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RESEARCH

Trade-offs and management strategies for ecosystem services in mixed Scots pine and Maritime pine forests

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Abstract

Mixed forests are increasingly recognized for their resilience to climate change and enhanced ecosystem services (ESs) provision, making them a focal point for sustainable forest management strategies. This study examines the trade-offs in ESs provision between pure and different proportions of mixed stands of Scots pine (*Pinus sylvestris* L.) and Maritime pine (*Pinus pinaster* Ait.) in the Northern Iberian Range, Spain. Using the SIMANFOR simulation platform, we evaluated various silvicultural scenarios developed to obtain different ESs such as carbon sequestration, timber and mushroom yields. Our findings reveal that ESs provision varies depending on the forest type (pure or mixed) and the mixture proportion, following different trends on each ES. The initial species proportions and their maintenance were less critical than the management approach itself, which significantly influenced ESs outcomes. Focusing solely on individual ESs can lead to trade-offs, as highlighted by our study on silviculture focused on large saw timber yields. However, adopting a balanced approach that considers multiple ESs can mitigate these trade-offs. Our findings underscore the effectiveness of this approach in maximizing yields of mushrooms, sequestered carbon, and small saw timber. This research provides valuable insights for forest managers aiming to balance productivity and sustainability in ESs provision, providing strategies to maximize compatible ESs effectively.

Keywords Mediterranean forests · Carbon sequestration · Mushroom production · Wood production · Simulation

Introduction

Mixed forests buffer climate change impacts, thus turning the researchers' and managers' attention to their potential in the present context of climate change (Toïgo et al. 2015; Bravo 2022). Comparative studies have revealed the enhanced stability (Muñoz-Gálvez et al. 2021; del Río et al. 2022a, b) and even heightened productivity (Pretzsch and Schütze 2009, 2016; Forrester 2014; Pretzsch and Forrester 2017) of mixed forests over monocultures, which is attributed to complementary effects (Toïgo et al. 2015; Pretzsch and Schütze 2016; Del Río et al. 2017; Riofrío et al. 2017b, a, 2019) and more efficient resource utilization (Pretzsch 2014; Pretzsch and Schütze 2016; Riofrío et al. 2017a, b) in mixed forests. Mixed stands also display greater resilience and resistance to biotic and abiotic disturbances compared to pure stands (Del Río and Sterba 2009; Del Río et al. 2017; Pardos et al. 2021). With such findings, forest management techniques can be tailored to promote mixed forests as a promising strategy for alleviating forest drought stress (Steckel et al. 2019; del Río et al. 2021, 2022a, b).

Forests play a crucial role in providing a wide range of goods and services essential to human well-being. These ecosystem services (ESs) encompass biomass production, habitat provisioning, carbon sequestration, and cultural benefits, among others (Brockerhoff et al. 2017). However, while some ESs can be generated under the same silvicultural scenario (Ordóñez et al. 2024), maximizing the provision of these ESs presents a significant challenge due to inherent trade-offs, leading to situations where the overall maximum is not possible for all ESs simultaneously (Aldea et al. 2014). Mixed forests have emerged as a promising solution in this regard. For example, mixed stands comprising Scots pine, Norway spruce, and birch in Sweden have demonstrated higher levels of ESs compared to monocultures

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(Jonsson et al. 2019). Forest management practices also play a pivotal role in navigating these trade-offs. Strategies such as enhancing structural diversity, for instance by preserving large trees and fostering canopy gaps, have been shown to promote the supply of multiple ESs, thereby potentially mitigating trade-offs among them (Felipe-Lucia et al. 2018). Forest management can modulate trade-offs between timber production, biodiversity conservation, and protection against natural hazards, resulting in efficient optimal silvicultural scenarios (Lafond et al. 2017).

Despite the growing interest in mixed stands, there is a lack of management guidelines for those stands and detailed studies of such stands over time. Experimental and observational studies cannot cover all the potential silvicultural combinations, but modelling has emerged as a way of gaining insight into the effects of management on forest adaptation (Bravo and Vázquez-Veloso 2024). The field is developing quickly, and the possibility of integrating mixed stands growth models into simulation platforms can be a valuable alternative to explore silviculture effects in mixed stands without previous expertise. This applied to the Spanish climate-sensitive growth models (Rodríguez de Prado 2022) that have been integrated into the SIMANFOR simulator (Bravo et al. 2012, 2025). The SIMANFOR platform is a cloud service that allows simulating different forest silvicultural scenarios for each operational unit, comparing and ranking them to select the one that better reaches the management goal. Therefore, SIMANFOR enables the understanding of the factors influencing forest dynamics at both the tree and stand levels by allowing the comparison of silvicultural alternatives, as demonstrated in previous studies (Bravo and Diaz-Balteiro 2004; Bravo et al. 2008). By including mixed stand models on the SIMANFOR platform, new possibilities open up for exploring management alternatives in situations where observational and experimental data are scarce due to high forest complexity or changing drivers of forest dynamics (Pretzsch and Schütz 2014). Growth and yield information is provided on simulations for both wood and non-wood resources, and some of them were previously studied such as fungi (De La Parra Peral et al. 2017) and pine nuts (Vázquez-Veloso et al. 2022) using that simulator. Carbon content is also provided and has been studied through several silviculture alternatives in pure stands (Martín Ariza et al. 2017) and under varying future climate scenarios for mixed stands (Rodríguez de Prado et al. 2023). These examples illustrate how simulations offer valuable insights to support decision-making in selecting silvicultural strategies for scenarios lacking prior experimental data, such as most Mediterranean mixed forests.

Our study focuses on pure and mixed forests containing Scots pine (*Pinus sylvestris* L.) and Maritime pine (*Pinus pinaster* Ait.) in the Northern Iberian Range (Spain). Scots pine thrives across Europe, with approximately 1,000,000 hectares of pure stands just in Spain (Del Río and Sterba 2009). Its ecological and commercial significance has spurred extensive research across Europe. While Scots pine commonly occurs in pure stands within natural and forested areas (Durrant et al. 2016), it also appears in mixed stands with various coniferous and broadleaf species. In Spain, it creates natural mixed stands in low-altitude areas with Maritime pine and Pyrenean oak (*Quercus pyrenaica* Willd.), while in high-altitude areas it mixes with European beech (*Fagus sylvatica* L.), European black pine (*Pinus nigra* J. F. Arnold), Mountain pine (*Pinus uncinate* Ramond ex A. DC.) and Sessile oak (*Quercus petraea* (Matt.) Liebl.) (Del Río et al. 2022a, b). Maritime pine, native to the western Mediterranean Basin and the Atlantic coast, is also widely distributed in both natural and planted forests throughout Spain (MITECO 2024). Its ecological resilience and adaptability have led to its use in reforestation efforts beyond its native range (Alía and Martín 2003; Pardos et al. 2021). In Spain, it naturally appears in mixed stands with Scots pine as well as with Stone pine (*Pinus pinea* L.), Pyrenean oak, Holm oak (*Quercus ilex* L.), Portuguese oak (*Quercus faginea* Lam.) and even with juniper species (Ruano et al. 2022). These two prominent forest species frequently occur in both pure and mixed stands, either naturally or by deliberate selection for reforestation, with mixed stands being widespread in Spain (Montero et al. 2008). The benefits of this mixture have been observed. Both differences in growth phenology (Camarero et al. 2010; Vieira et al. 2014) and response to climate conditions (Bogino and Bravo 2008; Bogino et al. 2009) reduce inter-specific competition during part of the growing season, thus resulting in complementarity between the species. Higher productivity in the *Pinus sylvestris*—*Pinus pinaster* mixture was also observed due to crown complementarity and vertical stratification (Riofrío et al. 2017a, b; Cattaneo et al. 2018). In addition, comparing the mixture with pure stands of both species, it is observed that CO_2 reserves and accumulation rates increase over time in the mixed stands (Rodríguez de Prado et al. 2023). At the soil level, the organic matter quality shows higher values in mixed stands when compared to pure stands as a contribution of both overstory (both pine species) and understory (vascular plant species) diversity (López-Marcos et al. 2024).

In this study, we evaluated alternatives for silvicultural scenarios according to the provision of different ESs in pure and mixed stands. Our main goal is to evaluate the trade-offs provided by each reference silviculture in maximizing ESs and quantify their provision in both mixed and pure stands. To accomplish this objective, a case study in the Northern Iberian Range of Spain was developed testing different silvicultural alternatives for Scots pine and Maritime pine. Specifically, we aim to address the following research questions:

1. Is the maintenance of the initial mixture proportions crucial for the provision of ESs?
2. How will the provision of ESs differ between mixed and pure stands?
3. Does the initial proportion of species mixtures influence the provision of ESs?
4. Will the lack of management result in a decrease in ESs?
5. Does silviculture targeting a specific ES enhance that service while reducing others?

Materials and methods

Study area and data

The selected study area was in Pinar Grande (Fig. 1), a Public Utility Forest located in Castilla and León (Spain), which covers the northwest area of Soria province. Both Scots pine and Maritime pine are highly representative in the study area. This area has been managed by the public forest service for more than 100 years, adapting their management techniques over time and producing different ecosystem services (ESs) like wood, resin, mushrooms, pasture for cattle, hunting and recreation, among others (Domínguez-Lerena 2007; Pascual-Arranz 2012; Aldea et al. 2014). The data used in this study is based on previous research carried out in the same area. Species proportion rates and the average productivity of the area, determined by its Site Index, were obtained from Riofrío et al. (2017b). The productivity of the study area is relatively high on a regional scale, with a Site Index of 21 for both species, averaging across various local conditions. With these values as reference, inventory data on species proportions was taken from the observed silviculture for Scots pine and Maritime pine in Castilla and León region (Del Río et al. 2006). Therefore, five representative plots were selected as initial data, representing pure

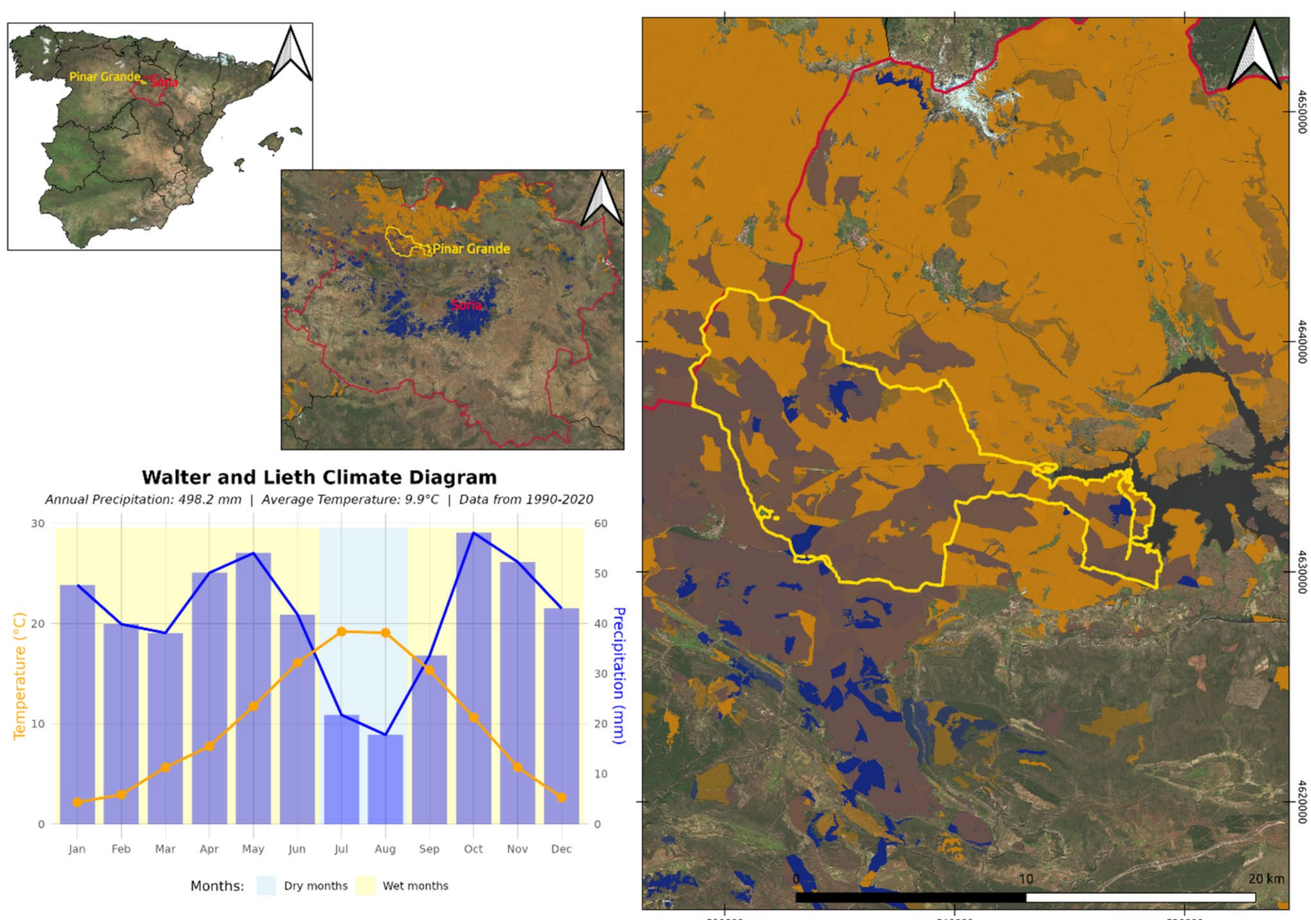

Fig. 1 Location of Soria province (red polygon) and Pinar Grande (yellow polygon) in Spain along with the distribution of Scots pine (blue) and Maritime pine (orange) stands according to the Spanish Forest Map (MITECO 2024). Intense colors represent the locations where each species is dominant, while light colors represent areas where species are secondary, thus highlighting areas with mixtures. At the left-bottom a Climodiagram of Walter and Lieth was included summarizing the mean monthly precipitation and temperature values of the period 1990–2020. (Color figure online)

Scots pine and Maritime pine stands and their mixtures in three proportions: pure Scots pine (PS), mixed stand with initial Scots pine proportions of 30% (PS30), 50% (PS50) and 70% (PS70), and pure Maritime pine (PP). All plots have the same initial characteristics to allow fairer comparisons among results: the initial age is 30 years, the stand density is 1500 trees $\cdot$ ha^{-1}, the stand basal area is 36.8 m^2 $\cdot$ ha^{-1}, the dominant height is 13.5 m, and the stand volume is 220.1 m^3 $\cdot$ ha^{-1}.

Climate data was necessary for simulation purposes. Thus, the studied period was established from 2000 to 2120 according to the silviculture applied, detailed in the following section. Climate conditions were considered homogeneous for the study area and plot coordinates of the "Pinar Grande" area were used as the reference for extracting climate data (41.88166327 N, 3.13207041 W). Historical monthly climate data was obtained from WorldClim2 (Fick and Hijmans 2017) for the available 2000–2021 period, while the downscaled future climate projections were obtained from the same source using the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Petrie et al. 2021). For future climate data, annual minimum temperature, maximum temperature and total precipitation values were predicted by the 6th version of the Model for Interdisciplinary Research on Climate (MIROC6) (Tatebe et al. 2019) under the Shared Socioeconomic Pathway 2 (SSP2). Data resolution is provided for four different periods (2021–2040, 2041–2060, 2061–2080, and 2081–2100), so climate values were selected according to the period where each step of the simulation is developed. SSP2 was selected because it represents a "middle of the road" future climate scenario (O'Neill et al. 2017). The Martonne Aridity Index (Martonne 1926) was calculated for each period of 20 years, as it is also required for the simulation. Data was processed using R (R Core Team 2021) and the packages tidyverse (Wickham et al. 2019), raster (Hijmans 2023), rgdal (Bivand et al. 2023) and ggplot2 (Wickham 2016).

Silvicultural scenarios definitions

Different silviculture scenarios were simulated according to different management purposes. To achieve this, various sources on the silvicultural practices for each species and management objective were reviewed and tested through multiple simulations. From these, a single alternative was selected for each management goal that maximized the target ES (whether wood, carbon, or mushrooms):

A control scenario (CONTROL) without silviculture was simulated as the reference of natural growth, with no thinning during the simulation.

Business-as-usual scenario (BAU) was simulated according to the guidelines provided by Pascual-Arranz (2012) for the "Pinar Grande" study area, where both Scots pine and Maritime pine occur in both pure and mixed stands. This scenario includes a precommercial thinning at 20 years of stand age to establish the initial stand density after the natural regeneration, and two additional thinning from below at 40 and 60 years with intensities around 30–35% of stand basal area. The shelterwood method is applied at the end of the rotation period to facilitate natural regeneration.

Three more scenarios focused on the production of one ecosystem service were defined according to the bibliography:

A scenario focused on wood production (WOOD) to provide a larger amount of saw wood was simulated as well, using as a reference the silvicultural scenarios described by Del Río et al. (2006) and adapted to our species mixtures. Here, systematic thinning that preserving future trees is applied at different stand ages, reducing thinning intensity when increasing stand age and tree sizes. These interventions pursue the growth of a selected percentage of the bigger trees by extracting their neighbors, independently of the neighbor's size. As a result, this scenario tries to reduce the target trees' competition while reaching higher stem dimensions.

A scenario focused on carbon sequestration (CARBON) was included using the silvicultural guidelines provided by Ruiz-Peinado et al. (2017). In this scenario, systematic thinning is conducted every 15 years, removing on average 20% of the stand basal area. The authors argue that such intensive thinning can promote tree growth and achieve higher carbon sequestration rates.

Lastly, a scenario focused on mushroom production (MUSHROOM) was also included using the guidelines detailed by Sánchez-González et al. (2019) and adapting them to the rotation period selected. This scenario is based on short intervention periods of 10 years aiming to extract the same amount of basal area produced during the previous 10-year period, thus opening the canopy cover and promoting mushroom fructification. To do that, systematic thinning interventions are applied every 10 years removing the incremental basal area of the last period (on average 20% of the stand basal area).

To directly compare these scenarios in terms of production, a common rotation period was established at 120 years. This rotation length falls within the range limits established for the business-as-usual management scenario (Pascual-Arranz 2012), and can satisfy the requirements suggested for both wood production (Del Río et al. 2006) and carbon sequestration (Ruiz-Peinado et al. 2017) silvicultural scenarios.

The same scenarios and rotation period were used to test the effect of maintaining the initial species proportion in the stand. Scenarios with thinning's based on tree size (i.e. thinning from below) were used without considering an equal proportion of species extracted, thus having the possibility to modify the species proportion of the field. However, when aiming to develop the simulations maintaining the initial mixture of the stand, the already mentioned types of thinning were adapted to extract the same amount of wood from both species, maintaining the species proportion in the field.

Finally, scenarios regardless of the ES for which it was intended and forest types were directly compared for each ES at the end of the simulation period, ranking them according to their total production. Both wood and carbon ES productivity in the final ranking included the harvested trees, while losses associated with deadwood and the carbon stock decay rates of harvested trees were not taken into account. A summary of each scenario and their thinning types, intensities and periodicity can be consulted in Appendix 2.

Models and simulations

The SIMANFOR forest management simulator was used to perform all the simulations. In its initial version (Bravo et al. 2012), the simulator was limited in terms of the models implemented. Recently the simulator was entirely rewritten, making its structure more flexible and allowing the integration of models with different structures as detailed in Bravo et al. (2025). One example is the implementation of distance-independent individual-tree growth models, developed for mixed stands and incorporating the effects of climate (Rodríguez de Prado 2022). These models were chosen for this study, and they are composed of three core modules: basal area increment (BAI) (Rodríguez de Prado et al. 2022a), the height-diameter relationship (h/d) (Rodríguez de Prado et al. 2022b) and both the Stand Density Index (SDI) and the Maximum Stand Density Index (SDImax) (Rodríguez de Prado et al. 2020). Details about models' implementation are available in Fig. 2, and further information about the SIMANFOR platform is provided in (Bravo et al. 2025) and in Appendix 1.

When using those models through the SIMANFOR simulator, the initialization process completes user data by filling in default tree variables (i.e., crown, biomass), species-specific variables (i.e., intra- and inter-specific basal area of the tree) and stand variables (i.e. dominant height). After initialization, each step programmed on the silvicultural scenario is developed. When the projection is selected, survival, growth and ingrowth modules are applied. The survival module is based on the SDI and SDImax values for each species; these are estimated using the climate-dependent maximum size-density relationship (MSDR) models developed by Rodríguez de Prado et al. (2020) for each species. Thus, when SDImax $\geq$ SDI for a given species, mortality does not occur, but when SDImax $<$ SDI, the mortality rate is assumed to be a 2% for all the trees in the stand of the already mentioned species. The growth model is activated next, using BAI equations (Rodríguez de Prado et al. 2022a) to update the tree basal area and the h/d relationship equations (Rodríguez de Prado et al. 2022b) to update each tree height value, both using the corresponding species parameters. Ingrowth is not considered in these models. Finally, the general and species-specific tree and stand variables are updated using the same structure as the initialization process.

When the thinning module is selected, affected trees according to the thinning setup are labelled as "dead" and not included in the following simulation steps. After that, each tree and plot variable are also updated. Harvest modules are part of the simulator core and are independent from the models implemented. They can develop thinning of different types (systematic, from above and from below), including different intensities (from 0 to 100% in terms of density, basal area and volume of the stand), with the possibility to preserve a percentage of the bigger trees in the stand (i.e. for wood production purposes) or apply harvest to just one of the species in the stand (when using mixed stands).

To fulfil the desired management objectives, modules for calculating wood production, carbon content and mushroom production were included in the simulator. The wood production target is estimated for two different saw wood products based on the log dimensions for the studied species according to Rodríguez et al. (2008). Thus, the requirements for big saw timber are 2.5 m length and 40 cm diameter on the thinnest side, while the smaller saw products require 2.5 m length and 25 cm diameter on the thinnest side. To calculate them, the taper equations published for each species (Lizarralde 2008) were used, extracting the diameter of the tree at different heights and considering each log that fulfilled the previous requirements. A biomass module was used to estimate the dry biomass weights of different tree compartments (Ruiz-Peinado et al. 2011) and their carbon content according to the biomass-carbon ratios of Montero (2005), considering the sum of all compartments (stem, branches, leaves and roots). This study presents values for both wood and carbon sequestered, including the amount of wood extracted on harvests and also the wood that remains in the field at the end of the simulation, which summarizes the total production of the simulated silvicultural scenarios. Yields from deadwood were excluded, and decay rates for carbon stocks associated with harvested trees were not estimated, as the primary focus of the study is on productivity linked to silviculture. Lastly, a module for mushroom productivity was also used based on the equations provided by Sánchez-González et al. (2019). These equations estimate the mushroom production of both Scots pine and Maritime pine in pure stands, so the average production on mixed stands was estimated based on the species proportion using the following equation:

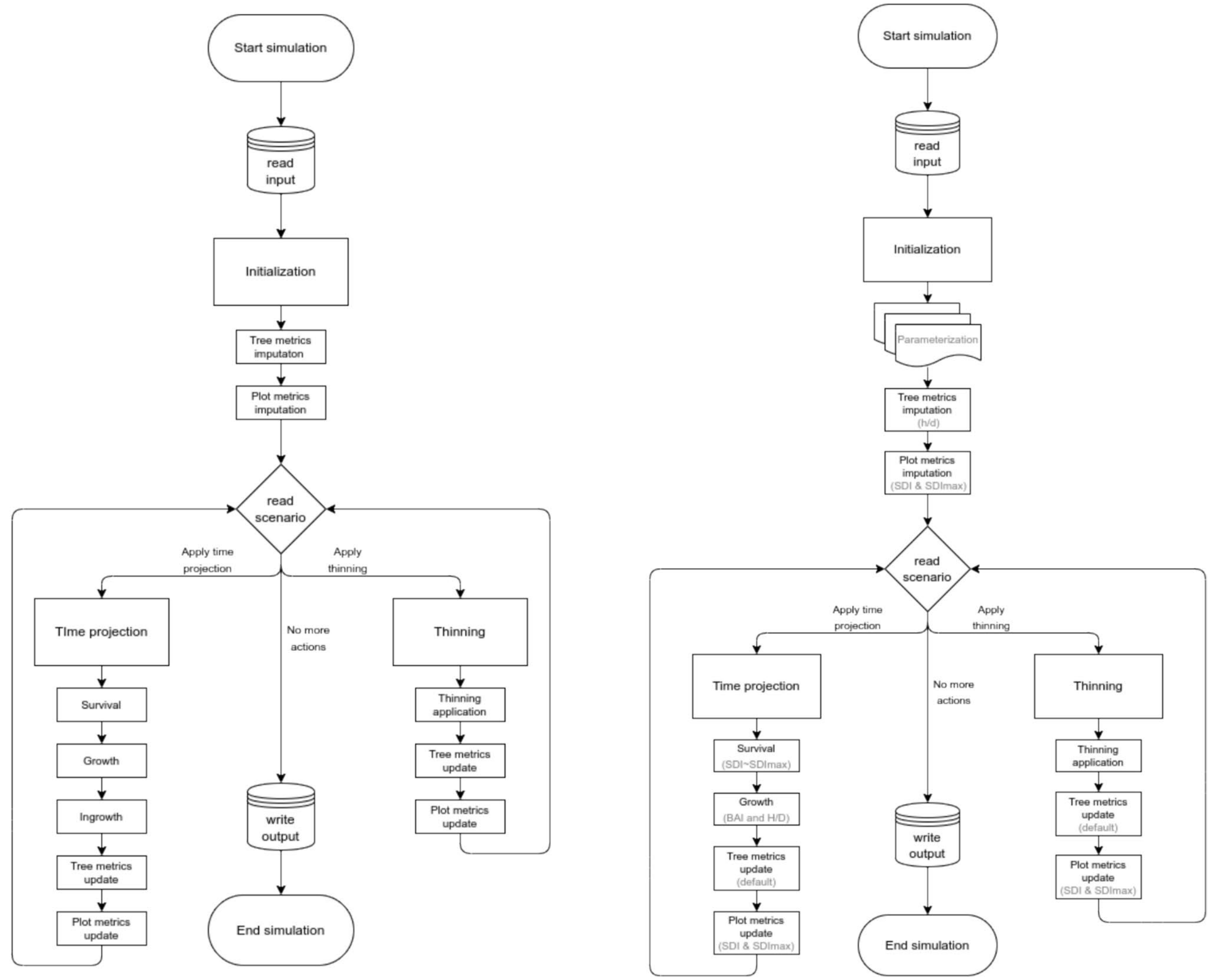

Fig. 2 SIMANFOR main structure and processes (data input, initialization, silvicultural scenario (including projection and thinning), output generation) (left); SIMANFOR structure after the implementation of mixed-stand models, including new sub-models in grey (right). Adapted from Bravo et al. (2025)

$$Mushroom = Mushroom_{sp1} * G\_prop_{sp1} + Mushroom_{sp2} * G\_prop_{sp2} \quad (1)$$

where *Mushroom* is the total stand mushroom production (kg · ha^{-1} · $year^{-1}$), $Mushroom_{sp1}$ and $Mushroom_{sp2}$ is the stand mushroom production for pure stands of species 1 and 2 (kg · ha^{-1} · $year^{-1}$), and G_prop_{sp1} and G_prop_{sp2} represent the stand basal area proportion of species 1 and 2 at the stand level (%). Additionally, while the same equations have different parametrizations according to different non-excluding mushroom groups (ectomycorrhizal, edible and marketed), only ectomycorrhizal mushroom productivity was considered in that study to represent higher species diversity and to simplify the silvicultural scenarios comparisons. Different modules covering tree increment, allometry, density and provisioning ecosystem services are included in SIMANFOR (Table 1).

Results

Species proportion over time

The simulations start with an initial species mixture proportion, which can vary over time. The final species mixture in terms of stand density and basal area for each management scenario is summarized in Appendix 3. Simulations were conducted twice: once maintaining the initial species

Table 1 Overview of SIMANFOR simulator modules, variables employed, units and their explanation in terms of calculations

SIMANFOR module	Variable name or abbreviation	Unit	Explanation
Basal area increment	BAI	cm^2	Increment in basal area parametrized for each species in mixture
Height-diameter relationship	h/d	m	Relationship between height and diameter parametrized for each species in mixture
Stand density index	SDI	trees · ha^{-1}	SDI based on the species-specific mixture and the climate conditions
Maximum stand density index	SDImax	trees · ha^{-1}	Maximum SDI based on the species-specific mixture and the climate conditions
Wood production	Big saw Small saw	$m^3 \cdot ha^{-1}$	Production in terms of wood volume estimated using the species-specific taper equations and the wood characteristics of each product: - Big saw: 2.5 m length and 40 cm thinnest diameter - Small saw: 2.5 m length and 25 cm thinnest diameter
Biomass	Biomass Carbon	tn · ha^{-1}	- Biomass: the dry biomass weight of a tree including all parts of each individual (stem, branches, leaves and roots) - Carbon: the carbon content of a tree, calculated for all parts of each individual (stem, branches, leaves and roots). Carbon content is estimated from dry biomass weight as a species-specific percentage: 50.9% for *Pinus sylvestris* and 51.1% for *P. pinaster*
Mushroom productivity	Mushroom	kg · ha^{-1} · $year^{-1}$	Mean annual ectomycorrhizal mushroom production

proportions and once without, to assess the importance of species mixture maintenance on ESs productivity (2).

Differences in ESs production were small when comparing the same silvicultural scenarios in mixed stands with when maintaining the initial species proportions or not. Aimed at providing a higher wood supply, the products with bigger sizes are maximized when initial species proportions are not maintained through silviculture, while when starting with a 30% of Scots pine results make no difference. In addition, when aiming to get products of small sizes, if maintaining the initial species proportion through silviculture then production is slightly lower in all the species proportions.

Results for mushroom productivity and carbon sequestration from silvicultural practices are equal, as silviculture is based on systematic thinning and the original silvicultural scenarios deviations from original proportions are slow.

ESs provision can also be analyzed in the BAU silvicultural scenario as it is the actual management of the study area. In this scenario, wood supply for higher dimensions is achieved only in one of the initial mixture proportions (PS70); while Maritime pine is the species that achieves the minimum required size for that purpose, production was higher when maintaining the initial species proportion. However, when the target product sizes are smaller, production is slightly higher when initial species proportions are not maintained through silviculture consistently for all the cases. Results for mushroom productivity showed the opposite trend, as higher productivity was obtained when initial species proportions were maintained through silviculture, consistently for all the cases. Carbon content at the end of the simulation was practically the same in all the cases studied (Fig. 3).

Forest type and mixture proportions on ecosystem services provision

We have simulated different silvicultural scenarios to analyze the provision of ESs under two forest types, including pure and mixed stands. Additionally, three levels of mixture were also considered.

In order to facilitate interpretation, Table 2 presents a simplified subset of the more detailed calculations provided in Table 3. This approach in Table 2 allows us to detail the ESs provisions based on mixture proportions, considering exclusively the ES for which each silvicultural scenario was developed. Our results showed differences in ESs outcomes provided by each type of forest. In terms of wood supply, Maritime pine pure stands reached higher production levels than Scots pine pure stands. The different mixture proportions were able to provide higher big saw production when Scots pine initial proportions were 30% and 50%. Small saw production was lower across all mixture proportions compared to pure stands of Maritime pine and declined further as the percentage of Scots pine increased (Table 2).

When considering the management of mushroom production, Scots pine pure stands provided higher production than Maritime pine pure stands by far. For the different mixture proportions, higher Scots pine presence in the stand resulted in increased mushroom production, though this was consistently lower than both pure stand productions (Table 2).

In terms of carbon content, mixed stands sequestered more carbon than either of the pure stands, although the differences between mixture proportions were not significant. Among the pure stands, Maritime pine sequestered more carbon than Scots pine (Table 2).

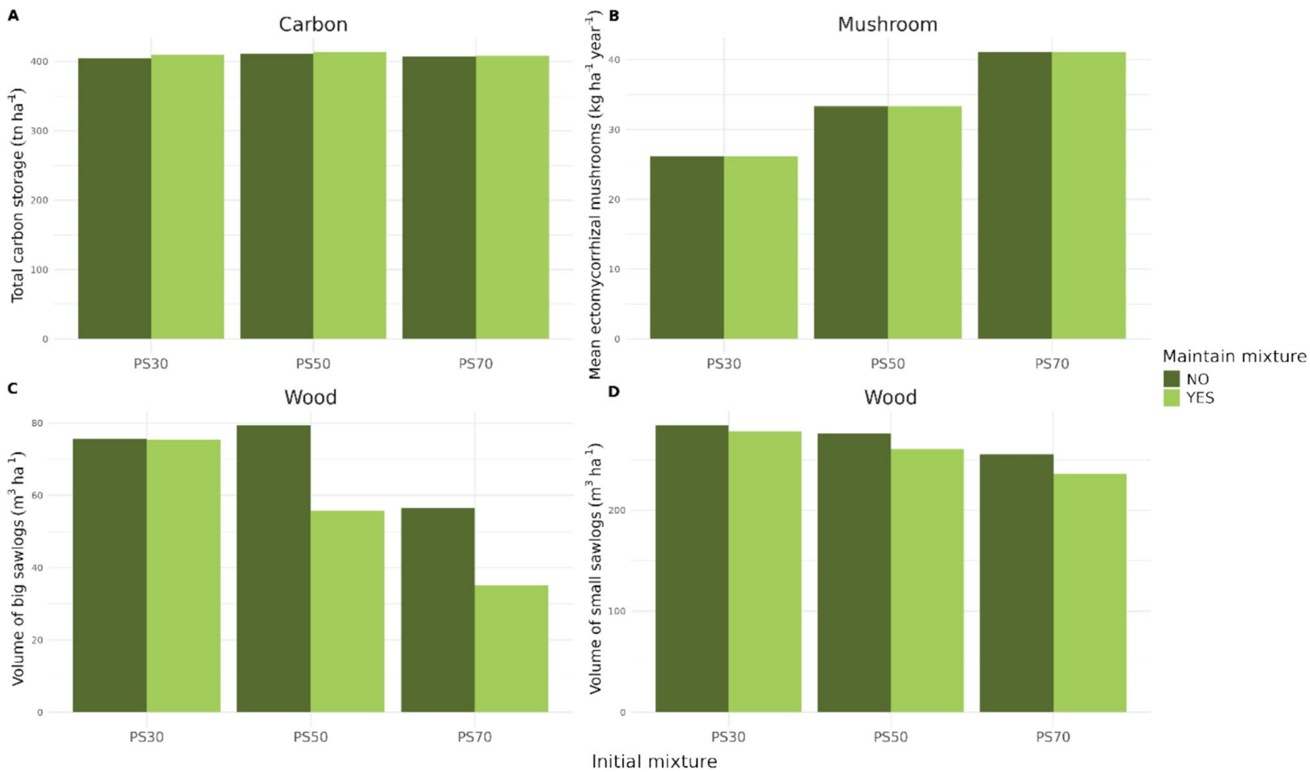

Fig. 3 Comparison of each silvicultural scenario and its target ecosystem service when initial mixture proportion is maintained (light green) or not (dark green) for the different mixture proportions studied (mixed stand with initial Scots pine proportions of 70% (PS70), 50% (PS50) and 30% (PS30)). The values for big saw, small saw and carbon included both harvested and remaining yields in the field at the end of the simulation period. (Color figure online)

Table 2 Provision of target ecosystem services (big saw, small saw, mushroom and carbon) for each of the silvicultural scenarios (WOOD, MUSHROOM, CARBON) and forest type according to its initial mixture proportions [pure Scots pine (PS), mixed stand with initial Scots pine proportions of 70% (PS70), 50% (PS50) and 30% (PS30), and pure Maritime pine (PP)]

Silvicultural scenarios		**WOOD**		**MUSHROOM**	**CARBON**	
Ecosystem services		**Big saw ($m^3 \cdot ha^{-1}$)**	**Small saw ($m^3 \cdot ha^{-1}$)**	**Mushroom ($kg \cdot ha^{-1} \cdot year^{-1}$)**	**Carbon ($tn \cdot ha^{-1}$)**	higher
Forest type	***PS***	0.00	193.19	54.33	364.94	
	PS70	56.51	318.06	39.76	406.74	
	PS50	79.43	353.15	32.45	411.37	
	PS30	75.54	407.90	25.80	405.10	
	PP	59.00	428.63	16.00	386.54	lower

The values for big saw, small saw and carbon included both harvested and remaining yields in the field at the end of the simulation period, excluding deadwood and carbon stock decay rates on harvested trees. The scale at the right indicates the color code employed to order the production according to the forest type

Table 3 Summary of all the ecosystem services provision (big saw, small saw, mushroom and carbon) under each silvicultural scenario (WOOD, MUSHROOM, CARBON, BAU, CONTROL) and forest type according to its initial mixture proportions [pure Scots pine (PS), mixed stand with initial Scots pine proportions of 70% (PS70), 50% (PS50) and 30% (PS30), and pure Maritime pine (PP)]

Stand type	Silvicultural scenarios	Ecosystem services: Big saw ($m^3 \cdot ha^{-1}$)	Small saw ($m^3 \cdot ha^{-1}$)	Mushroom ($kg \cdot ha^{-1} \cdot year^{-1}$)	Carbon ($tn \cdot ha^{-1}$)
PS	WOOD	0.00	193.19	54.16	302.25
	MUSHROOM	0.00	262.05	54.33	382.46
	CARBON	0.00	251.13	55.18	364.94
	BAU	0.00	204.70	49.81	293.92
	CONTROL	0.00	220.76	36.49	237.28
PS70	WOOD	56.51	318.06	29.23	324.23
	MUSHROOM	22.32	456.82	39.76	420.35
	CARBON	22.66	437.71	39.25	406.74
	BAU	17.14	355.86	31.32	324.80
	CONTROL	0.00	335.80	22.36	279.02
PS50	WOOD	79.43	353.15	21.83	321.47
	MUSHROOM	24.50	532.82	32.45	424.68
	CARBON	20.31	495.92	31.77	411.37
	BAU	0.00	391.82	24.42	327.84
	CONTROL	0.00	370.16	17.56	293.46
PS30	WOOD	75.54	407.90	17.98	315.19
	MUSHROOM	25.61	568.22	25.80	418.00
	CARBON	27.42	539.59	25.14	405.10
	BAU	0.00	411.78	18.65	321.54
	CONTROL	0.00	392.80	13.71	292.53
PP	WOOD	59.00	428.63	14.80	299.31
	MUSHROOM	25.90	580.78	16.00	399.33
	CARBON	38.08	562.45	15.47	386.54
	BAU	0.00	425.65	12.93	302.47
	CONTROL	0.00	433.86	8.24	277.44

higher

lower

The values for big saw, small saw and carbon included both harvested and remaining yields in the field at the end of the simulation period, excluding deadwood and carbon stock decay rates on harvested trees. The scale at the right indicates the color code employed to order the production according to the forest type

Joint provision of ecosystem services

When ranking the provision of the different ESs among the silvicultural scenarios, this time without maintaining the initial species proportion, a clear comparison can be established (Table 3). The control scenario that simulates natural growth without management was ranked as the worst option for almost all the ESs considered in our study except for small saw wood, never being one of the best options. The wood scenario was the one that better satisfied the production of big saw wood, while it provoked a huge reduction in the provision of the other ESs considered in the study. The BAU scenario served as the "middle on the road" option for all the studied ESs but failed to reach the minimum stem sizes for big saw wood in most of the plot types. Both mushroom and carbon scenarios were the options able to maximize most of the ESs studied (small saw production, mushroom productivity, and carbon content), and even able to reach a minimum productivity of big saw wood. Additional forest variables not discussed here are available in Appendix 4 and the Data Attachment to this study.

Discussion

The interest in improving knowledge about the future of ESs in Mediterranean areas is increasing (Morán-Ordóñez et al. 2020, 2021; Calama et al. 2021) but there is limited knowledge on mixed stands (Nocentini et al. 2022). This study contributes to this field by simulating ESs provision under various silvicultural scenarios in both pure and mixed stands.

While different initial species proportions were studied, ESs provision can vary depending on whether or not these proportions are maintained until the end of the simulations. Management guidelines not considering the maintenance of initial species proportions are a closer approach to managing mixed stands based on pure stands expertise. In this approach, the different species in the stand can be considered as a single unit, and thinning criteria are driven by the tree size, location, shape or other factors, not considering species as an additional criterion. On the other hand, maintaining initial species proportions can be challenging for managers and operators, as a new factor must be considered in the thinning plan. In that situation, if the extra effort is compensated with higher ESs productivity, then implementation can be justified becoming an interesting additional thinning criterion. Our results show that maintaining initial species proportion does not lead to significant differences in ESs production overall, although some exceptions were found, answering our first research question. For wood production, higher yields were observed when having higher Maritime pine proportion at the stand level in the big size saw production. As mentioned earlier, Maritime pine has a higher growth rate than Scots pine (Fernandes et al. 2017), and silvicultural scenarios that include thinning from below reduce Scots pine proportion, boosting Maritime pine growth due to size-asymmetric competition (Riofrío et al. 2017a; Askarieh et al. 2024). This situation increases the average growth rate of the stand, resulting in larger big saw wood production. When maintaining both species proportions, the lower yield on each mixture is driven by the greater reduction in Maritime pine proportion compared to the scenario without that restriction. However, in the case of small saw timber production, where both species reach the required wood size, differences in maintaining species proportions or not are minimal. Consistently, in both products, higher yields were observed with a higher proportion of Maritime pine in the stand, but maintaining species proportions still resulted in similar yields, as the size requirements are lower, allowing Scots pine to reach them within the established rotation period (120 years). This should be considered when establishing the management goals according to the study area, as Maritime pine tends to dominate at low altitudes, while Scots pine prevails at higher altitudes according to their behavior (Del Río et al. 2022a, b). In turn, when analyzing mean annual mushroom production and the carbon sequestered, maintaining or not the initial species proportion doesn't make a difference in the results. This is because only systematic thinning was applied in that scenario, and thus both species were removed in the same proportions in both cases. The results are also interesting, as they demonstrate how species proportion can be easily maintained in the stand, while operational requirements are higher when trying to apply selective thinning (from below/above) aiming to preserve species proportion.

Pure and mixed stands showed differences in ESs production across the studied silvicultural scenarios, although the species proportion in mixtures seems to play a less important role. This finding addresses our second and third research questions about the variation of the ESs provision according to the forest type (pure and mixed) and the mixture proportion in the case of mixed stands. Specifically, for saw timber, Maritime pine pure stands showed higher production. The higher productivity of Maritime pine in terms of big saw timber supply is closely related to its growth rate. As that species has a higher growth rate than Scots pine (Fernandes et al. 2017), the minimum required sizes for big saw are satisfied faster, thus producing more when longer Maritime pine proportion on the stand. While Scots pine is also able to reach the same stem sizes, it takes longer to do so. The mixture proportions reduced the big saw timber production in some cases according to the 120-year rotation period established in our study. While Maritime pine growth efficiency in mixtures is increased with higher Scots pine proportions (Riofrío et al. 2017a; Cattaneo et al. 2018) and its higher wood production per tree can be obtained in mixed stands (Vilà et al. 2007), the lower growth rate of Scots pine reduces overall wood production. Thus, from a strict point of view, pure Maritime pine stands produce longer big size saw timber than mixtures when considering a 120-year rotation period, which results must be shifted if considering longer rotation periods. Under this silvicultural scenario, thinning interventions up to 80 years could focus on selective thinning by removing the Maritime pine trees that have already reached the desired stem size. This approach would yield the targeted products while reducing competition for Scots pine, allowing for their later harvesting.

When focusing on carbon sequestration, higher levels on both alive and harvested trees were also found in Maritime pine pure stands due to its higher growth rate (Fernandes et al. 2017). The percentage of carbon estimated from biomass is almost the same in both species (Montero 2005). Since Maritime pine can achieve larger sizes in less time, the biomass and carbon content are also higher. When analyzing the different mixture proportions of both species, carbon sequestration rates were higher than in either pure stand, regardless of the mixture proportions. This result is in line with Rodríguez de Prado et al. (2023), where mixed stands of the same species were able to sequester higher carbon content than either pure stands in 100 years of natural growth without management. On the other hand, the initial species proportion of mixed stands did not show substantial differences in terms of carbon sequestration. Overyielding, driven by species mixing pattern and mixture degree, was observed in other common European mixtures, and authors suggested the possibility of increasing stand density due to species complementarity (Pretzsch 2022). Thus, increasing initial stand density in our study could increase productivity and reveal differences among different species proportion degrees. At the end of the simulation, our biomass yields per tree fell within the range of those used to fit the biomass equations applied in our study (Ruiz-Peinado et al. 2011), and the stand values are on similar scales to those reported by Aguirre et al. (2021) for the same species. Neither carbon sequestered in deadwood nor decay rates from harvested trees were assessed in this study. While including these factors would alter the final simulation values, our focus was on evaluating the effects of silvicultural practices on production to rank each alternative by the ESs provided. Although some studies have addressed this topic using the approach suggested in literature (IPCC 2006, 2019; Pingoud and Wagner 2006), further research is needed to deepen our understanding of the carbon cycle effects associated with silviculture.

In the case of mushroom production, pure Scots pine stands reached higher productivity levels than the other pure and mixed stands included in the study. Consequently, higher productivity was also reported in Scots pine stands compared to Maritime pine stands in the same area by the model authors (Sánchez-González et al. 2019). It is already known that mushroom productivity is highly dependent on weather conditions, especially in Autumn (Martínez-Peña et al. 2012; Aldea et al. 2014) and that stand basal area around 30–40 $m^2 \cdot ha^{-1}$ maximizes its production (Martínez-Peña et al. 2012; de-Miguel et al. 2014; Sánchez-González et al. 2019). However, details about productivity in mixed stands are lacking. As models are not available yet, mixed stand production was averaged according to species proportion on the stand, which explains that higher Scots pine proportions in the mixed stand provided higher mushroom rates. While this approach provides the opportunity to compare the productivity of different forest types, further research is needed to understand if species mixtures can lead to higher mushroom productivity than pure stands. In this context, a greater variety of mushroom species could be expected in the stand due to the presence of both tree species and the higher understory richness they support (López-Marcos et al. 2024). This combination integrates species associated with each forest type, but the overall level of mushroom productivity might follow a different trend.

ESs production analyzed in our study was consistently lower across the different stand types when no management was applied. The results answer our fourth research question regarding the provision of ESs without management. This highlights the importance of human intervention in forest dynamics when aiming to obtain different ESs, even when there is no specific target tree size, and the purpose of the stand is carbon sequestration (Ruiz-Peinado et al. 2017). Additionally, damages by biotic factors altering forest conditions and reducing ESs productivity can be boosted when no management is applied (Prieto-Recio et al. 2015; De La Fuente et al. 2018) or it is done poorly (Branco et al. 2014). Another factor to consider is the impact of fire, as the lack of harvest leads to higher horizontal and vertical fuel continuity, increasing the fire spread rates and flame length when it occurs (Piqué and Domènech 2018).

Since the production of all the ESs considered in our study is lower without management, it is crucial to identify the most effective management alternatives that align with the management goals. Forest managers need evidence-based silvicultural scenarios to sustain mixed stands and maximize the production of the desired ESs (Coll et al. 2018). This is addressed in our final research question. Silvicultural scenarios tested in this work focus on maximizing one ES. This is the case of the wood scenario, as a reasonable amount of big saw wood was only obtained under the wood scenario. In this case, both carbon and mushroom production were reduced in all the plots studied compared to other scenarios. This reduction occurred because the target silviculture differed, and neither product was compatible, as reported in previous studies (Aldea et al. 2014). Scenarios focused on mushroom and carbon maximized yields for both ESs, along with a small saw timber yield, achieving higher production than the BAU scenario across all products. This again supports the possibility of producing multiple ESs with the same thinning regime (Ordóñez et al. 2024). Both scenarios are characterized by applying frequent silviculture interventions (every 10–15 years) with low intensities, aimed at increasing light availability for fungal fructification (Herrero et al. 2019) and avoiding carbon loss by natural mortality (Ruiz-Peinado et al. 2016). While they demonstrate being a good choice for ESs provision, the high number of thinning interventions in the stand could be a weakness when analyzing economic profitability. More field interventions with lower intensity result in lower yields per thinning, thus reducing the profitability of each harvest and engaging the economic sustainability of these silvicultural scenarios. However, the continuous yield provided by mushroom picking and the recreational activity linked to it can balance the situation, also improving long-term forest health and sustainability (Navarro-Cerrillo et al. 2022). Finally, when analyzing the BAU scenario, it was not able to produce a big saw timber yield in most of the cases, while it was sufficient to obtain small saw timber yield, mushroom production, and carbon content, as certain thinning regimes can generate multiple ESs (Ordóñez et al. 2024). Our results are in line with previous findings for the same species (Bravo and Diaz-Balteiro 2004; Bravo et al. 2008), where traditional management does not maximize any ES but achieves satisfactory results for most of them. While efficiency in the production of those services could be improved, results are quite good if we consider that just two thinning interventions were planned during the study period (90 years), assuming minimal effort in forest management.

Lastly, it is important to highlight the numerical results of simulations may be biased due to the lack of regional adaptation of the model in the case of BAI (Rodríguez de Prado et al. 2022a), h/d (Rodríguez de Prado et al. 2022b) and SDI/SDImax (Rodríguez de Prado et al. 2020). While other models are available and specifically fitted for the study area in both pure (Lizarralde 2008) and mixed conditions (Riofrío et al. 2017b, 2019; Askarieh et al. 2023), they are not climate-sensitive models. Due to the inclusion of mushroom productivity models in our study (Sánchez-González et al. 2019) and its close relationship with weather conditions (Martínez-Peña et al. 2012; Aldea et al. 2014; Sánchez-González et al. 2019), we considered more appropriate to use the selected ones in our study even assuming certain bias on the predictions. However, while numerical results can be biased and accumulate errors at each step of the simulation, ranking different scenarios, as in our case, has proven to be a good approach for silvicultural scenarios selection in both pure (De La Parra Peral et al. 2017; Vázquez-Veloso et al. 2022) and mixed stands (Bravo and Vázquez-Veloso 2024). In addition, the data used for this study is quite specific and was used as an initial approach, so future studies should aim to cover broader stand variability to have stronger conclusions regarding the most suitable silviculture for each case.

Mechanisms behind overyielding in mixed stands are based on species complementarity. In general terms, an increase in species diversity tends to increase stand productivity (Pretzsch and Forrester 2017) and stability (del Río et al. 2022a, b), and differences in phenology (Camarero et al. 2010; Vieira et al. 2014) and response to climatic conditions (Bogino and Bravo 2008; Bogino et al. 2009) enhance complementary, as resources competition is non-synchronous during the growing season. Different studies explored species complementarity at the crown level, as even low trait differences can lead to positive effects at stand level (Riofrío et al. 2017a). On the one hand, while crown architecture is quite similar (Poorter et al. 2012), the slightly higher shade tolerance of Scots pine (Sánchez-Gómez et al. 2006; Gaudio et al. 2011; Riofrío et al. 2017a) and its slower growth rate (Fernandes et al. 2017) create a size-asymmetric stand where both species can progress due to their different crown morphology and structure in mixture (Riofrío et al. 2017b). This situation stimulates Maritime pine growth, as Riofrío et al. (2017a, 2019) reported that size-asymmetric competition has a stronger influence on its growth. Thus, Maritime pine tends to occupy the dominant canopy layer and larger diameter distribution class in mixture (Riofrío et al. 2017a, b) as was also found in our study, taking competitive advantage of its position (Askarieh et al. 2024; Ordóñez et al. 2024). Both species crown plasticity and size distribution are drivers that explain the higher productivity of mixed compared to pure stands (Riofrío et al. 2017b), and its complementarity allow for an increase in the stand density (Del Río et al. 2022a, b). In terms of production, higher basal area increment (Riofrío et al. 2019), volume increment (Riofrío et al. 2017b), radial inter-annual increment (Askarieh et al. 2024) and growth efficiency (Cattaneo et al. 2018) was reported for Maritime pine in mixed stands as evidence of their complementarity, with our study also reporting overyielding in carbon sequestration.

Conclusion

Our study compared the provision of ecosystem services between pure different mixture proportions of mixed Scots pine and Maritime pine stands. The initial species proportions and their maintenance during the management period were found to be less critical than the implementation of suitable silvicultural practices. The results indicate that while mixed stands consistently enhance carbon sequestration regardless of initial species proportions, the patterns for mushroom and timber yields vary. Focusing on a single ecosystem service often leads to trade-offs, but sometimes it is the only way to achieve desired yields of certain ecosystem services, as demonstrated in our study with the yield of big size saw timber. However, a balanced approach that considers multiple ecosystem services can mitigate these trade-offs and enhance overall forest resilience, as we found when aiming to maximize mushroom yields, sequestered carbon, and small saw timber yield. This research provides valuable insights for forest managers aiming to balance productivity and sustainability in ecosystem services provision. Further research is needed to assess the provision of additional ecosystem services under varying management strategies and to explore the impact of different initial stand characteristics on ecosystem services provision, both for this and other representative species mixtures.

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Data availability A repository with the original data, code and results of: *Trade-Offs and Management Strategies for Ecosystem Services in Mixed Scots Pine and Maritime Pine Forests* Zenodo repository with https://doi.org/10.5281/zenodo.13904531 Github repository: https://github.com/aitorvv/Pinus_sylvestris_and_pinaster-trade_offs_and_ecosystem_services.

Declarations

Competing interests The authors declare no competing interests.

References

Aguirre A, del Río M, Ruiz-Peinado R, Condés S (2021) Stand-level biomass models for predicting C stock for the main Spanish pine species. For Ecosyst 8:29. https://doi.org/10.1186/s40663-021-00308-w

Aldea J, Martínez-Peña F, Romero C, Diaz-Balteiro L (2014) Participatory goal programming in forest management: an application integrating several ecosystem services. Forests 5:3352–3371. https://doi.org/10.3390/f5123352

Alía R, Martín S (2003) EUFORGEN technical guidelines for genetic conservation and use for maritime pine (*Pinus pinaster*).

Askarieh A, del Río M, Aldea J et al (2024) Radial increment dynamics of Maritime pine (*Pinus pinaster* Ait.) in pure and mixed stands with Scots pine (*Pinus sylvestris* L.) under changing environmental conditions. Eur J for Res 143:671–686. https://doi.org/10.1007/s10342-023-01650-0

Askarieh A, Ruano I, Bravo F (2023) Is it needed to integrate mixture degree in Stand Density Management Diagram (SDMD)? Iforest - Biogeosci for 16:274. https://doi.org/10.3832/ifor4005-016

Bivand R, Keitt T, Rowlingson B (2023) rgdal: Bindings for the "Geospatial" Data Abstraction Library

Bogino S, Fernandez Nieto MJ, Bravo F et al (2009) Climate effect on radial growth of Pinus sylvestris at its southern and western distribution limits. Silva Fenn 43:609–623

Bogino SM, Bravo F (2008) Growth response of *Pinus pinaster* Ait. to climatic variables in central Spanish forests. Ann For Sci 65:1. https://doi.org/10.1051/forest:2008025

Branco M, Bragança H, Sousa E, Phillips AJ (2014) Pests and Diseases in Portuguese Forestry: current and new threats. In: Reboredo F (ed) Forest context and policies in portugal: present and future challenges. Springer, Cham, pp 117–154

Bravo F (2022) Adaptación al cambio climático: directrices para la adaptación de la gestión del patrimonio natural y la política forestal al cambio climático en Castilla y León. Ed. Universidad de Valladolid, 507 pp

Bravo F, Bravo-Oviedo A, Diaz-Balteiro L (2008) Carbon sequestration in Spanish Mediterranean forests under two management alternatives: a modeling approach. Eur J for Res 127:225–234. https://doi.org/10.1007/s10342-007-0198-y

Bravo F, Diaz-Balteiro L (2004) Evaluation of new silvicultural alternatives for Scots pine stands in northern Spain. Ann for Sci 61:163–169. https://doi.org/10.1051/forest:2004008

Bravo F, Ordóñez C, Vázquez-Veloso A, Michalakopoulos S (2025) SIMANFOR cloud decision support system: structure, content, and applications. Ecol Model 499:110912. https://doi.org/10.1016/j.ecolmodel.2024.110912

Bravo F, Rodríguez F, Ordóñez C (2012) A web-based application to simulate alternatives for sustainable forest management: SIMANFOR. For Syst 21:4–8. https://doi.org/10.5424/fs/2112211-01953

Bravo F, Vázquez-Veloso A (2024) Mixed forest model parameterization and integration into simulation platforms as a tool for decision-making processes. Palencia (Spain)

Brockerhoff EG, Barbaro L, Castagneyrol B et al (2017) Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers Conserv 26:3005–3035. https://doi.org/10.1007/s10531-017-1453-2

Calama R, de-Dios-García J, del Río M, et al (2021) Mixture mitigates the effect of climate change on the provision of relevant ecosystem services in managed *Pinus pinea* L. forests. For Ecol Manag 481:118782. https://doi.org/10.1016/j.foreco.2020.118782

Camarero JJ, Olano JM, Parras A (2010) Plastic bimodal xylogenesis in conifers from continental Mediterranean climates. New Phytol 185:471–480. https://doi.org/10.1111/j.1469-8137.2009.03073.x

Cattaneo N, Bravo-Oviedo A, Bravo F (2018) Analysis of tree interactions in a mixed Mediterranean pine stand using competition indices. Eur J for Res 137:109–120. https://doi.org/10.1007/s10342-017-1094-8

Coll L, Ameztegui A, Collet C et al (2018) Knowledge gaps about mixed forests: What do European forest managers want to know and what answers can science provide? For Ecol Manag 407:106–115. https://doi.org/10.1016/j.foreco.2017.10.055

De La Fuente B, Saura S, Beck PSA (2018) Predicting the spread of an invasive tree pest: the pine wood nematode in Southern Europe. J Appl Ecol 55:2374–2385. https://doi.org/10.1111/1365-2664.13177

De La Parra Peral B, Oria De Rueda JA, Ordóñez AC, et al (2017) Simulación de la productividad de setas bajo distintos escenarios selvícolas en la plataforma SIMANFOR. In: Actas del 7° Congreso Forestal Español, Plasencia

de-Miguel S, Bonet JA, Pukkala T, Martínez de Aragón J (2014) Impact of forest management intensity on landscape-level mushroom productivity: a regional model-based scenario analysis. For Ecol Manag 330:218–227. https://doi.org/10.1016/j.foreco.2014.07.014

Del Río M, Bravo-Oviedo A, Robledo JJ (2022) Fichas de impactos, vulnerabilidad y oportunidades de adaptación al cambio climático para ecosistemas arbolados: Pinares de *Pinus sylvestris*. In: Bravo F (ed) Adaptación al cambio climático: directrices para la adaptación de la gestión del patrimonio natural y la política forestal al cambio climático en Castilla y León. Universidad de Valladolid, p 507

Del Río M, López E, Montero G (2006) Manual de gestión para masas procedentes de repoblación de *Pinus pinaster* Ait., *Pinus sylvestris* L. y *Pinus nigra* Arn. en Castilla y León. Junta de Castilla y León, Castilla y León (España)

Del Río M, Pretzsch H, Ruíz-Peinado R et al (2017) Species interactions increase the temporal stability of community productivity in *Pinus sylvestris–Fagus sylvatica* mixtures across Europe. J Ecol 105:1032–1043. https://doi.org/10.1111/1365-2745.12727

del Río M, Pretzsch H, Ruiz-Peinado R et al (2022b) Emerging stability of forest productivity by mixing two species buffers temperature destabilizing effect. J Appl Ecol 59:2730–2741. https://doi.org/10.1111/1365-2664.14267

Del Río M, Sterba H (2009) Comparing volume growth in pure and mixed stands of *Pinus sylvestris* and *Quercus pyrenaica*. Ann for Sci 66:1–11. https://doi.org/10.1051/forest/2009035

del Río M, Vergarechea M, Hilmers T et al (2021) Effects of elevation-dependent climate warming on intra- and inter-specific growth synchrony in mixed mountain forests. For Ecol Manag 479:118587. https://doi.org/10.1016/j.foreco.2020.118587

Domínguez-Lerena S (2007) Pinar Grande. 100 años de gestión sostenible. 1907–2007

Durrant TH, de Rigo D, Caudullo G (2016) *Pinus sylvestris* in Europe: distribution, habitat, usage and threats. Eur Atlas for Tree Species 14:845–846

Felipe-Lucia MR, Soliveres S, Penone C et al (2018) Multiple forest attributes underpin the supply of multiple ecosystem services. Nat Commun 9:4839. https://doi.org/10.1038/s41467-018-07082-4

Fernandes C, Gaspar MJ, Pires J et al (2017) Within and between-tree variation of wood density components in *Pinus sylvestris* at five sites in Portugal. Eur J Wood Wood Prod 75:511–526. https://doi.org/10.1007/s00107-016-1130-2

Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int J Climatol 37:4302–4315. https://doi.org/10.1002/JOC.5086

Forrester DI (2014) The spatial and temporal dynamics of species interactions in mixed-species forests: From pattern to process. For Ecol Manag 312:282–292. https://doi.org/10.1016/j.foreco.2013.10.003

Gaudio N, Balandier P, Perret S, Ginisty C (2011) Growth of understorey Scots pine (*Pinus sylvestris* L.) saplings in response to light in mixed temperate forest. For Int J for Res 84:187–195. https://doi.org/10.1093/forestry/cpr005

Herrero C, Berraondo I, Bravo F, et al (2019) Predicting Mushroom Productivity from Long-Term Field-Data Series in Mediterranean Pinus pinaster Ait. Forests in the Context of Climate Change. Forests 10:206. https://doi.org/10.3390/f10030206

Hijmans RJ (2023) raster: Geographic data analysis and modeling

IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme, Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds). Published: IGES, Japan

IPCC (2019) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland

Jonsson M, Bengtsson J, Gamfeldt L et al (2019) Levels of forest ecosystem services depend on specific mixtures of commercial tree species. Nat Plants 5:141–147. https://doi.org/10.1038/s41477-018-0346-z

Lafond V, Cordonnier T, Mao Z, Courbaud B (2017) Trade-offs and synergies between ecosystem services in uneven-aged mountain forests: evidences using Pareto fronts. Eur J for Res 136:997–1012. https://doi.org/10.1007/s10342-016-1022-3

Lizarralde I (2008) Dinámica de rodales y competencia en las masas de pino silvestre (*Pinus sylvestris* L.) y pino negral (*Pinus pinaster* Ait.) de los sistemas central e ibérico meridional). http://purl.org/dc/dcmitype/Text, Universidad de Valladolid

López-Marcos D, Turrión MB, García-Duro J, et al (2024) Quality and quantity of topsoil organic matter in monospecific and mixed pine forests: role of overstory and understory vegetation. Manuscr. Prep

Martín Ariza A, Bravo F, Ordóñez AC (2017) Evaluación de alternativas selvícolas para el almacenamiento de carbono en los ecosistemas forestales de *Pinus nigra* Arnold. In: Actas del 7° Congreso Forestal Español, Plasencia

Martínez-Peña F, de-Miguel S, Pukkala T, et al (2012) Yield models for ectomycorrhizal mushrooms in *Pinus sylvestris* forests with special focus on *Boletus edulis* and *Lactarius* group *deliciosus*. For Ecol Manag 282:63–69. https://doi.org/10.1016/j.foreco.2012.06.034

Martonne E (1926) L'indice d'aridité. Bull L'Association Géographes Fr 3:3–5

MITECO (2024) Mapa Forestal de España (MFE50). In: Minist. Para Transic. Ecológica El Reto Demográfico. https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/mfe50.html

Montero G (2005) Producción de biomasa y fijación de CO2 por los bosques españoles. G. Montero, R. Ruiz-Peinado, M. Muñoz (Eds.), Monografías INIA: Serie Forestal no, 13

Montero G, del Río M, Roig S, Rojo A (2008) Selvicultura de *Pinus sylvestris*. In: Serrada R, Montero G, Reque JA (eds) Compendio de Selvidultura Aplicada en España. INIA-Ministerio de Educación y Ciencia, Madrid, pp 503–534

Morán-Ordóñez A, Ameztegui A, De Cáceres M et al (2020) Future trade-offs and synergies among ecosystem services in Mediterranean forests under global change scenarios. Ecosyst Serv 45:101174. https://doi.org/10.1016/j.ecoser.2020.101174

Morán-Ordóñez A, Ramsauer J, Coll L et al (2021) Ecosystem services provision by Mediterranean forests will be compromised above 2℃ warming. Glob Change Biol 27:4210–4222. https://doi.org/10.1111/gcb.15745

Muñoz-Gálvez F, Herrero A, Pérez-Corona M, Andivia E (2021) Are pine-oak mixed stands in Mediterranean mountains more resilient to drought than their monospecific counterparts? For Ecol Manag 484:118955. https://doi.org/10.1016/j.foreco.2021.118955

Navarro-Cerrillo RM, Ruiz-Gómez FJ, Camarero JJ et al (2022) Long-term carbon sequestration in pine forests under different silvicultural and climatic regimes in Spain. Forests 13:450. https://doi.org/10.3390/f13030450

Nocentini S, Travaglini D, Muys B (2022) Managing mediterranean forests for multiple ecosystem services: research progress and knowledge gaps. Curr for Rep 8:229–256. https://doi.org/10.1007/s40725-022-00167-w

O'Neill BC, Kriegler E, Ebi KL et al (2017) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob Environ Change 42:169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Ordóñez C, Maguire DA, Pando V, Bravo F (2024) Stand structural effects on growth distribution and growth efficiency in Scots pine and Mediterranean pine in Spain. Eur J for Res. https://doi.org/10.1007/s10342-024-01698-6

Pardos M, Del Río M, Pretzsch H et al (2021) The greater resilience of mixed forests to drought mainly depends on their composition: analysis along a climate gradient across Europe. For Ecol Manag 481:118687. https://doi.org/10.1016/j.foreco.2020.118687

Pascual-Arranz A (2012) Elaboración de un nuevo modelo selvícola de gestión en el monte Pinar Grande (Soria). Universidad de Valladolid

Petrie R, Denvil S, Ames S et al (2021) Coordinating an operational data distribution network for CMIP6 data. Geosci Model Dev 14:629–644. https://doi.org/10.5194/gmd-14-629-2021

Pingoud K, Wagner F (2006) Methane emissions from landfills and carbon dynamics of harvested wood products: the first-order decay revisited. Mitig Adapt Strateg Glob Change 11:961–978. https://doi.org/10.1007/s11027-006-9029-6

Piqué M, Domènech R (2018) Effectiveness of mechanical thinning and prescribed burning on fire behavior in *Pinus nigra* forests in NE Spain. Sci Total Environ 618:1539–1546. https://doi.org/10.1016/j.scitotenv.2017.09.316

Poorter L, Lianes E, Moreno-de las Heras M, Zavala MA (2012) Architecture of Iberian canopy tree species in relation to wood density, shade tolerance and climate. Plant Ecol 213:707–722. https://doi.org/10.1007/s11258-012-0032-6

Pretzsch H (2014) Canopy space filling and tree crown morphology in mixed-species stands compared with monocultures. For Ecol Manag 327:251–264. https://doi.org/10.1016/j.foreco.2014.04.027

Pretzsch H (2022) Mixing degree, stand density, and water supply can increase the overyielding of mixed versus monospecific stands in Central Europe. For Ecol Manag 503:119741. https://doi.org/10.1016/j.foreco.2021.119741

Pretzsch H, Forrester DI (2017) Stand dynamics of mixed-species stands compared with monocultures. In: Pretzsch H, Forrester DI, Bauhus J (eds) Mixed-species forests: ecology and management. Springer, Berlin, pp 117–209

Pretzsch H, Schütz GJ (2014) Size-structure dynamics of mixed versus pure forest stands. For Syst 23:560–572

Pretzsch H, Schütze G (2016) Effect of tree species mixing on the size structure, density, and yield of forest stands. Eur J for Res 135:1–22. https://doi.org/10.1007/s10342-015-0913-z

Pretzsch H, Schütze G (2009) Transgressive overyielding in mixed compared with pure stands of Norway spruce and European beech in Central Europe: evidence on stand level and explanation on individual tree level. Eur J for Res 128:183–204. https://doi.org/10.1007/s10342-008-0215-9

Prieto-Recio C, Martín-García J, Bravo F, Diez JJ (2015) Unravelling the associations between climate, soil properties and forest management in *Pinus pinaster* decline in the Iberian Peninsula. For Ecol Manag 356:74–83. https://doi.org/10.1016/j.foreco.2015.07.033

R Core Team (2021) R: a language and environment for statistical computing. R Foundation for Statistical Computing

Riofrío J, Del Río M, Bravo F (2017a) Mixing effects on growth efficiency in mixed pine forests. For Ecol Manag 390:381–392. https://doi.org/10.1093/forestry/cpw056

Riofrío J, del Río M, Maguire DA, Bravo F (2019) Species mixing effects on height-diameter and basal area increment models for scots pine and maritime pine. Forests 10:249. https://doi.org/10.3390/f10030249

Riofrío J, Del Río M, Pretzsch H, Bravo F (2017b) Changes in structural heterogeneity and stand productivity by mixing Scots pine and Maritime pine. For Ecol Manag 405:219–228. https://doi.org/10.1016/j.foreco.2017.09.036

Rodríguez de Prado D (2022) New insights in the modeling and simulation of tree and stand level variables in Mediterranean mixed forests in the present context of climate change. Universidad de Valladolid

Rodríguez de Prado D, Riofrío J, Aldea J et al (2022a) Competition and climate influence in the basal area increment models for Mediterranean mixed forests. For Ecol Manag 506:119955. https://doi.org/10.1016/j.foreco.2021.119955

Rodríguez de Prado D, Riofrío J, Aldea J et al (2022b) Species mixing proportion and aridity influence in the height-diameter relationship for different species mixtures in Mediterranean forests. Forests 13:119. https://doi.org/10.3390/f13010119

Rodríguez de Prado D, San Martín R, Bravo F, Herrero C (2020) Potential climate influence on maximum stand carrying capacity for 15 Mediterranean coniferous and broadleaf species. For Ecol Manag 460:117824. https://doi.org/10.1016/j.foreco.2019.117824

Rodríguez de Prado D, Vázquez-Veloso A, Quian YF et al (2023) Can mixed forests sequester more CO2 than pure forests in future climate scenarios? A case study of *Pinus sylvestris* combinations in Spain. Eur J for Res 142:91–105. https://doi.org/10.1007/s10342-022-01507-y

Rodríguez F, Broto M, Lizarralde I (2008) CubiFOR: Herramienta para cubicar, clasificar productos y calcular biomasa y CO2 en masas forestales de Castilla y León. Rev Montes 95:33–39

Ruano I, Madrigal-González J, Calama R, Mutke S (2022) Fichas de impactos, vulnerabilidad y oportunidades de adaptación al cambio climático para ecosistemas arbolados: Pinares de *Pinus pinaster*. In: Bravo F (ed) Adaptación al cambio climático: directrices para la adaptación de la gestión del patrimonio natural y la política forestal al cambio climático en Castilla y León. Universidad de Valladolid, p 507

Ruiz-Peinado R, Bravo Oviedo JA, López Senespleda E et al (2017) Forest management and carbon sequestration in the Mediterranean region: a review. For Syst 26:10

Ruiz-Peinado R, Bravo-Oviedo A, Montero G, del Río M (2016) Carbon stocks in a Scots pine afforestation under different thinning intensities management. Mitig Adapt Strateg Glob Change 21:1059–1072. https://doi.org/10.1007/s11027-014-9585-0

Ruiz-Peinado R, Del Río M, Montero G (2011) New models for estimating the carbon sink capacity of Spanish softwood species. For Syst 20:176–188. https://doi.org/10.5424/fs/2011201-1164

Sánchez-Gómez D, Valladares F, Zavala MA (2006) Functional traits and plasticity in response to light in seedlings of four Iberian forest tree species. Tree Physiol 26:1425–1433. https://doi.org/10.1093/treephys/26.11.1425

Sánchez-González M, de-Miguel S, Martin-Pinto P, et al (2019) Yield models for predicting aboveground ectomycorrhizal fungal productivity in *Pinus sylvestris* and *Pinus pinaster* stands of northern Spain. For Ecosyst 6:52. https://doi.org/10.1186/s40663-019-0211-1

Steckel M, Heym M, Wolff B et al (2019) Transgressive overyielding in mixed compared with monospecific Scots pine (*Pinus sylvestris* L.) and oak (*Quercus robur* L., *Quercus petraea* (Matt.) Liebl.) stands–Productivity gains increase with annual water supply. For Ecol Manag 439:81–96. https://doi.org/10.1016/j.foreco.2019.02.038

Tatebe H, Ogura T, Nitta T et al (2019) Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. Geosci Model Dev 12:2727–2765. https://doi.org/10.5194/gmd-12-2727-2019

Toïgo M, Vallet P, Perot T et al (2015) Overyielding in mixed forests decreases with site productivity. J Ecol 103:502–512. https://doi.org/10.1111/1365-2745.12379

Vázquez-Veloso A, Ordóñez C, Bravo F (2022) Simulación de la productividad de recursos no maderables (hongos y piñón) bajo diferentes escenarios selvícolas utilizando SIMANFOR. In: 8° Congreso Forestal Español (Comunicación Oral). Lleida, España

Vieira J, Rossi S, Campelo F et al (2014) Xylogenesis of Pinus pinaster under a Mediterranean climate. Ann for Sci 71:71–80. https://doi.org/10.1007/s13595-013-0341-5

Vilà M, Vayreda J, Comas L et al (2007) Species richness and wood production: a positive association in Mediterranean forests. Ecol Lett 10:241–250. https://doi.org/10.1111/j.1461-0248.2007.01016.x

Wickham H (2016) ggplot2: Elegant graphics for data analysis. Springer, New York

Wickham H, Averick M, Bryan J, et al (2019) Welcome to the tidyverse. J Open Source Softw 4:1686. https://doi.org/10.21105/joss.01686