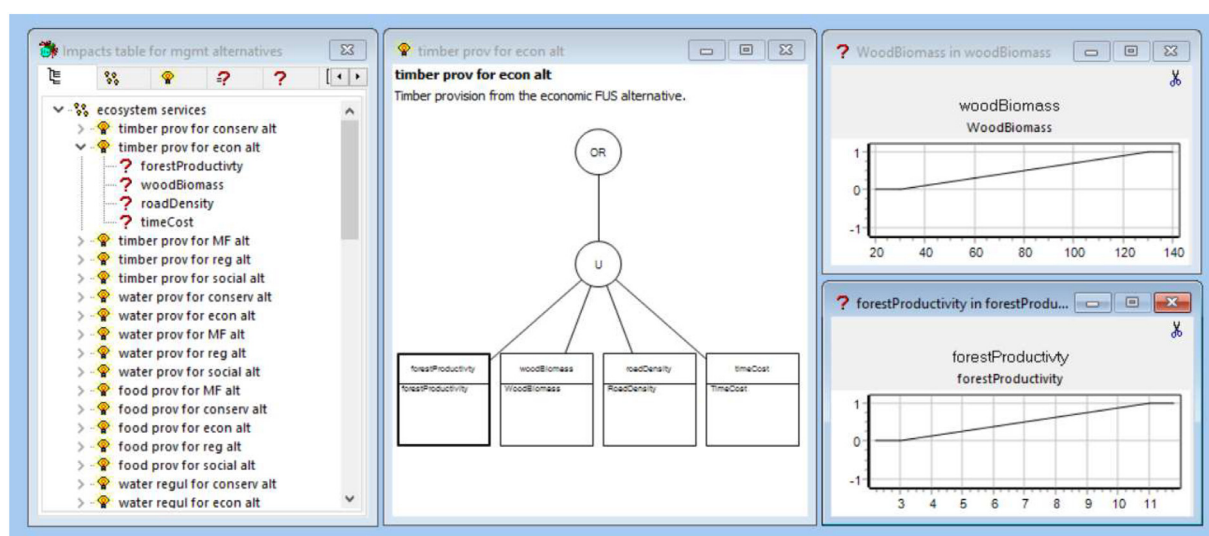


Fig. 3. Graphic of the logic for evaluating the contribution of timber provision to the economic forest use suitability. The lefthand frame displays a partial view of the network components with the outline expanded under the alternative for timber provision in the economic context. The middle frame 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, wood biomass and forest productivity.

ditionally, we introduced a special category for peri-urban forests, depending on the distance to the nearest urbanized area with more than 10,000 inhabitants (Catalan Statistics Institute, 2015).

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 [(Miller and Saunders, 2006), hereafter NetWeaver], an analytical component of the EMDS spatial decision support framework (Reynolds and Hessburg, 2014). 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 (Miller and Saunders, 2006). 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 modeling 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 (Fig. 3). The evalu-

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 suitable uses of the forest.

FES indicators	FUS alternatives				
	<i>Multi-functional</i>	<i>Productive</i>	<i>Protective</i>	<i>Conservation</i>	<i>Social</i>
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

ation of timber provision considers four metrics (Table 1), each evaluated by a fuzzy membership function (Table 2). The U operator (Fig. 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.

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-modeling phase (step 3 in Fig. 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 Fig. 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 (Fig. 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.

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 (Murphy and Solan, n.d.). 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 (Fig. 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 rating 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.

2.2.4. Assignment of FUS priorities and robustness analysis

In step 4 of the overall assessment (Fig. 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

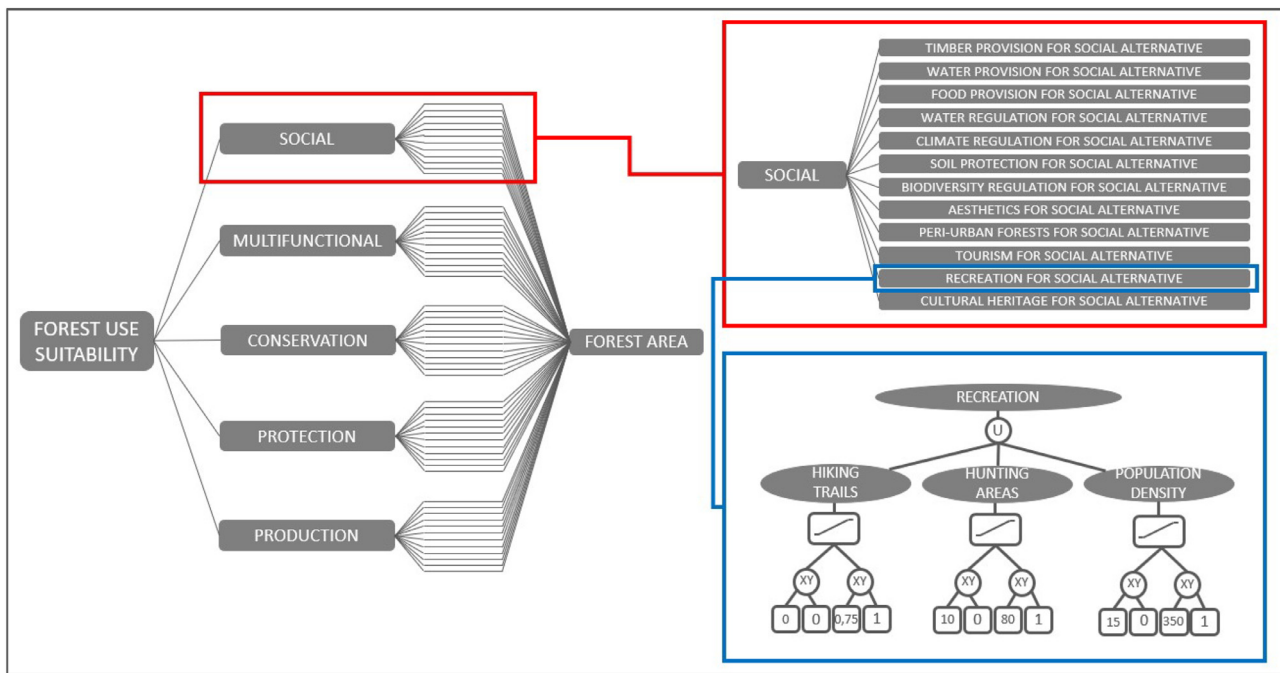


Fig. 4. Schematic design of CDP model. The left-hand pane shows the overall MCDA model, with the five FUSs being the nodes to the right of the Goal. The upper right pane zooms into show the 12 FES indicators under that FUS, and the lower right pane shows 3 networks in the NetWeaver model that calculate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

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 (Fig. 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 characterized by very high provision values near coastal areas, where most of the population is concentrated. Tourism and cultural heritage values have rather irregular spatial patterns. 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.

3.2. Forest use suitability

Forest use suitability maps are shown on Fig. 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 (Fig. 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 northeast. 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 (Fig. 6b). Productive use was selected as the most common secondary suitability option (31%), since it is the dominant secondary option to primary protective

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.

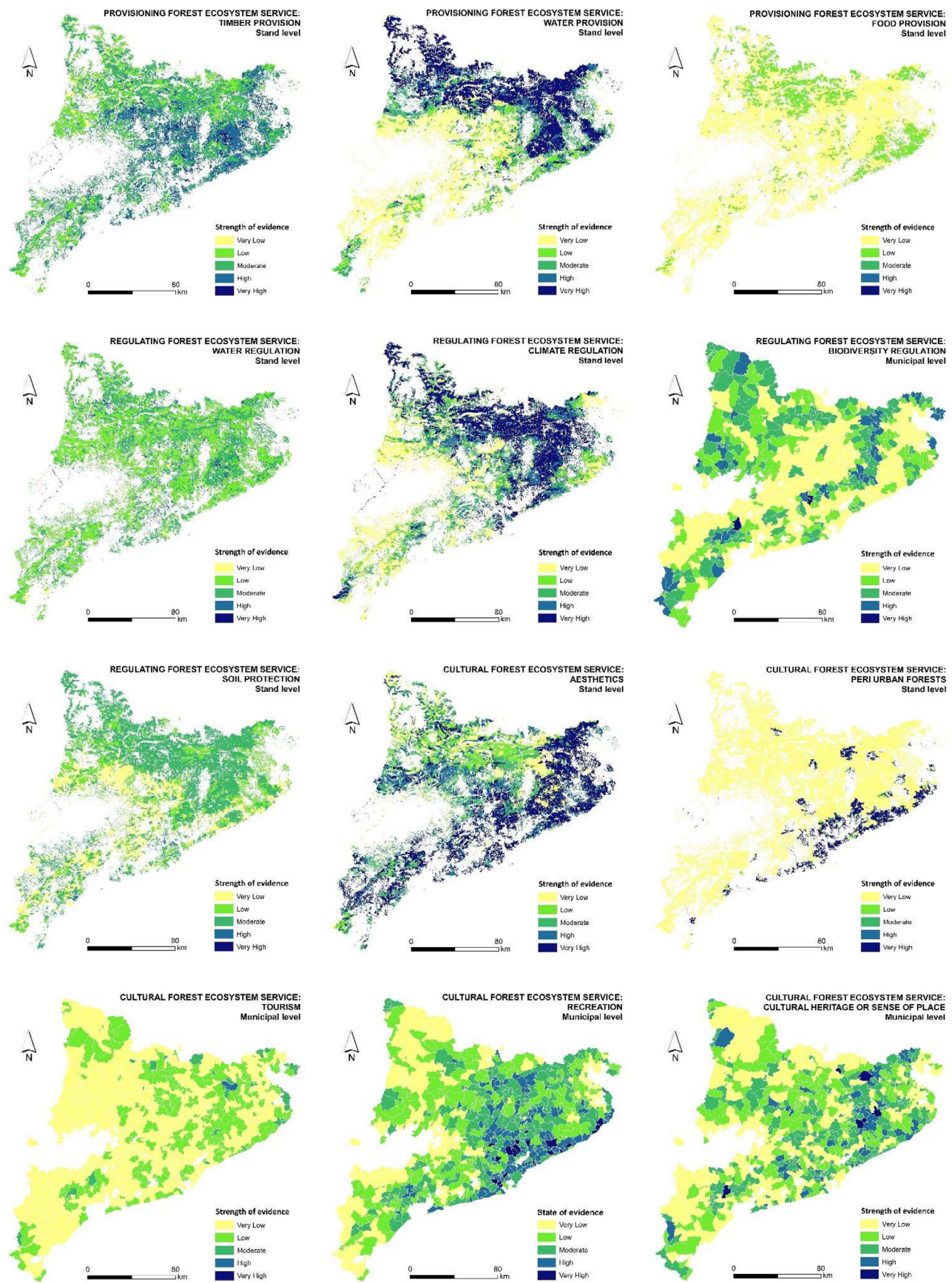


Fig. 5. Maps of provision of each of 12 analyzed forest ecosystem services.

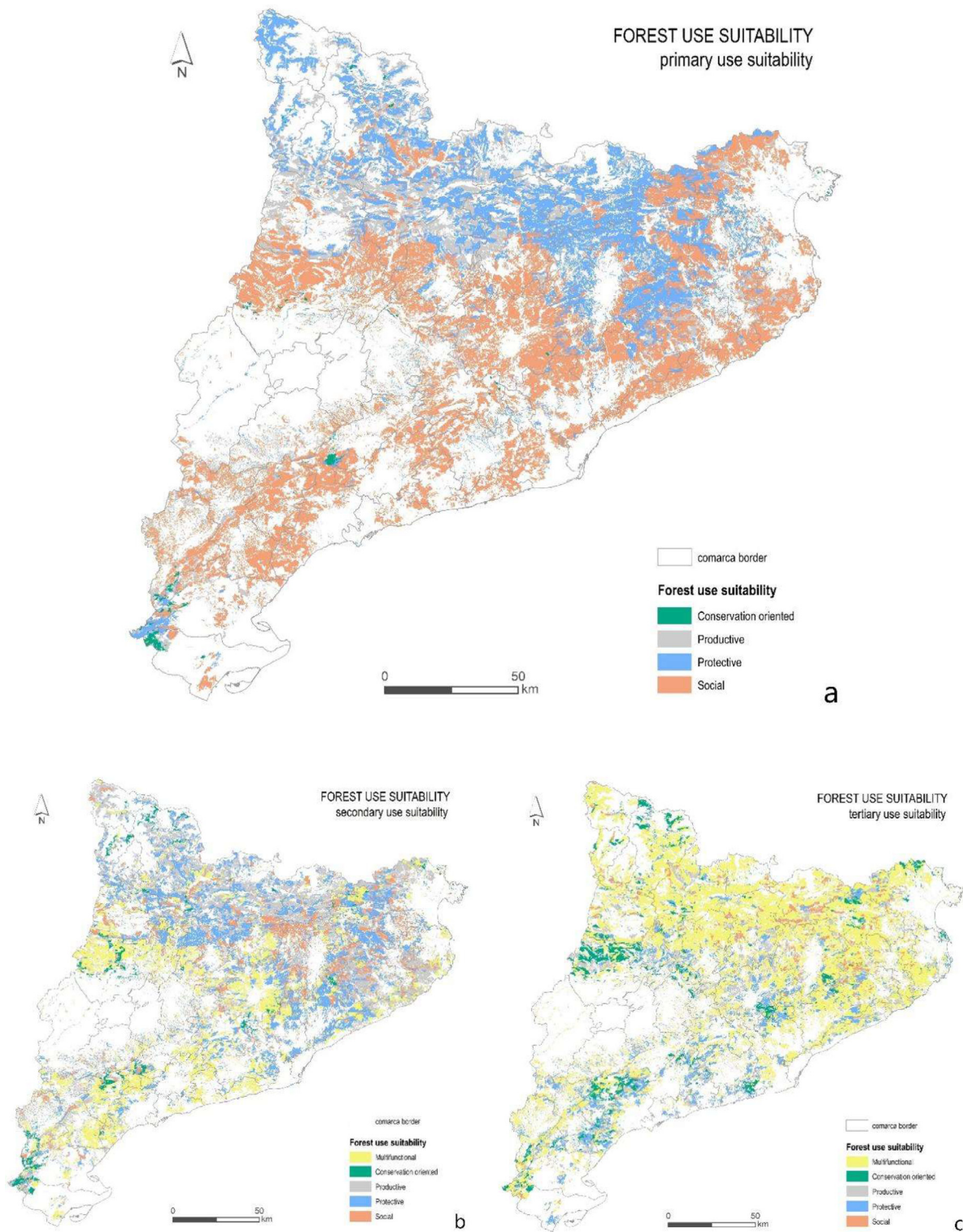


Fig. 6. Maps of forest use suitability.

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 representa-

tion of multifunctional use as important, even if not selected as primary option, was further reflected when considering it as a third ranked option (Fig. 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 (Table 5).

The robustness analysis between primary and secondary FUS performance scores is shown on Fig. 7. Large differences between the highest

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

Primary FUS	% of total plots	Secondary FUS (% of Primary FUS)				
		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
Multi-functional	0	x	x	x	x	x

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

Secondary FUS	% of total plots	Tertiary FUS (% of Secondary FUS)				
		Productive	Protective	Con.-oriented	Social	Multi-functional
Productive	31.02	x	5.71	4.83	7.56	81.89
Protective	27.34	717	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
Multi-functional	21.51	35.22	42.04	16.22	6.53	x

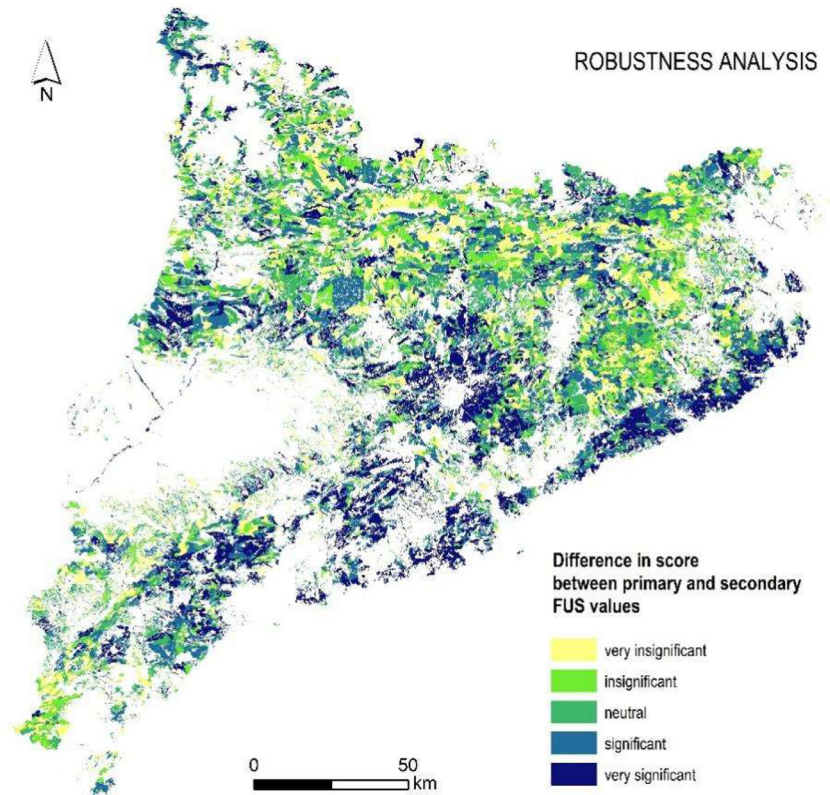


Fig. 7. Robustness analysis between primary and secondary FUS score values.

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.

4. Discussion

4.1. Forest use suitability: towards solution-oriented forest management

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 con-

straints in assessment of ecosystem services, aiming to ease the incorporation of the framework into decision making processes and management strategies (Fisher et al., 2009). 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 (Hauck et al., 2013; Laurans et al., 2013). 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 (Daily et al., 2009). 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 (Akinci et al., 2013; Liu et al., 2014) and it has not 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 (Malczewski, 2004; McDowell et al., 2018). The term land use suitability has been used, among other applications, in agriculture to determine suitable lands for agricultural use (Akinci et al., 2013), land use planning to assess economic competitiveness and sustainable development (Joerin et al., 2001), urban planning for urban development (Liu et al., 2014), and assessment of rural tourism, aiming to define the most appropriate touristic activities in different rural landscapes (Kaptan Ayhan et al., 2020). 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, 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.

4.2. Forest multi-functionality

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.

4.3. Dataset limitations in FES assessment

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 (Maes et al., 2012). 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 (Roces-Díaz et al., 2018; Yahdjian et al., 2015). 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 (Satz et al., 2013). For example, instead of possibly more complete open-source data, we used only homologized 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 (Roces-Díaz et al., 2018).

4.4. Multi-criteria spatial planning

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 (Marques et al., 2021; Povak et al., 2020). 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 neighboring 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 neighbors. 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 released version 8.7.

Lastly, weight assignment is necessary in any decision-making process (Acosta and Corral, 2017). 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 (Goosen et al., 2007; Menzel et al., 2012). 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 modeling, 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 a 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.

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Data availability

Archive 1 and Archive 2, containing data used in the analysis, are elaborated and available upon request from the corresponding author.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Goran Krsnik: Conceptualization, Data curation, Formal analysis, Writing – original draft, Formal analysis, Writing – review & editing. **Keith M. Reynolds:** Conceptualization, Supervision, Methodology, Writing – review & editing. **Philip Murphy:** Conceptualization, Supervision, Methodology, Writing – review & editing. **Steve Paplanus:** Conceptualization, Supervision, Methodology, Writing – review & editing. **Jordi Garcia-Gonzalo:** Conceptualization, Formal analysis, Writing – review & editing. **José Ramón González Olabarria:** Conceptualization, Formal analysis, Writing – review & editing.

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