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Assessing the dynamics of forest ecosystem services to define forest use suitability: a case study of *Pinus sylvestris* in Spain

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Abstract

Adopting a multi-criteria approach in forest management is essential for preserving 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 changes in forest characteristics over time. 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 dynamics in the 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 simulation-based changes over time of diverse ecosystem services of *Pinus sylvestris* stands in Spain and utilize a decision model to determine the most suitable FUS alternative that enhances the provision of these services. The assignment of the most appropriate FUS alternative aims to help in decision-making processes and in the selection of the most adequate management strategies. 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. Participatory planning actions based on Delphi principles and Analytic Hierarchy Process (AHP) analysis were applied and combined with geospatial logic-based modelling. According to the results, the dominant FUS is protective, followed by productive alternative, exhibiting high levels of multifunctionality.

Keywords Long-term forest management strategies, Spatial environmental planning, Ecosystem management decision support (EMDS), Multi-criteria analysis, Geographical information technologies in forestry

Introduction

Decision making in forest management is a challenging process that involves ecological, socio-economic, and political factors, requiring consideration of numerous potentially conflicting elements [1]. Inadequate management practices and their impacts can significantly influence the provision of ecosystem services (ES) and lead to environmental degradation, emphasizing the importance of defining environmental and sustainability goals in strategic planning [2, 3]. Forests typically provide numerous ES, whose yield depends on the forests' intrinsic characteristics [4]. However, due to trade-offs between the

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services they provide, forests often cannot deliver high levels of multiple ecosystem services sustainably [5]. Therefore, efficient management strategies that focus on maximizing specific uses while minimizing negative impacts on the provision of other ES should be the foundation 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 ES provision [9, 10]. Because of this, defining management strategies based solely on current forest features may negatively impact the development of future ecosystems [10].

Sustainable mid-term and long-term forest management, aimed at ensuring adequate provision of multiple forest ES, 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 [1, 15]. Therefore, models that can forecast forest dynamics and highlight aggregate features of forest yield, including forest ecosystem services supply, can facilitate choosing an appropriate long-term management strategy [16, 17]. Identifying the uses to which a forest is best suited, based on the ES 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 and improve spatial planning [17]. 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 [18, 19]. These models provide a means to approximate future forest characteristics and the associated supply of ES. Together with the mapping and quantification of ES provision, forest dynamics simulations are recommended as the first step towards a comprehensive long-term management plan [20, 21].

Spatial modelling of the ES indicators is a challenging task due to the heterogeneous nature of factors influencing their provision and the diverse range of benefits they encompass [22, 23]. While the assignment of an appropriate management strategy directly depends on spatial modelling processes, the comprehensiveness and veracity of the models are crucial for decision-making [24]. 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 provides a broader overview of future characteristics and enables more accurate long-term planning [25]. In addition, terminological constraints have hindered the development of such a framework due to the lack of consensus in ES-related studies [26].

For this reason, we assert it is necessary to assess the provision of forest ES, considering forest dynamics and changes in ES supply, evaluate the ES 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 the present and future socio-economic and biogeophysical realities of each forest unit. In other words, the knowledge of current and future ES 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 with the management action that should be adopted over time [27]. In these terms, a *productive* FUS supports the maximization of economic profitability of the forest and related ES, whereas a *protective* FUS is associated with long-term goals that mitigate harmful natural or human-induced processes, a *conservation-oriented* FUS highlights the habitat value of the forest, a *social* FUS aims to increase non-material values that contribute to human physical and psychological health and a *multifunctional* FUS combines two or more of the previous forest *alternatives*.

The spatial scale and the variability on structural and environmental conditions of *Pinus sylvestris* forests, offers an interesting opportunity to evaluate variation of potential FUS allocation. At the same time, this variability can generate diverse forest dynamics that require further understanding [28] as a condition to generate site specific and objective-oriented management alternatives. By assessing the dynamics of such diverse set of forest stands, under a no management scenario, we can retrieve a valuable insight on the forest capability to deliver ES. An additional definition of goals through a participatory process, and evaluation of potential trade-offs between objectives can support large scale strategic planning processes [29].

In recent years, there has been an increasing number of studies on ES assessment in the literature (see [23] for a review). However, there are still limited research efforts concerning ES dynamics in relation to long-term forest management decision-making [30–32], presenting very

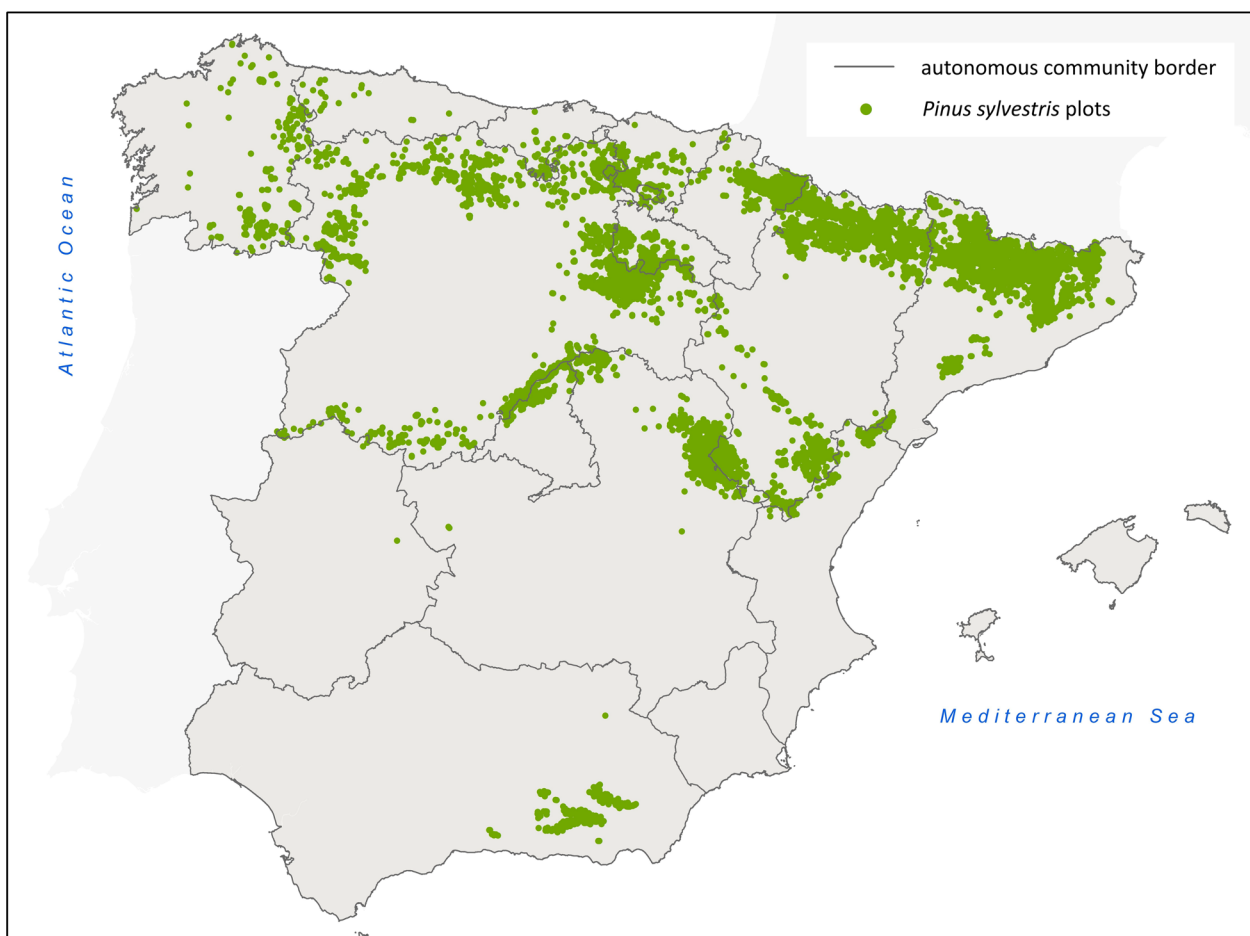


Fig. 1 Forest plots with presence of *Pinus sylvestris* included in the analysis

diverse methodological approaches [33, 34]. In this study, we apply the ecosystem management decision support (EMDS) system aiming to spatially assign and define FUS in selected Spanish forests. EMDS is a decision support framework for environmental spatial analysis and planning [35, 36], which provides a consistent methodological approach that can handle the complexity of multi-objective strategic decision-making concerning FUS allocation [27]. The main objective is to assign the most appropriate planning direction based on the dynamic biogeophysical characteristics of the forest, to facilitate the definition of appropriate management strategies. For that, we aim to first define indicators of ES associated to each stand and simulate stand dynamics linked to changes in the provision of those ES, which will serve the basis to assess the main and secondary FUS in all stands. By these means, we do not aim to define specific management actions, but to provide a basis to define them in the future, contributing to a better forest planning at landscape level and providing a methodological approach to be further applied in other locations.

Materials and methods

Study area

The study area included all Spanish forest stands where *Pinus sylvestris* L. was present, whether it is the dominant species or not. The analysis was based on the 3rd Spanish National Forest Inventory (NFI3; approx. 91.900 plots), from which we identified 10.033 plots with *P. sylvestris* [37] to be included in the calculations (Fig. 1).

P. sylvestris represents 14% of total wood volume in Spain (153 million m³), the second tree species in growing stock after *Pinus pinaster*, and covers an area of approximately 1 million ha, being the second conifer in area after *Pinus halepensis*. In general, Spanish forests are predominantly privately owned (approx. 70%) and exhibit high spatial fragmentation, which significantly hinders effective long-term forest management planning [38, 39].

Conceptual design

The main objective of the study is to define and spatially assign a FUS to each plot of the NFI with *P. sylvestris* present. The assignment was based on temporal simulations

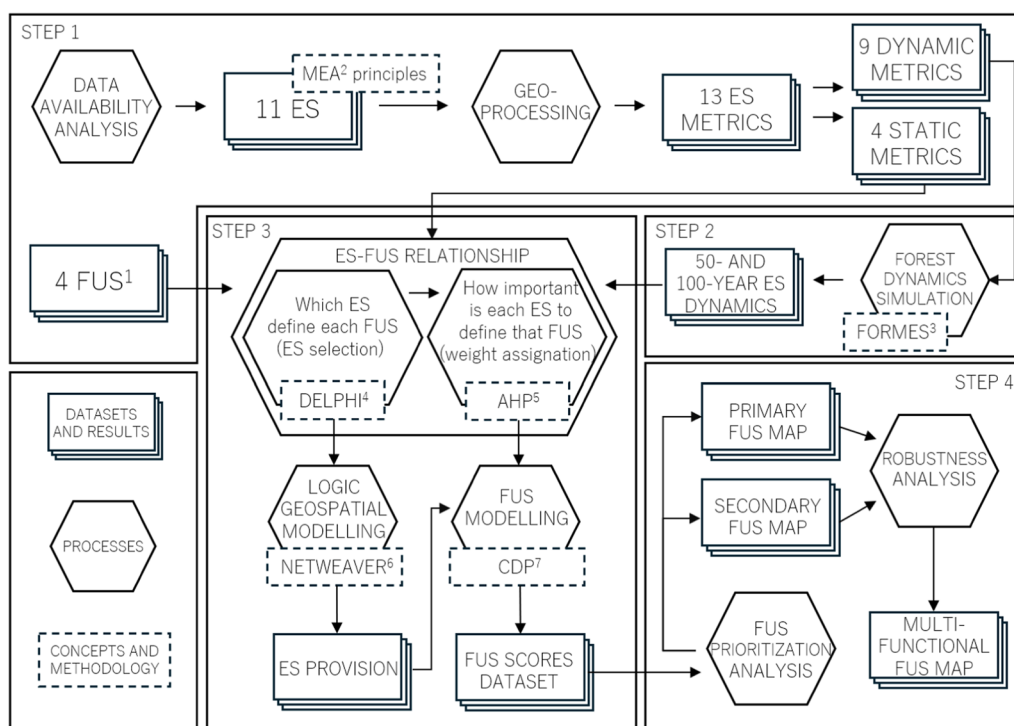


Fig. 2 Schematic design of the project workflow. FUS: forest use suitability, ES: ecosystem services, FORMES: a forest dynamics projection system, AHP: analytical hierarchy process, CDP: Criterium Decision Plus. ¹ [27], ² [41], ³ [40], ⁴ [42], ⁵ [43], ⁶ [44], ⁷ [45]

of forest characteristics and considers ES dynamics to define the most suitable forest use. To meet this goal, the study was organized in four steps (Fig. 2):

- 1) *Define indicators of forest ES 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 FUS 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 ES provision* The forest dynamics of the 10,033 selected plots were simulated over a 100-year period with a forest dynamics modelling framework and under no-management scenario based on empirical individual tree growth, mortality, and ingrowth models (using the FORMES projection system for multi-objective forest planning, [40]). The model outputs were then linked to 9 *dynamic metrics* that were directly related to the biophysical characteristics of the plot.
- 3) *Assess all plot's FUS* 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. The estimated current and future provisioning of ES was used as input in the FUS

assessment, as well as the results of a participatory analysis to retrieve the relative importance of the forest ES to identify the FUS alternative.

- 4) *Robustness analysis among FUS alternatives* The FUS performance scores resulting from the preceding step were prioritized as primary or secondary, and the differences between scores were used to determine the most suitable FUS for each plot.

Step 1: Definition of forest ES and metrics

The first step in the FUS analysis consists of a definition of forest ES provision. ES approximate existing biogeophysical processes and social concerns in the forest environment. They are defined by datasets or 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 11 forest ES, 9 of which were dynamic (Table 1). Forest ES definition followed the Millennium Ecosystem Assessment (MEA) [46].

Table 1 Selected metrics to describe the forest ecosystem services (ES)

Forest ES and ES groups	Forest ES (metrics)	Metric description	Metric 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

Therefore, a forest ES indicator is a composite score for a stand in which a high value indicates likely provision of the ES, and low scores indicate that the ES are likely absent. All data were geoprocessed using ArcMap 10.8 to derive suitable metrics for subsequent analysis.

Provisioning services are the products people obtain from the ecosystems [46]. Within provisioning group, we selected three metrics to quantify two ES; the metrics for calculating timber provision were calculated using the NFI3 data [37], while the dataset for water provision, using distance as a proxy value, was obtained from the Catalan Government digital database [47]. Regulating services are the benefits people obtain from the regulation of ecosystem processes [46]. Within regulating group, we defined four regulating ES 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. [48] to assess the erosion probability and the equation of González Olabarria et al. [49] to evaluate fire disturbances risk. Cultural services are nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, recreation, reflection, and aesthetic experiences [46]. Here, four metrics were used to quantify four ES. We used the Catalan Government database to assess accessibility, official hiking trails to evaluate recreation [50], NFI3 data for health assessment, and the equation of Blasco et al. [51] to calculate the scenic beauty index.

Step 2: Simulation of the forest dynamics and changes in ES provision

Forest dynamics simulation was done to estimate future forest characteristics and, therefore, quantify the provision of forest ES 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 [40]. 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

Table 2 Weights of the relative contribution of the Forest Ecosystem Service metrics to the benefits of each forest use suitability alternative

Forest Ecosystem Service (metrics)	Forest use suitability			
	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	0.31
Natural heritage	0	0	0.16	0.12
Peri-urban forests	0	0	0	0.24
Recreation	0	0	0	0.23

FUS weights sum = 1

tree spatial coordinates) but are less computationally demanding than the latter.

Step 3: Forest use suitability (FUS) assessment

We proceed to establish the relationship between ES and FUS alternatives, quantify ES provision and assess the FUS identification. For that, a participatory workshop utilizing Delphi principles was conducted to identify the ES indicators that best describe each of the FUS alternatives [42]. Overall, Delphi is a methodology established as an effective tool for gathering expert opinions on complex problems. Since there are no specific guidelines on how to conduct a Delphi process, it raised some criticism [52]. There are diverse design options and elements for the Delphi technique [53]. In this study we conceptualized the Delphi Workshop “as a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem” [54]. We applied iteration, participant response anonymity and statistical response as key common features in a Delphi study [55].

Eleven doctoral researchers from different forestry-related fields (e.g., biology, environmental sciences, bio-economy, forest engineering, geography etc.) were asked, using a 5-point Likert scale, to evaluate the degree of contribution of each of the 13 selected ES metrics to the definition of each FUS. Both positive and negative contributions of ES to the definition of FUS 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 ES-FUS combinations were evaluated using the same approach.

Iteration is especially important if the main purpose of the Delphi technique is to seek consensus, as it is the case in the Classical Delphi. After the first round of evaluations using 5-point Likert scale, results were presented to the participants and jointly discussed. When the divergence of a ranking was high, participants were asked to provide a justification and rationale for their choice, fostering deliberation in the discussion.

After the discussion, the same questionnaire was repeated. From the second questionnaire, the five most highly rated ES metrics per each FUS were identified. In the second part of the workshop, the Analytic Hierarchy Process (AHP) analysis was conducted using only five selected metrics per FUS. On that way, we wanted to choose only the most suitable metrics to define each of FUS and eliminate insignificant inputs. In the AHP analysis, all selected ES metrics were compared using Saaty’s verbal scale [56], asking which of each pair is more important, and how much more important, for a specific FUS. As a result, weights for each ES metric were obtained, quantifying the importance that a specific ES 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

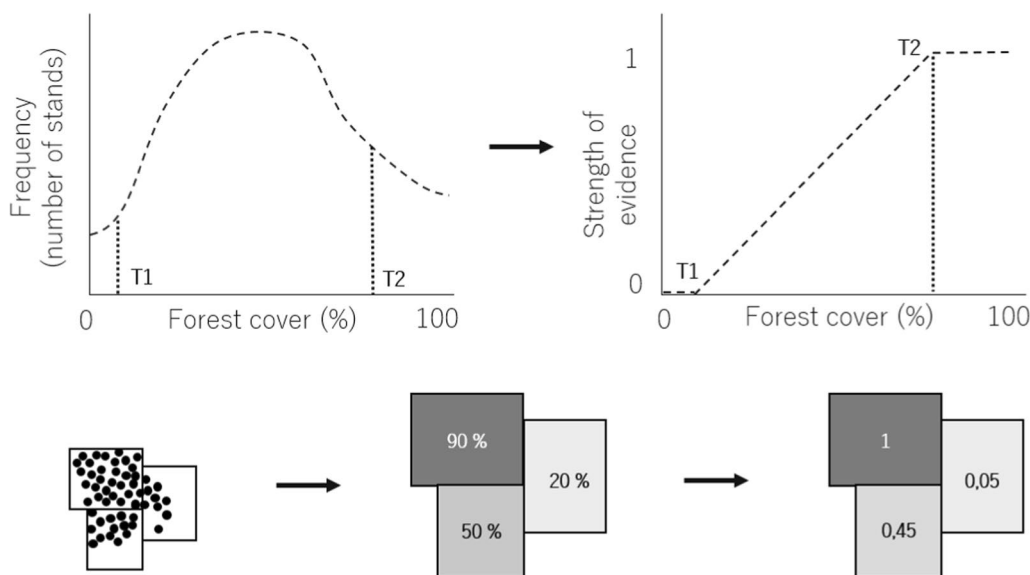


Fig. 3 Simplified schematic visualization of conversion of original observed values of each metric to strength of evidence values

use alternative (0.09), and does not contribute to the protective and social use alternatives.

Once selected the metrics that define each FUS, forest ES 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: i.e., no evidence, or no provision of ES, to 1: i.e., full evidence, or full provision of ES) by fixing thresholds that designate the degree of ES provision (Fig. 3). The 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.

The thresholds were defined separately for the 50-year and 100-year simulation datasets (Table 3). Typically, NetWeaver models implement a complex network structure (e.g., networks of networks), but for the purposes of this study, each logic network consisted of one elementary network (e.g., with no antecedents). In total, 52 logic networks were created, representing all possible combinations of the 13 ES metrics and four FUS alternatives (Fig. 4, shows the structure of the model in NetWeaver and includes a display of the logic connectors to evaluate the contribution of timber provision (stock) to the protective FUS, and recreation to the social FUS; Fig. 5 provides an example corresponding to the respective elementary networks built in NetWeaver).

With forest ES provision values being obtained, ES metrics that are most suited to define each FUS being identified, and weights for each ES 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 ES, which could subsequently be used as a basis for long-term strategic management planning. The Criterium Decision Plus (CDP) model, based on the AHP 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 in the hierarchy model are the 13 ES metrics for each FUS (Fig. 5). The CDP model structure (Fig. 5) is a novel implementation of an AHP model, in which the alternatives being evaluated are actually the four FUS, 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 ES 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 MCDM 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

Table 3 Thresholds defining fuzzy membership function to quantify the provision of forest Ecosystem Services (ES)

Forest Ecosystem Service (metrics)	Forest use suitability							
	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	–	–	–	–	–	–	25,000–1000	25,000–1000
Recreation	–	–	–	–	–	–	1000–0	1000–0

code was integrated into the EMDS to extract and record the FUS scores for each forest polygon.

Step 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. In addition, to determine the frequency of association between a primary FUS and a specific secondary FUS, we constructed transition matrix tables.

Each plot 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 (e.g. less than 20%), 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. Two categories were established: highly suitable and suitable, using the 10th percentile as a threshold value, the same one that was used in the evidence scale definition. The analysis was conducted using the ArcGIS 10.8

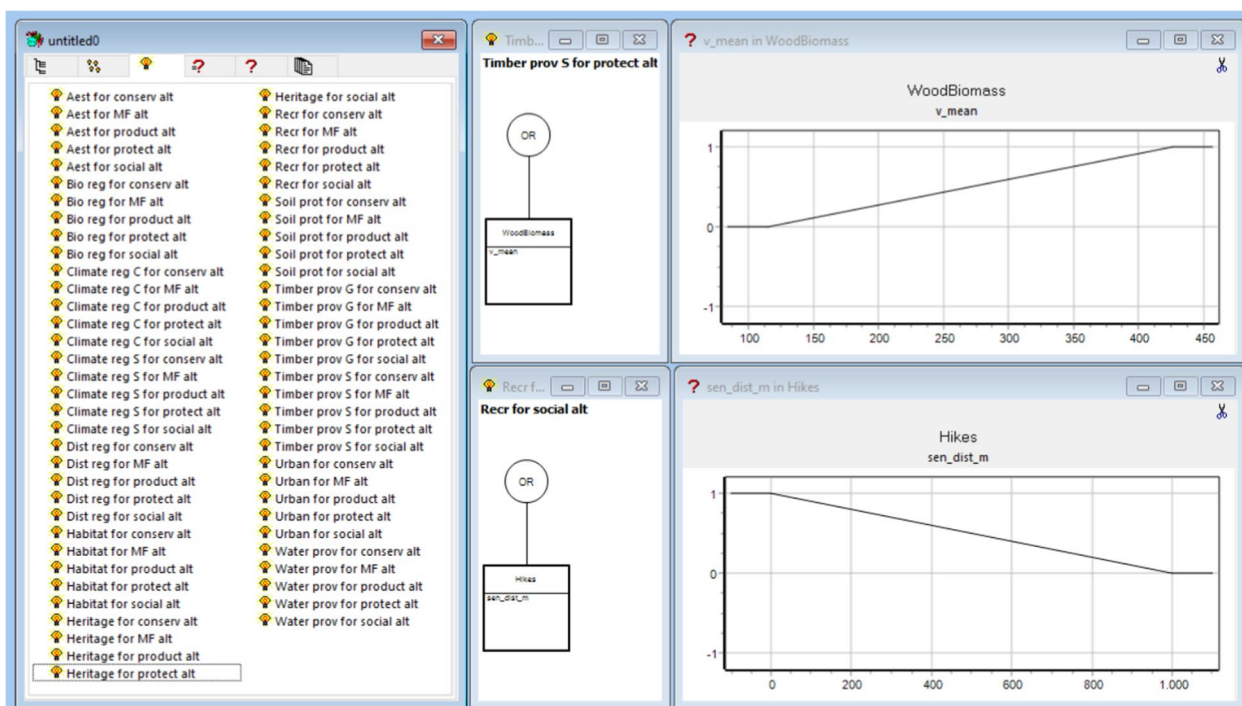


Fig. 4 Display of the logic connectors to evaluate the contribution of timber provision to the protective forest use suitability (FUS) and recreation to the social FUS. The left frame displays a view of the network components, the middle frames display the details of the logic specification for two mentioned alternatives. The right frames display two examples of how arguments are defined to obtain the measure of strength of evidence for two metrics, wood biomass and hiking

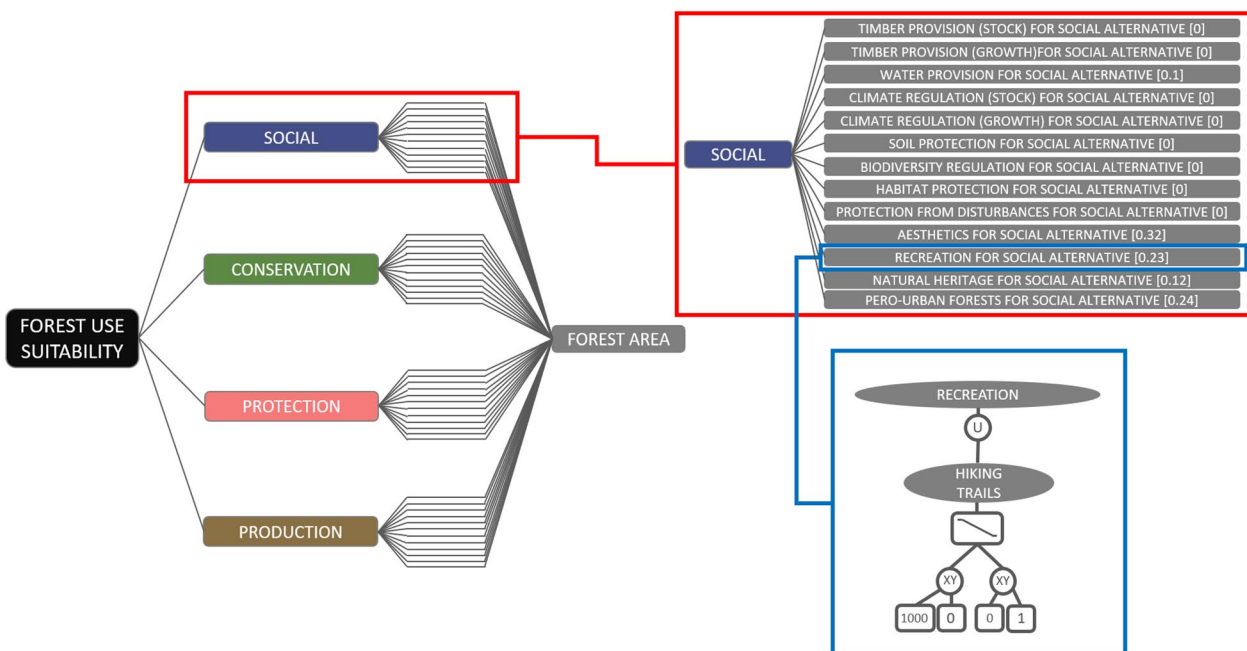


Fig. 5 Schematic design of Criterium Decision Plus model. The left-hand panel shows the overall Multiple-criteria decision analysis model, with the four forest use suitability (FUS) alternatives considered, being the nodes to the right of the goal. The upper right pane zooms in to show the 13 forest ES 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

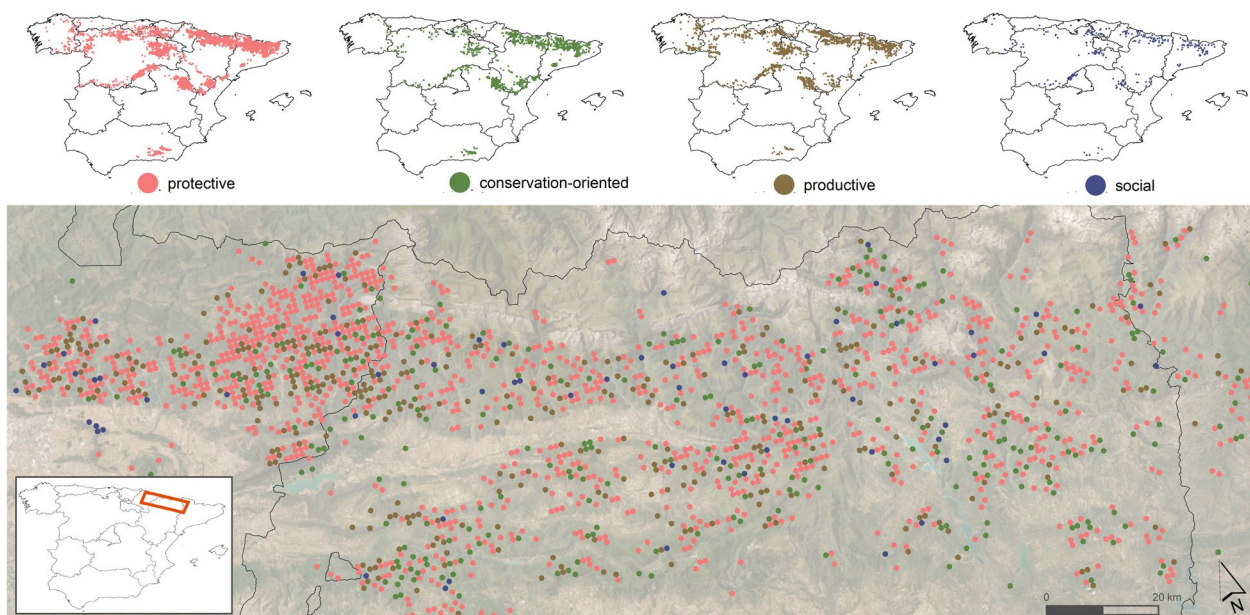


Fig. 6 Primary forest use suitability based on a 100-year simulation

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/>.

Results

Primary forest use suitability based on a 100-year simulation is shown on Fig. 6. 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 (ES), 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 increases in the central area (Fig. 6). On the other hand, the productive alternative is more prevalent in the north and exhibits slightly lower density in the central part of the study area. The protective alternative demonstrates a

high dominance across all areas. For the secondary FUS (Fig. 7), the spatial distribution of the various FUS alternatives follows a similar pattern to that of the primary FUS, although in this case, there are changes in the alternatives' frequencies. It is important to highlight that only one primary and one secondary use is assigned to each plot (see Figs. 6 and 7, where a more detailed overview of the northeastern part of Spain is shown on the lower part).

The productive use is the most common secondary suitability option, accounting for 59% of the cases, due to its role as the dominant secondary option to the primary protective and social uses (Fig. 8). 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, for that reason, cartographic representation of FUS alternatives was elaborated and shown only for 100-year simulation results. In addition, the combination of primary and secondary FUS (Fig. 8) gives a broader overview of

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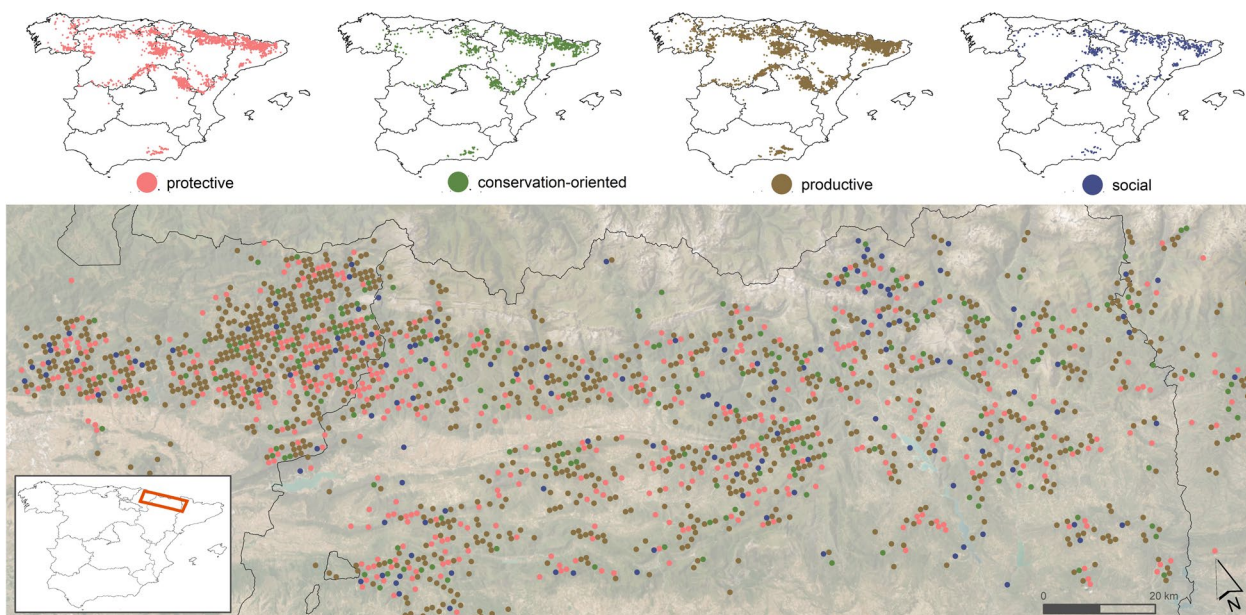


Fig. 7 Secondary forest use suitability based on a 100-year simulation

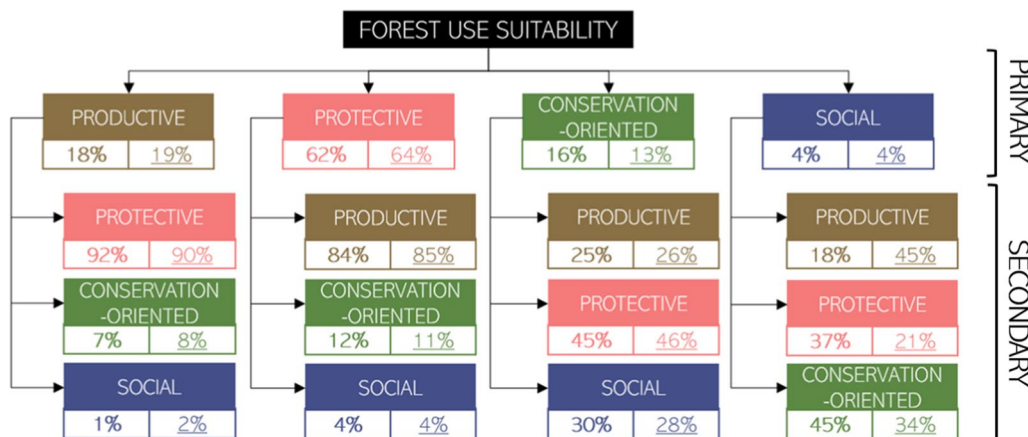


Fig. 8 Relationship between primary and secondary forest use suitability (FUS), showing the frequency of each alternative identified as primary and secondary to each of the primary ones (percentages refer to a 50-year and 100-year simulation for the left and right values, respectively)

possible multifunctionality-oriented strategy plans based on the applicability of common management strategies for different FUS alternatives.

Evidence values for the assignment of primary and secondary FUS alternatives vary depending on each alternative (Fig. 9). The primary protective FUS exhibits the highest mean values, followed by productive and conservation-oriented alternatives. In the case of secondary FUS options, productive alternatives score the highest, followed by protective and conservation-oriented choices. Social FUS, when chosen as both the primary and secondary alternative, shows the lowest mean

values. Low standard deviation values across all cases affirm a narrow distribution of values.

The results of the robustness analysis, comparing the primary and secondary FUS based on a 100-year simulation are shown on Fig. 10. 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. In addition, 57% of the plots fall within the 20% threshold, further demonstrating the

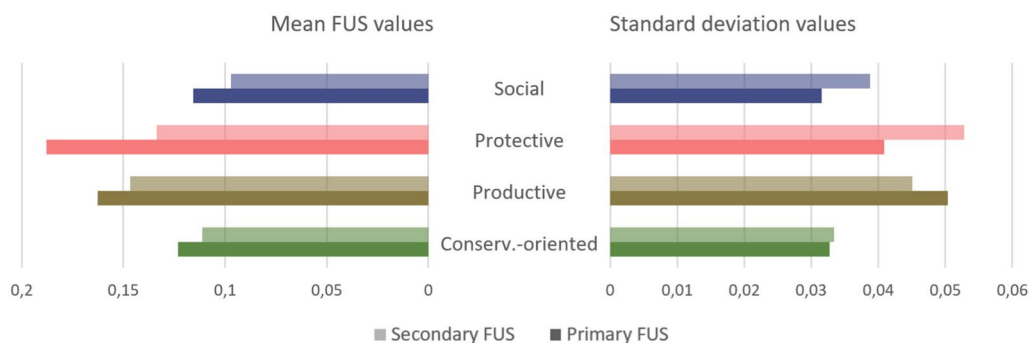


Fig. 9 Mean suitability and standard deviation values for each of four forest uses (primary and secondary FUS for a 100-year simulation)

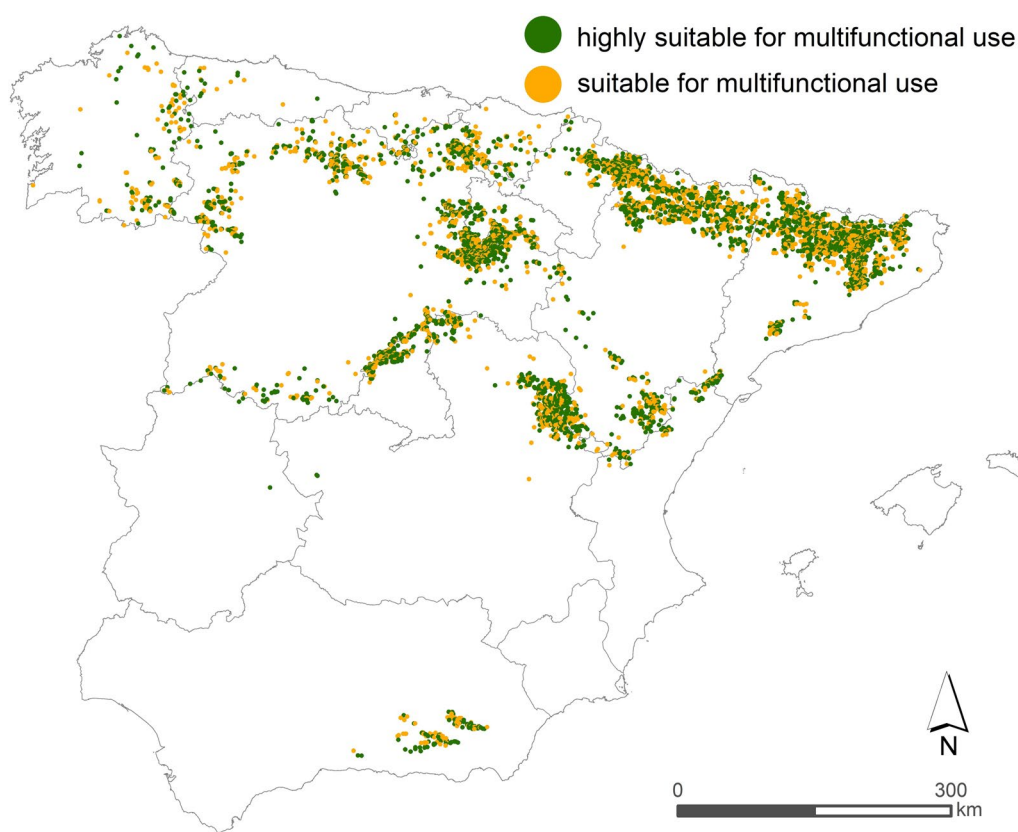


Fig. 10 Plots with potential multifunctional forest use suitability (FUS) based on 100-year simulations applying robustness analysis between primary and secondary FUS

significant presence of multifunctional forests. Spatially, the forests with potential multifunctional FUS are proportionally distributed throughout the study area.

Discussion

A novel methodological framework for assessing forest ES

This study employed a less commonly examined logical and methodological approach to forest management research. Our aim was to address the methodological

limitations in ecosystem services (ES) assessment, with the goal of facilitating the integration of this framework into decision-making processes and management strategies [57]. The intricate nature of the forest ES concept presents challenges in conducting comprehensive studies [58]. 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 [59]. The dynamic nature of forest ES concepts demands strategic management actions that account for changes in forest characteristics [10, 60]. In such a scenario, decision-making processes can effectively adapt to environmental conditions and enhance the provision of ES while considering the capacity of ecosystems to supply them [11].

Although previous studies have addressed forest dynamics and the implementation of forest management strategies [11, 61], there is a limited number of research works investigating whether these management actions necessarily align with the most appropriate uses for each forest, even if they result in ES values [62]. While most studies simulate forest dynamics and ES changes using well-defined forest management actions [12, 63–65], we have chosen to take a different approach.

We believe that solution-oriented research is the most effective way to address these challenges. ES-related studies primarily focus on assessing the supply of ecosystem services, but they often do not succeed providing actionable solutions to enhance the desired provision of services through effective management strategies [24]. We argue that defining appropriate management strategies can help address conflicting interests and significantly facilitate decision-making processes, minimising potential conflicts and maximising desired outcomes. For that reason, we recommend the adoption of the forest use suitability (FUS) approach as a foundational step towards achieving sustainable management of forest ES.

Typically, forest management actions are based on specific goals set by decision-makers (e.g., local owners, regional administration, and government), usually aimed at maximising the provision of ES values [66, 67]. However, these objectives often do not align with the forest's capacity to provide the desired ES. Even if the goals are achieved and higher ES values are attained, the intended use may not correspond to the forest's ideal use based on its biogeophysical characteristics, leading to a use of the forests that could compromise the sustainability of the forests' ES.

In this sense, we did not consider any management actions in our forest dynamics simulation or the definition of FUS. Our main objective was to develop management strategies that are less driven by immediate interests and more focused on the forest's capacity. We analysed the ES characteristics to determine the most suitable use, which then helps in the selection of appropriate management actions. By applying dynamic metrics instead of relying solely on static ones, we could anticipate possible future forest characteristics and define long-term strategies. Since current and future forest characteristics may differ, this approach also allows for

the consideration of different FUS alternatives, which is an important contribution of the approach.

In addition, 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 [68]. 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. Specific actions resulting from the FUS assignment are not 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. In other words, the conceptual design and idea of the study do not aim to provide specific management actions, but to aid in the decision-making process, detect the most appropriate use for each forest based on its characteristics, and, considering that use, ease the identification of appropriate management strategies in the future.

Interpretation of results

The results of this study show heterogeneous characteristics of Spanish *P. sylvestris* forests, prioritizing protective and productive use suitability. While the FUS alternatives are clearly distinguishable, 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 secondary FUS alternative, as well as carefully assessing the robustness analysis 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.

Data limitations

The outcomes of the study and their implications are highly influenced by the metrics employed to define each individual ecosystem service. Therefore, when interpreting results, it is necessary to recall which metrics represent each of the FUS alternatives [69, 70]. At the same time, the contribution of the ES metrics to the four FUS alternatives is based on preference methods, which entail a subjective component. We involved doctoral researchers, as they were familiar with the subject, had an academic background and demonstrated interest and motivation participating in the workshop. The number was appropriate and in line with AHP methods (see [71]).

Also, data availability represents one of the main constraints of the simulation-based FUS assessment. While integrating forest dynamics into ES 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 ES assessment. An inventory-based approach can appropriately assess forest ES 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 ES indicators that depend, at least in part, on non-material and intangible characteristics (e.g., most of the cultural ES).

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 [72, 73]. 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 to conduct comprehensive analysis and obtain objective and comparable results.

Applicability of EMDS system in ES dynamics assessment

The 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. First, 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. In addition, EMDS facilitates the integration of expert knowledge and scientific methods, particularly through the weighting processes and evaluation of criteria and network relations [74, 75]. 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 weights 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 limitations 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 [76].

Conclusions

This study demonstrates the effective application of the EMDS system, a decision-support framework with spatial capabilities, facilitating the exploration of innovative approaches in the field. It enables the use of participatory planning-based techniques in multi-criteria decision-making. We incorporated simulation-based metrics to evaluate the dynamics of forest ecosystem services (ES), aiming to define suitable forest uses and establish a foundation for long-term forest management planning. We also addressed methodological constraints regarding forest management strategies, as

well as the strengths and weaknesses of implementing dynamic metrics. The assignment of forest use suitability (FUS) alternatives followed similar spatial patterns but varied in spatial density, with protective FUS being the most prevalent primary alternative. The level of multifunctionality was relatively high, but the compatibility between dominant FUS alternatives was questionable. In addition, social FUS was underrepresented due to the unequal spatial distribution of input data.

This study proposes an approach aimed at defining the most suitable forest use based on biogeophysical characteristics, facilitating the selection of the most appropriate management actions. Our focus is on understanding the capacity of forests to sustainably provide ES, rather than prioritizing the interest-driven maximization of ES values. While our study does not offer definitive solutions, and is presented as a case study focusing on a single species, we believe that our approach represents a crucial first step towards more sustainable forest management strategies, prioritizing forest characteristics over the interest-driven maximization of ES values.

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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. M.P.B. conducted the participatory process. G.K., J.R.G.O. and J.G.G. analysed the results. All authors participated in editing process of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

Upon request to the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent of publication

The authors consent to the publication of this article.

Competing interests

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

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