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Full Length Article

Integrating multiple landscape management strategies to optimise conservation under climate and planning scenarios: a case study in the Iberian Peninsula

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ABSTRACT

Global change demands dynamic landscape management that integrates different strategies (e.g. promoting rewilding or traditional farming practices) to address the impact of climate and land use change. Planning for management strategies individually can lead to severe trade-offs between objectives, high opportunity costs and challenging implementation. Integrated management plans are needed to optimise the combination of multiple management strategies. We used the multi-action planning tool ‘Prioriactions’ to prioritise the spatial allocation of four management strategies (Afforestation, Rewilding, Farmland Return and Agroforestry Return) in the Meseta Ibérica transboundary Biosphere Reserve. We aimed to achieve targets for conservation of species suitable area and ecosystem services supply while minimising fire hazard under different climate scenarios. We tested this approach under contrasting planning scenarios depicting different management priorities (*Equally Weighted, Forest Maximising* and *Open Maximising*). By integrating multiple management strategies, we could achieve management goals for biodiversity and ecosystem services under different planning scenarios, minimising trade-offs and deriving recommendations easier to uptake. The spatial allocation and extent of management strategies varied according to climate change and planning scenarios. Afforestation was needed when putting more priority on forest species and carbon sequestration, while more Farmland Return was allocated when preserving open habitat species and agriculture. Fire hazard was higher in Rewilding areas and lower in Farmland Return and Agroforestry Return areas. The novelty of our approach lies in its capacity to combine different management strategies and provide an optimised spatial arrangement based on management features, making it suitable for planning in dynamic and complex environments where multiple pressures and objectives must be considered.

1. Introduction

Despite conservation efforts and international commitments to halt biodiversity loss (CBD, 2011; IPBES, 2019) biodiversity continues declining worldwide. Conservation efforts are challenged by global change, which puts long-term persistence of biodiversity and nature’s

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contribution to society at risk (Hoekstra & Wiedmann, 2014). These challenges require new and holistic conservation approaches capable of recognizing the dynamic relationship between people and nature and evolve towards policy and management strategies in which conservation and socioeconomic development can coexist. This coexistence requires multifunctional landscapes that can support both biodiversity and ecosystem services (Martinez-Harms et al., 2015), defined as the contributions that ecosystems make to human well-being, whether material or not and commonly divided in provisioning, regulating and cultural services (Haines-Young & Potschin, 2018). Management of multifunctional landscapes requires combining different management strategies to allow the coexistence of multiple objectives in harmony and minimising the trade-offs between them (Thomson et al., 2020). For example, a combination of climate-smart management, which aims to increase the climate regulation potential of vegetation via carbon sequestration (Bowditch et al., 2020), and a fire-smart approach, which aims to mitigate the impacts of wildfires by building a landscape mosaic with low fuel load and connectivity, by promoting sustainable agro-pastoral practices, also enhancing food production (Pulido et al., 2023; Regos et al., 2023). This combination could help integrate landscape use into the ecological network (O'Farrell and Anderson, 2010) while supporting a diverse array of biodiversity and ecosystem services. Integrating diverse management strategies at the landscape scale can enhance synergies while minimising conflicts and mitigating undesirable consequences of climate change, such as catastrophic wildfires (Moreira and Pe'er, 2018; Tedim et al. 2016).

Southern Europe is especially vulnerable to climate change as it is expected to be impacted by increased aridity, longer and more frequent droughts, and shifts in wildfires regimes as the current climate is being displaced by the northward expansion of Mediterranean and desert climates (Carvalho et al., 2022). Mountainous rural areas of southern Europe, such as those in the inner Iberian Peninsula, are of particular concern as they are severely impacted by altered fire regimes resulting from fuel accumulation and vegetation encroachment derived from depopulation and land abandonment (Moreira et al., 2011). Yet, the heterogeneity of these areas provides a great opportunity to develop multifunctional landscapes that can achieve multiple management goals while adapting to climate change (Hobbs et al., 2014).

Some mountain rural landscapes in the Iberian Peninsula are already under protection, whether Protected Areas (PAs) such as National or Natural Parks, other Natura 2000 sites or recognized as Biosphere Reserves by UNESCO. This recognition is usually bestowed because of their potential to develop multifunctional landscapes where natural and cultural heritage can be harmonised with sustainable economic development. However, the effectiveness of this conservation approach has been regarded as insufficient under global change, as PAs face multiple challenges (Araújo et al., 2007). Biodiversity distributional shifts driven by climate change affect the future effectiveness of PAs at the global level due to the static nature of PAs (Araújo et al., 2011; Watson et al., 2014, Elsen et al., 2020). At a more regional level, landscape changes are a critical threat to conservation, especially in fire-prone and highly dynamic Mediterranean ecosystems (Regos et al., 2016, Lanzas et al., 2021). Despite the great opportunity for sustainability and conservation, maintaining multifunctional landscapes requires strengthening the effectiveness of PAs while addressing the ecological and socio-economic risks associated with global change, thus making adequate management more complex (Hermoso et al., 2018; Morán-Ordóñez et al., 2016).

Scenario analysis is a powerful tool to account for a range of plausible futures, incorporating information on changes in biodiversity and ecosystem services into decision making (Peterson et al., 2003). Scenarios have been used to assess the changes and trade-offs that different pathways in climate and landscape change can have on biodiversity and ES (Campos et al., 2022). However, the application of these scenario analyses to decision making is still constrained by the lack of full integration of management recommendations derived from each scenario individually. For example, previous studies have explored the cost and benefits of management strategies that range from a focus on conservation to a focus on productive use of the landscape as if they were implemented individually (one at a time). These scenarios are then translated into potential land cover maps that would be derived from the application of the management tested under each scenario individually (Felipe-Lucia et al., 2022, Li et al., 2020, Wang et al., 2018), and the benefits associated with the implementation of that management. These analyses can be used to identify, for example, the most suitable management strategy to achieve a given objective or the areas where that management would deliver the highest benefits (Cánibe et al., 2022). However, given the lack of integration of management strategies, these studies have highlighted that trade-offs are bound to appear between different features, and no strategy in isolation is able to maximise the benefits across all management features simultaneously, such as ecosystem services (Morán-Ordóñez et al., 2020) or habitat for all species (Campos et al., 2022). Therefore, a spatial combination of the different scenarios is needed to minimise trade-offs while maximising the benefits across management features. However, the integration of multiple management strategies into a single landscape spatial prioritisation exercise has not been extensively explored. Here, we aim to develop a spatial planning framework to simultaneously prioritise the spatial allocation of management strategies to achieve multiple management objectives. We selected UNESCO's Meseta Ibérica Transboundary Biosphere Reserve (Iberian Peninsula) as a case study, as an example of sustainability and coexistence of social and ecological systems where different and potentially conflicting objectives are pursued. Biosphere Reserves are therefore of great interest to explore effective spatial prioritisation of multiple management strategies to achieve multiple management goals while minimising conflicts. In this study, we demonstrate how a multi-action prioritisation approach can be used to identify an optimal configuration of management strategies that brings the best possible benefits to the Meseta Ibérica Biosphere Reserve. The approach implemented here could be applicable elsewhere to enhance management for multiple objectives.

2. Methodology

2.1. Study area

Located in the north-western Iberian Peninsula, in Portugal and Spain, the Meseta Ibérica Transboundary Biosphere Reserve extends from the Bragança district, on the Portuguese side, to the Zamora and León provinces of the Castilla & León autonomous region of Spain (Fig. 1), constituting the largest Biosphere Reserve in Europe (Palliwoda et al., 2021). It spans over an area of 11.326 km^2, being the largest biosphere reserve in the Iberian Peninsula and the largest transboundary biosphere reserve in Europe. The altitude of the region oscillates between 100 and 2100 m.a.s.l. and the climate is mainly Mediterranean with cool, wet winters and dry, warm summers. The region is mostly agricultural and agro-pastoral, while containing extensive areas of dry heathland (mainly *Erica, Cytisus* and *Cistus* species) and forest habitats. Forests are commonly dominated by *Pinus pinaster, Quercus pyrenaica* and *Quercus rotundifolia.* Agroforestry is also an important economic activity, in particular based on *Castanea sativa* orchards. The Meseta Ibérica Biosphere Reserve constitutes a paramount area for conservation at the European level since it comprises 4 Natural Parks and over 20 Natura 2000 sites. It hosts a very significant part of the Spanish and Portuguese terrestrial fauna species, accounting for about 250 species of vertebrates and a rich and diverse array of invertebrate species. The selection of this area allows us to apply our framework over a heterogeneous landscape where different management strategies can coexist. Terrain conditions, land ownership, traditional management practices and national and European policies resulted in a landscape mosaic where semi-natural vegetation and forests are predominant at higher altitudes and agriculture at lower lands. The management of the reserve is rather complex, as it faces different socioeconomic challenges such as

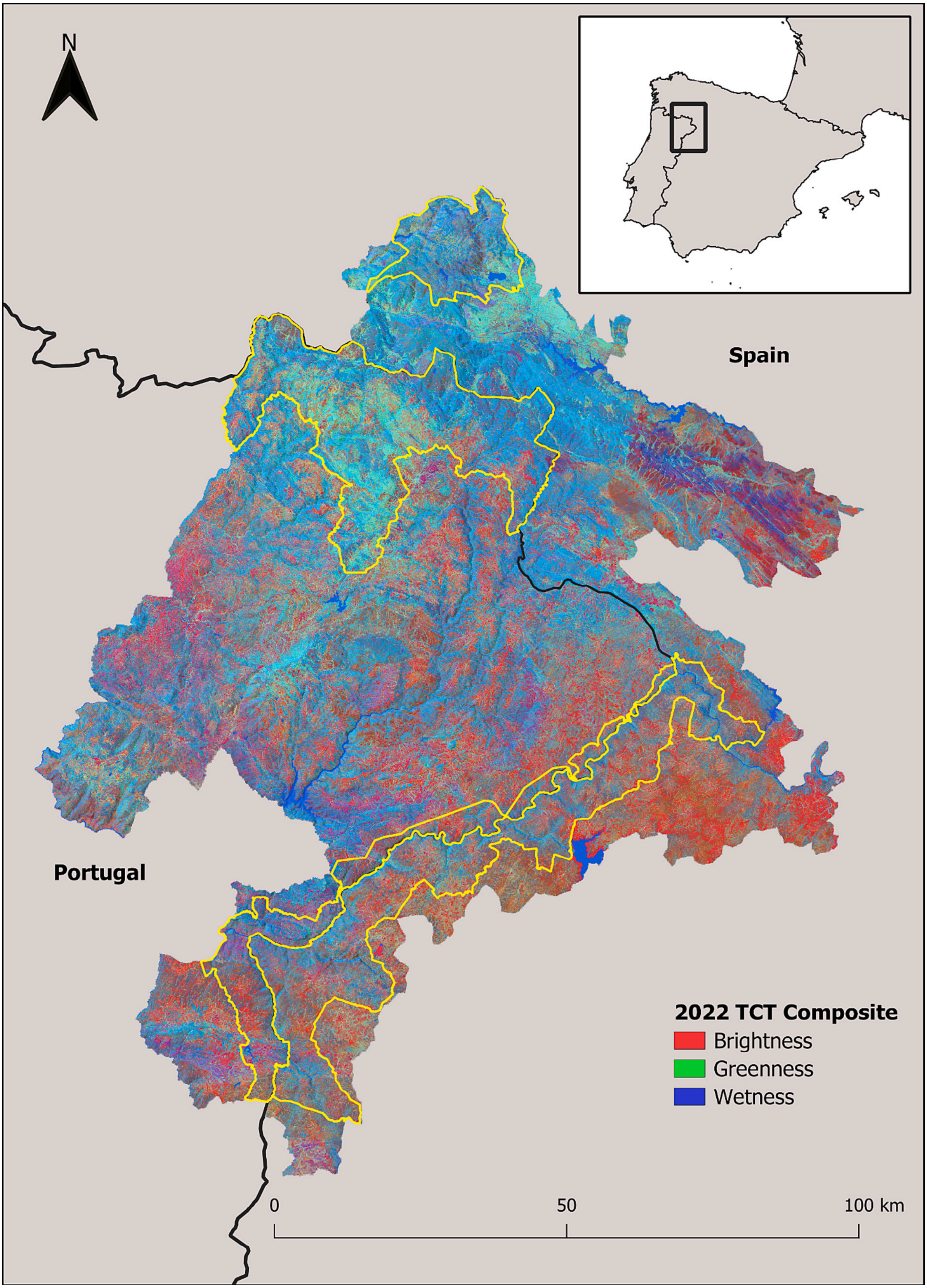

Fig. 1. Map of the Meseta Ibérica Transboundary Biosphere Reserve and its location within the Iberian Península. Represented is the Median composite of the Tasseled Cap Transformation (TCT) of the available images for 2023 in the Sentinel-2 Surface Reflectance collection. Red tones highlight areas with high brightness (albedo), green tones highlight vegetation biomass and blue tones highlight wetness. Highlighted in yellow are the 4 Natural Parks present in the Biosphere Reserve. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

depopulation ageing and demographic decline, resulting in land abandonment, which in combination with droughts during dry months can lead to extreme and uncontrollable wildfires. Previous work has shown that the area has potential to adapt and achieve management targets under contrasting management strategies thanks to its size and heterogeneity, although enhancing some habitats and ecosystem services over others, depending on the strategy (Cánibe et al., 2022).

2.2. Methodological framework

This study follows a systematic planning approach integrating data for biodiversity, ecosystem services and fire hazard projections to identify an optimal combination of four management strategies (Afforestation, Rewilding, Farmland Return and Agroforestry Return; Table 1), to achieve management goals for biodiversity conservation (% of suitable area) and ecosystem services (% of supply) while minimising fire hazard under two climate Representative Concentration Pathways (RCP 4.5 and RCP 8.5; Fig. 2). We started by making projections of species distributions, ecosystem services and fire hazard across the whole study area under each management strategy. These distributions were used to build the inputs used in the multi-action spatial prioritisation tool 'prioriactions' (Salgado-Rojas et al., 2023). We used the R package 'prioriactions' to spatially combine the management strategies with an optimal spatial allocation so user-defined targets for species and ecosystem services are achieved while minimising fire hazard (Fig. 2). We also tested the sensitivity of the approach to different sets of spatial planning scenarios (hereafter "planning scenarios") reflected in the targets for the different features, aiming to represent different management interests of the biosphere reserve. With the resulting distribution of management strategies, we ran analyses comparing the outputs for each planning scenario, climate RCP and replicates.

Table 1
Description of land use management scenarios in terms of CORINE land cover maps used for describing landscape change trends, storylines and main land cover transitions.

Strategy	Storyline
Afforestation	This management strategy follows the historic land cover change trends that took place between 1990 and 2000 to simulate changes associated with EU climate-smart policies aimed at meeting the increasing demand for wood and bioenergy as well as climate change mitigation. This strategy promotes natural succession and active planting in former semi-natural areas of shrubland and grassland. As a result, areas of coniferous (*Pinus pinaster)* and deciduous (*Quercus pyrenaica*) forests are favoured.
Rewilding	Simulates changes associated with potential EU climate-smart policies to boost natural regeneration through rewilding following the historic changes between 1990 and 2018. Socio-ecological processes of rural exodus leading to land abandonment are the main drivers of landscape change in this scenario (Azevedo et al., 2011). Consequently, agro-pastoral areas tend to decline and be replaced by grassland and dry heathland.
Farmland Return	Following land use trends between 2006 and 2012, this strategy represents a landscape in which agricultural policies such as the European Common Agricultural Policy support and promote sustainable low maintenance farming, aiming to revert land abandonment tendencies and support local development, fire mitigation and biodiversity conservation. Therefore, shrubland and grassland decrease in favour or agro-pastoral areas.
Agroforestry Return	This strategy simulates the integration of agroforestry activities with former agricultural activities to mitigate the negative impacts of wildfires, following the land cover changes that took place between 2006 and 2012, and between 2012 and 2018. The aim is to decrease flammability by interrupting and decreasing highly flammable cover types while supporting the development of the region. As a result, agroforestry cultures of *Castanea sativa* increase accompanied by a moderate increase in farmland, while semi natural areas and forests (especially coniferous) decrease.

2.3. Projection of management strategies

We used spatial projections of land cover under four management strategies for the Meseta Ibérica for the year 2050 (Table 1) depicting the implementation of different management policies aiming to deal with the different environmental and socioeconomic challenges affecting the Meseta Ibérica (Campos et al. 2022). Management strategies included two climate-smart (Afforestation and Rewilding) and two fire-smart options (Farmland Return and Agroforestry Return). Campos et al. (2022) used available CORINE Land Cover (CLC) maps to identify previous land cover change trends in the Meseta Ibérica and build land cover transition matrices representative of each management strategy, which were then applied to project land cover changes. The InVEST Scenario Generator (Sharp et al., 2020) was used to project the future land cover maps for 2050 using the CLC 2018 at 100 m resolution as the baseline map, considering 10 land cover classes, namely urban, agriculture, grassland, agroforestry, forest (deciduous, coniferous and mixed), shrubland, water, and others. To make projections more realistic, the transition rates between land cover classes were combined with suitability rules following physical and environmental factors such as altitude, aspect, slope and proximity to water lines and urban areas (Campos et al., 2022b). Projections included 10 replicates for each management strategy to account for stochasticity, thus totaling 40 different future land cover maps. These projections of land cover maps have been used in other studies in the area to develop projections for biodiversity and ecosystem services (Campos et al., 2022, Cánibe et al., 2022).

2.4. Spatial data

The projections of management scenarios, along with climate data, have been previously used in research for the Meseta Ibérica, to develop spatial projections for biodiversity, ecosystem services and fire hazard. The spatial projections available from these datasets served as inputs for our planning exercises to identify the most beneficial management strategies across the reserve. For biodiversity, we used projections of climatic (Campos et al., 2021) and habitat (Campos et al., 2022) suitability in the Biosphere Reserve obtained from species distribution models (SDMs) for 207 species (168 birds, 24 reptiles and 15 amphibians; see Table S1 for the detailed list of species). SDMs statistically correlate the occurrence of species to the environmental conditions they experience, allowing predictions of their distribution under future changes. The projections of climatic suitability under RCP 4.5 and 8.5 were combined with the projections of habitat suitability under each management strategy to identify areas both climatically and environmentally suitable for each species under each management strategy and RCP. For ecosystem services, we obtained projections under each of the management strategies for carbon sequestration rates (Campos et al., 2022), agricultural surface, avoided soil erosion and recreation potential (Cánibe et al., 2022). The selection of these ES is justified by their local relevance, as they are key in the socio-economy of the study area, based on sustainable practices, tourism and the carbon market. Lastly, given that climate and land use change affect fire regimes potentially increasing the frequency of extreme and uncontrollable wildfires (Turco et al., 2019), we used Fire Hazard as a penalty factor to be minimised within the 'prioriactions' objective function. Fireline intensity (kW m-1) under each management strategy and RCP (Cánibe et al. 2022) was used as surrogate of potential fire hazard. These projections use fuel models specific for Portugal (Fernandes et al., 2009) and assume that fires occur under extreme conditions of dry and windy weather. Fuel moisture content plays an important role in determining fire behaviour and responds to temperature and relative humidity (Matthews, 2014), while wind speed is crucial in determining the fire rate of spread (Cruz and Alexander, 2019). Given the complexity of modeling and projection spatial features in this research, we provide a summary of the data used in Table 2 and all technical details in Table S2.

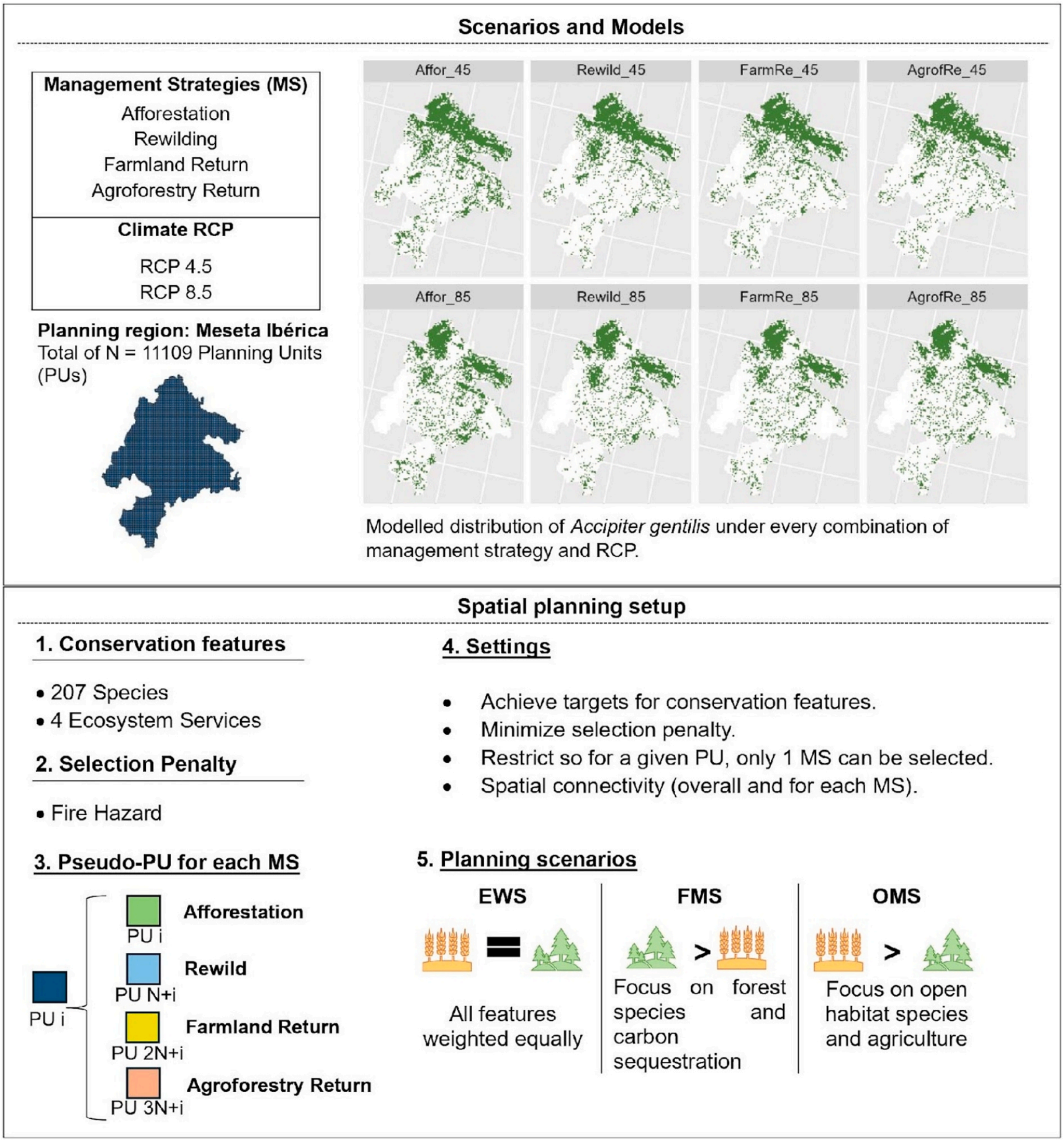

Fig. 2. Schematic workflow of the study. Using alternative land cover maps for 2050 simulating different management strategies, together with climate predictors under 2 representative concentration pathways (RCP), we obtained the modelled distributions of 207 species, 4 ecosystem services and fire hazard, under each management strategy combined with both RCP. These distributions were used as inputs for spatial planning. Planning Units (PU), which contain information on which features are present in each 1 km^2 cell, were replicated 4 times, to provide information of distributions under each management strategy, and then restricted so each PU could only be selected once. We ran 3 scenarios with increased targets for different groups of features. RCPs were analysed separately.

2.5. Spatial planning scenarios

In order to explore the sensitivity of our framework to different management objectives, we tested three planning scenarios using different sets of objectives: a first planning scenario representing an equilibrium between conservation efforts for all species and ecosystem services (*Equally Weighted Scenario;* EWS), a second planning scenario conveying management priorities aiming to facilitate establishment and conservation of forest dwelling species and to improve ecosystem services associated with forests, e.g.,climate regulation (*Forest Maximising Scenario*; FMS) and a third planning scenario conveying management priorities aiming to facilitate the relocation or expansion of agricultural land and open habitat as well as the establishment and conservation of open habitat species (*Open Maximising Scenario;* OMS). To carry out the spatial prioritisation of management strategies under each of these three planning scenarios, we classified each species into five classes according to its habitat preference: Forest, Open, Semi-Open, Wetlands and Generalist (Table S1). In this application, we established targets for the Equally Weighted Scenario according to the extent of suitable area for each species in initial model projections for 2005, keeping moderate targets for the more widespread species while increasing targets for rare species to almost their full distribution area (Table S3), following the rationale that rarer species are in more direct need of conservation efforts. We established a target of 60 % of the supply of ecosystem services

Table 2
Summary description of spatial data inputs used in the planning exercise.

Data	Method	Source
SDMs (Climate suitability)	Presence/absence maps derived from projections of climate suitability in 2050 for 207 species derived from SDMs built using climate predictors. Four climate models were used to account for model variability. Projections were obtained under RCP 4.5 and 8.5.	Campos et al., (2021)
SDMs (Habitat suitability)	Presence/absence maps derived from projections of habitat suitability in 2050 for 207 species derived from SDMs using land cover and topographic predictors. Projections were obtained for each management strategy and replicate considered in this study.	Campos et al., (2022)
Food supply	Agricultural surface obtained from land cover maps (Maes et al., 2011; Cabral et al., 2016).	Cánibe et al., (2022)
Climate Regulation	InVEST Carbon Storage module (Sharp et al., 2020), using four carbon pools in major land cover classes: aboveground and belowground biomass, soil organic carbon and dead organic matter (Sil et al., 2017).	Campos et al., (2022)
Soil retention	Calculated as the difference between the structural impact (the erosion that would occur when vegetation is absent and therefore no service is provided) and the soil erosion in the presence of vegetation. Calculations were done by applying the Revised Universal Soil Loss Equation following Guerra et al. (2014).	Cánibe et al., (2022)
Recreation	Recreation potential modelled following the Zulian et al. (2013) model for nature-based recreation using lookup tables to assign ES scores to land cover classes based on cross-tabulation from different input layers.	Cánibe et al., (2022)
Fire Hazard	Application of the FlamMap5 software (Finney et al. (2015) to obtain projections of Fireline Intensity (kW m^{-1}) reclassified into five fire danger classes according to Alexander & Lanoville (1989). Fires were modelled under severe conditions of dry and windy weather, expected to be more common under climate change. Custom fuel models for Portugal were used for each land cover class (Fernandes et al, (2009).	Cánibe et al., (2022)

in 2005. Whenever needed, we modified targets to ensure that they were achievable (i.e. avoiding targets higher than the amounts available in the projections). For the *Forest maximising* planning scenario, we doubled the representation targets of the more widespread Forest-dwelling species, affecting a total of 32 species, including birds of prey like *Accipiter nisus, Accipiter gentilis* or *Bubo bubo,* various forest-dwelling passerines like *Dendrocopos major, Phoenicurus phoenicurus,* or *Spinus spinus*. We also increased the target for the carbon sequestration ES. For the *Open maximising* planning scenario, we doubled the representation targets for the Open and Semi-Open habitat species, affecting a total of 45 species, including birds of prey like *Aquila chrysaetos, Circus cyaneus* or *Falco peregrinus,* many open habitats passerines like *Alauda arvensis* or *Emberiza cia,* and reptiles like *Anguis fragilis, Coronella austriaca* or *Lacerta schreiberi*, as well as the food provision ES. The other species and ES were left unmodified in all planning scenarios as they are not specific management priorities of the planning scenarios. Instead, for these species and ES, we established a moderate representation target in all planning scenarios.

2.6. Spatial planning framework

We used the ‘prioriactions’ R package (Salgado-Rojas et al., 2023) to prioritise the spatial allocation of management strategies within the reserve. ‘Prioriactions’ uses data on the spatial distribution of conservation features (biodiversity and ecosystem services) and penalties (fireline intensity) to identify the optimal allocation of management strategies subject to fulfilling all user-defined targets while minimising penalties and accounting for connectivity. To prioritise a combination of management strategies simultaneously, we included estimates of their consequences (e.g., change in the distribution of each species, habitat and ecosystem services if every planning unit was under each of the four management strategies) and their associated fire hazard projections (e.g., how fire hazard would be increased or reduced by each of the four management strategies) in the same planning exercise. Therefore, for each 1-km resolution grid cell in which the study area was divided, there are four different estimates of benefits for biodiversity and fire hazard, each depicting the situation if that grid cell was allocated under each of the four management strategies (Afforestation, Rewilding, FarmReturn and Agroforestry Return). The model that ‘prioriactions’’ solves can be specified as follows:

$$minimise : z^{*}min\sum\nolimits_{i\in I}\sum\nolimits_{k\in K}c_{ik}x_{ik} + blm\sum\nolimits_{i\in I}\sum\nolimits_{j\in I}cv_{ij}x(1-x_{jk}) \quad (1)$$

$$s.t.\sum\nolimits_{i\in I}b_{is}(x) \geq t_s, \forall s \in S \quad (2)$$

$$\sum\nolimits_{k\in K}x_{ik} \leq 1, \forall i \in I \quad (3)$$

$$x_{ik} \in \{0,1\}, \forall i \in I, \forall k \in K \quad (4)$$

where I is the set of planning units, K is the set of management strategies and S is the set of features, c_{ik} is the cost of planning unit i managed under management strategy k, x_{ik} is a binary variable such that $x_{ik} = 1$ if the unit i is managed under management strategy k and $x_{ik} = 0$ otherwise. The second term of Equation (1) measures the connectivity penalty, where *blm* (boundary length modifier) is a user defined weight parameter (set at 0.5 in this study) and cv_{ij} is a penalty calculated as the inverse of the distance between each pair of grid cells i and j, favouring the spatial aggregation of grid cells in the solution. The first constraint (Equation (2) ensures that the benefit b_{is} for any given feature in the solution is equal or higher than the representation target t_s. Equation (3) is an additional restriction that was manually added to the model for this study, indicating that each PU can only be subjected to one management strategy at a time. Equation (4) defines x_{ik} as a binary variable for any combination of unit i and management strategy k. Complete details on the formulation of the mathematical model can be found in Salgado-Rojas et al. (2020). We ran independent spatial prioritisation analyses for each of the 10 replicates available for each of the three planning scenarios and two climate change scenarios (60 different prioritisation exercises = 10 land use replicates x 3 planning scenarios x 2 climate change scenarios). As stopping criteria for the model, we specified a solution with a gap below 2 % of the optimal solution found or, if that gap was not reached, a running time of 1 h. The best solution found within each combination of land use change and planning scenario was selected for comparison purposes.

2.7. Analysis of ‘prioriactions’ outputs

The optimal integration of management strategies under each planning scenario was analysed in different ways. First, we compared the number of planning units allocated to each management strategy, as well as the extent of each land cover in each resulting solution, summarising the spatial outputs for the 10 replicates of each management strategy using boxplots, as well as applying an analysis of variance (ANOVA) to test if the number of PUs was different between management strategies, planning scenarios and RCPs. Given how the management strategies were set up in Prioriactions, all areas of the Meseta Ibérica required to meet the conservation targets were assigned one of the four management strategies. However, this does not always translate to land cover changes, as in fact most of the landscape of the Meseta Ibérica remains unmodified in our 2050 projections. Therefore, we evaluated the spatial differences in management strategy allocation between climate RCPs and planning scenarios by using selection frequency. Selection frequency summarises the spatial information of the replicates in a single map per management strategy, showing in how many replicates a given PU was allocated to a given management strategy, this allowed us to identify key areas for each management strategy, where land cover drives changes in the spatial distribution of biodiversity and ecosystem services. To assess possible trade-offs or management conflicts, we looked at how species distributions (grouped by their habitat preference) were represented under management strategies for each planning scenario and RCP. This analysis was also repeated for each ecosystem service. Finally, we compared the mean cost of planning units allocated to each management strategy to assess the degree to which each management strategy can secure management targets while under minimal fire hazard.

3. Results

3.1. Extent and spatial distribution of management strategies

All 'prioriactions' runs found a solution that achieved all conservation targets for biodiversity and ecosystem services with a gap below 2 % from the upper bound of the optimal solution. The ANOVA revealed strong differences between the number of PUs allocated to each management strategy ($p < 0.001$), with weaker, although still significant, differences across the total number of PUs required between RCPs ($p < 0.05$) and a non-significant difference across planning scenarios. The ANOVA also revealed that the difference in the number of PU allocated to each management strategy was modulated by second order interactions with RCPs and planning scenarios separately, as well as by a third order interaction effect among the three, thus revealing a complex relationship. For the EWS, the extent of Afforestation, Rewilding and Farmland Return were similar, while Agroforestry Return, had lower extents in both RCPs (Fig. 3). Solutions for the FMS allocated a higher amount of planning units to Afforestation under both RCPs at the expense of PUs allocated to Rewilding and Farmland Return, especially under RCP 4.5, where Agroforestry Return and not selected areas had very similar extents as in the EWS. The OMS under RCP 4.5 led to higher extents of Rewilding, Farmland Return and Agroforestry Return in comparison to the other spatial planning scenarios while Afforestation decreased, also requiring a larger overall extent to achieve conservation targets. For the OMS under RCP 8.5, the increase in Rewilding was higher and not coupled with increases in Farmland and Agroforestry Return. The changes in management alternative extents were associated with changes in the resulting land cover (Fig. 4). The total number of PUs that experienced a change in land cover in comparison to 2018 varied between 7.435 % and 15.419 %, with mean 10 ± 1.7 % for RCP 4.5 and 13.1 ± 1.2 % for RCP 8.5. For planning scenarios mean change rates were 11.7 ± 2.17 % for the EWS, 12.3 ± 1.89 % for the FMS and 10.6 ± 2.08 % for the OMS. Differences in total percentage of change were significant both for RCP and planning scenarios ($p < 0.001$). Agriculture was promoted when the extent of Farmland Return was higher, under OMS-RCP 4.5 and EWS-RCP 8.5. Coniferous and Deciduous forests were promoted under FMS, which had more Afforestation areas. Agroforestry was highest under OMS-RCP 4.5, the scenario with more Agroforestry Return and Shrublands were promoted under OMS in both RCPs, when Rewilding was higher (Fig. 4).

The selection frequency of management strategies in the different replicates showed that some areas of the reserve were assigned the same management strategy with consistency (hereafter 'focal areas'), with some notable differences between planning scenarios and RCPs. Under the EWS (Fig. 5) these focal areas were well differentiated across the Meseta Ibérica and were similar under both RCPs for Afforestation and Rewilding, while Farmland Return and Agroforestry focal areas were reallocated in RCP 8.5. Under the FMS, the focal areas of Afforestation

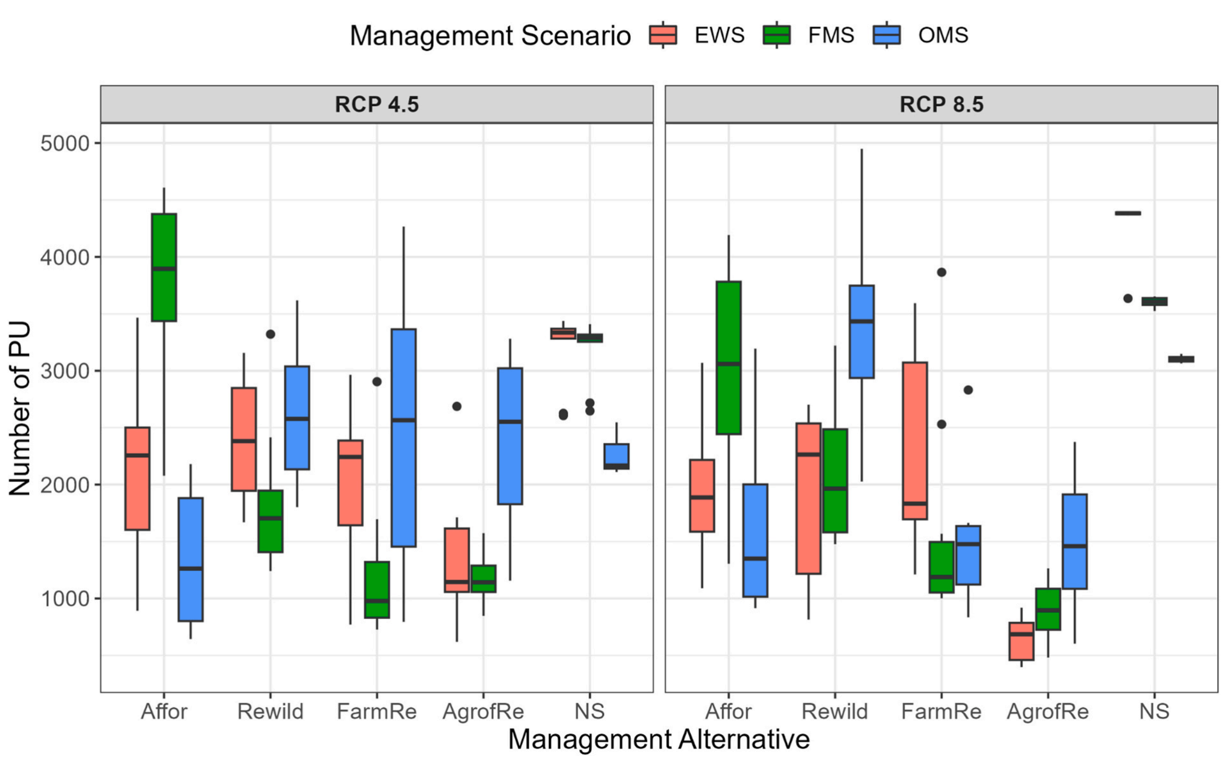

Fig. 3. Number of 1-km^2 planning units allocated to each management strategy per management and climate (RCP) scenario. "Affor": Afforestation; "Rewild": Rewilding; "FarmRe": Farmland Return; "AgrofRe": Agroforestry Return; "NS": Not Selected, "EWS": Equally Weighted Scenario, "FMS": Forest Maximising Scenario, "OMS": Open Maximising Scenario. Boxplots aggregate results of 10 replicates per management strategy. Lower and upper hinges of the boxplots correspond to the first and third quartiles (Q1 and Q3), while the horizontal line inside the box represents the median. Lower whisker represents data at Q1 – 1.5 * IQR and upper whisker represents data at Q3 + 1.5 * IQR. Data beyond that range are considered outliers and are represented individually with points.

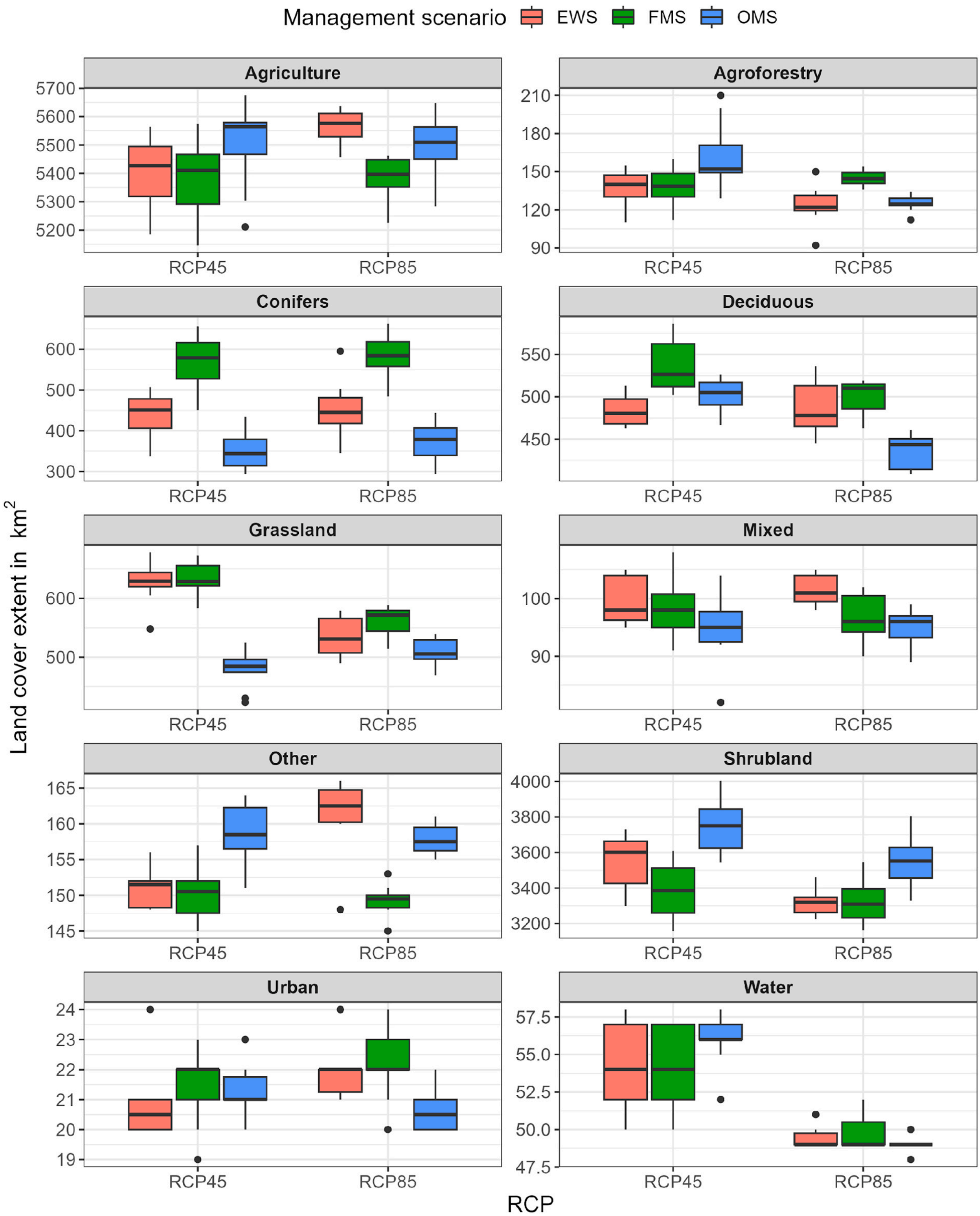

Fig. 4. Extent of each land cover class resulting from the spatial arrangement of management strategies under each planning and climate scenario. "EWS": Equally Weighted Scenario, "FMS": Forest Maximising Scenario, "OMS": Open Maximising Scenario. Boxplots aggregate results of 10 replicates of each management strategy. Lower and upper hinges of the boxplots correspond to the first and third quartiles (Q1 and Q3), while the horizontal line inside the box represents the median. Lower whisker represents data at Q1 – 1.5 * IQR and upper whisker represents data at Q3 + 1.5 * IQR. Data beyond that range are considered outliers and are represented individually with points.

were much larger under both RCPs (Fig. 6), while the focal areas of the other 3 management alternatives remained stable compared to the EWS. For the OMS, the focal areas for Rewilding replaced some of the focal areas for Afforestation in the EWS and FMS, especially under RCP 8.5 in the northeastern part of the reserve (Fig. 7). The spatial arrangements of land cover classes in the resulting land cover maps show that these focal areas drive important patterns of land cover change associated with each management strategy. Focal areas for Afforestation show areas of conversion to Conifers and Deciduous Forest, and the same happens for Shrubland in Rewilding areas, Agriculture in Farmland Return areas and

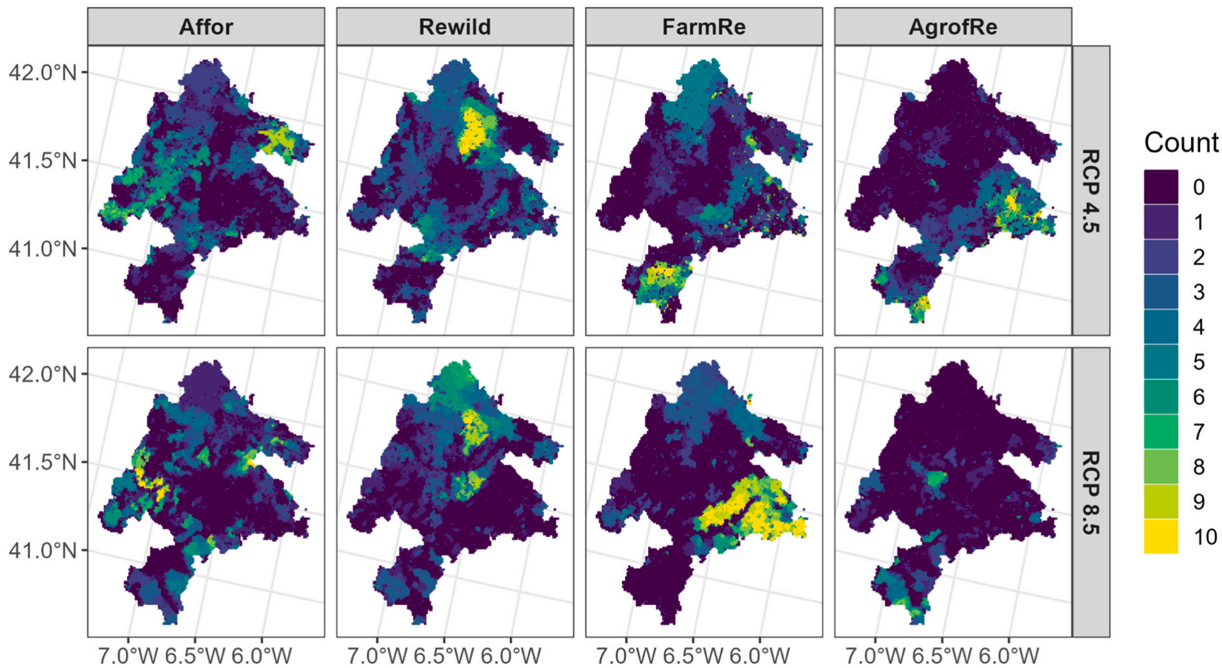

Fig. 5. Selection frequency of planning units across the 10 'prioriactions' runs for four management strategies and two climate scenarios (RCPs 4.5 and RCP 8.5) under the Equally Weighted planning scenario. "Affor": Afforestation; "Rewild": Rewilding; "FarmRe": Farmland Return; "AgrofRe": Agroforestry Return.

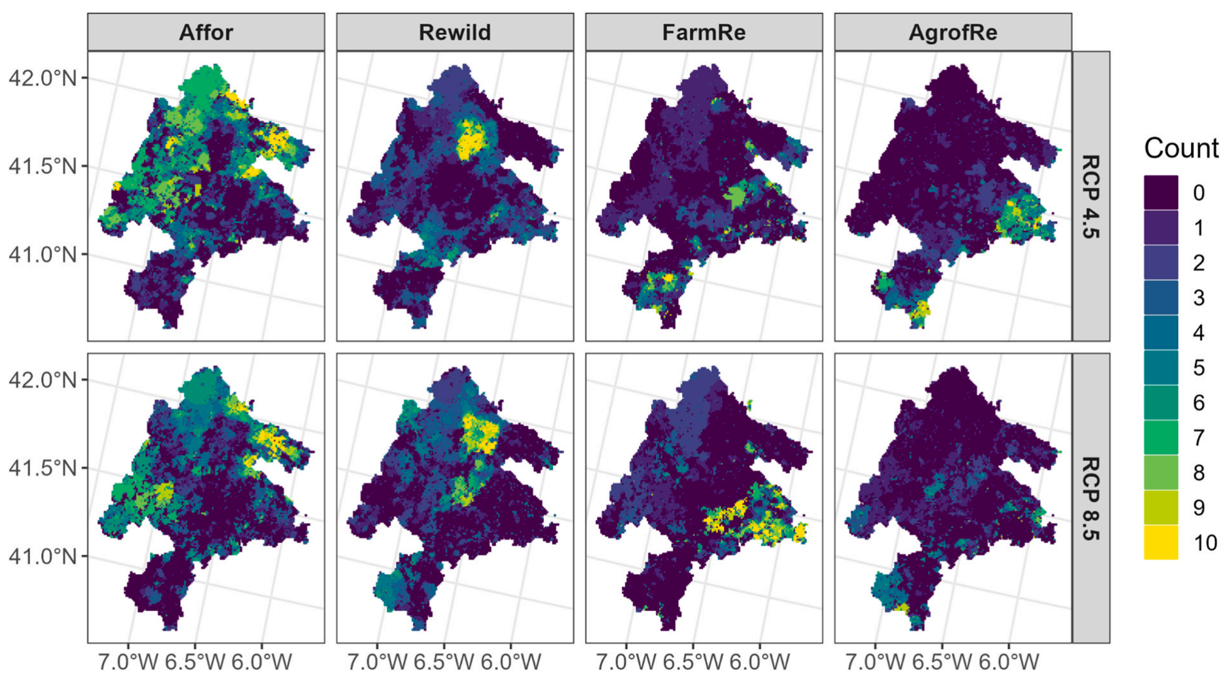

Fig. 6. Selection frequency of planning units across the 10 'prioriactions' runs for four management strategies and two climate scenarios (RCPs 4.5 and RCP 8.5) under the Forest Maximising planning scenario. "Affor": Afforestation; "Rewild": Rewilding; "FarmRe": Farmland Return; "AgrofRe": Agroforestry Return.

Agroforestry in Agroforestry return areas (Supplementary Material 4).

3.2. Feature coverage under climate change and planning scenarios

The extent of species distributions falling under each of the management strategies (Fig. 8) showed interesting patterns when comparing planning scenarios and RCPs. Species with preference for forested habitats were mainly distributed within areas allocated to Afforestation, especially under the FMS, while many of them were covered under areas allocated to other management strategies under the OMS. Generalist and Wetland species were distributed in areas allocated to all management strategies, although more species were distributed in Afforestation PUs under the FMS and in Rewilding PUs under the OMS, especially in RCP 8.5. Open and Semi-Open habitat species were mostly distributed in areas allocated to Rewilding and Farmland Return under the EWS and OMS planning scenarios, although under the FMS these species were distributed in areas allocated to Afforestation. Regarding ecosystem services, most agricultural land would be placed under Afforestation and Farmland Return, with Agroforestry Return covering more agricultural area under the OMS instead of Afforestation. Carbon sequestration was

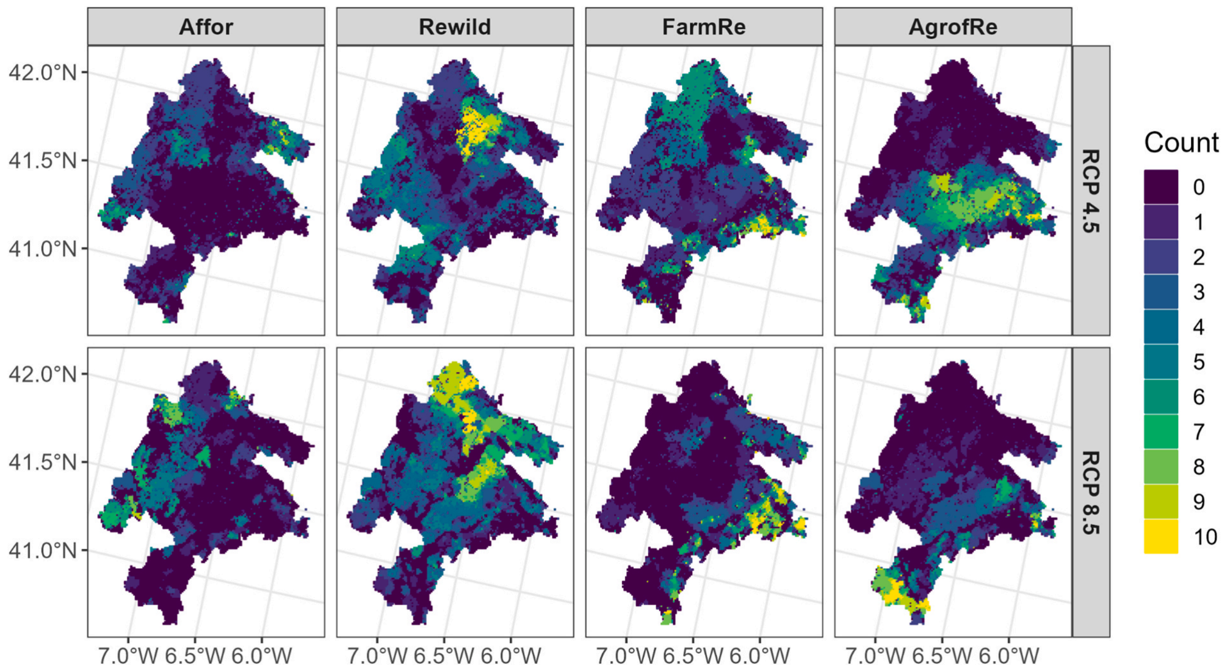

Fig. 7. Selection frequency of planning units across the 10 'prioriactions' runs for four management strategies and two climate scenarios (RCPs 4.5 and RCP 8.5) under the Open Maximising planning scenario. "Affor": Afforestation; "Rewild": Rewilding; "FarmRe": Farmland Return; "AgrofRe": Agroforestry Return.

mostly represented in Afforestation or Rewilding areas, depending on the planning scenario (Fig. 9). Erosion control was shared among all management strategies in the EWS and OMS scenarios, whereas it was mostly represented in Afforestation in the FMS. Lastly, areas with higher recreation potential varied among planning scenarios, with an increase in Afforestation areas in the FMS and in Farmland Return areas in the OMS.

3.3. Fire hazard

Fire hazard showed differences between management strategies, with Rewilding always having the highest fire hazard under all climate and planning scenarios. Under RCP 4.5, Afforestation, Farmland Return, and Agroforestry Return showed similar fire hazards, with Afforestation being slightly higher under the FMS (Fig. 10). Under RCP 8.5, however, Agroforestry Return showed higher fire hazards than Afforestation and Farmland Return, which was always the lowest. The greatest contrast between management strategies were found under the RCP 8.5 FMS (Fig. 10), where Farmland Return showed the lowest fire hazard in comparison to any other management strategy, while Afforestation and Agroforestry Return showed increases in comparison to the EWS and OMS scenarios (Fig. 10).

4. Discussion

In this study, we showcase how the integration of different landscape management strategies into spatial planning provides a novel framework to harmonise biodiversity conservation with other management goals (Sil et al., 2016, Turkelboom et al., 2018). Our approach prioritises the spatial allocation of a mix of management strategies based on their adequacy and effectiveness to meet the established management goals under different policy and climate change scenarios. This spatial combination allowed us to identify areas of the reserve where each management strategy would be translated into land cover transitions that would enhance habitat suitability and ecosystem service supply under climate change. This approach is, therefore, valuable for identifying optimal management solutions in areas where different management strategies can or must coexist in space (Palliwoda et al., 2021), such as Biosphere Reserves. With the increasing availability of modelling data and the ease of use of modelling tools, the approach presented here can be adapted and applied in other areas, if future applications consider management strategies, features and penalties suitable to their study area, providing a novel tool to address other planning problems aiming to develop multifunctional landscapes.

Previous research on management strategies has shown that changes in land use will impact ES supply and species distributions in different ways, leading to unavoidable trade-offs depending on which land uses and policies are prioritised (Campos et al., 2022; Morán-Ordóñez et al., 2020). Most of these studies compare scenarios that depict the implementation of policies focused on either conservation or production and economic development objectives, with clear winners and losers in each of them (Wang et al., 2018; Kabaya et al., 2019; Li et al., 2020; Gomes et al., 2021). However, Felipe-Lucia et al., (2022) found that scenarios depicting a combination of both conservation and production policies led to less overall losses. Our approach allowed a combination of management strategies that achieved management targets similar to when planning under a single strategy (Cánibe et al., 2022). This combination optimally allocated in space where each strategy should be implemented to achieve the targets and minimise potential trade-offs. Recent landscape changes in regions of the Meseta Ibérica Biosphere Reserve show that agricultural abandonment might be declining, and that the landscape is heading towards a diversification of land uses (Imbrechts et al., 2024). Our approach does not imply total land cover turnover, but rather a facilitation of specific land cover transitions at sustainable rates. Therefore, it could aid in this transition towards diversification by identifying the most suitable areas to promote specific land use changes in a way that would derive benefits for climate regulation capacity and high potential for long term biodiversity conservation (Pais et al., 2020). Our spatial planning scenarios show how different overall management interests in the Meseta Ibérica translate into different spatial management strategies. In most cases, the key areas for each management strategy do not overlap, with the notable exception of the Natural Parks of Montesinho, in Portugal, and the Sanabria lakes and mountain ranges of Segundera and Porto, in Spain, both located in the higher altitude regions of the Reserve. These areas became key for both forest and open habitat species when increasing their conservation targets, implying that

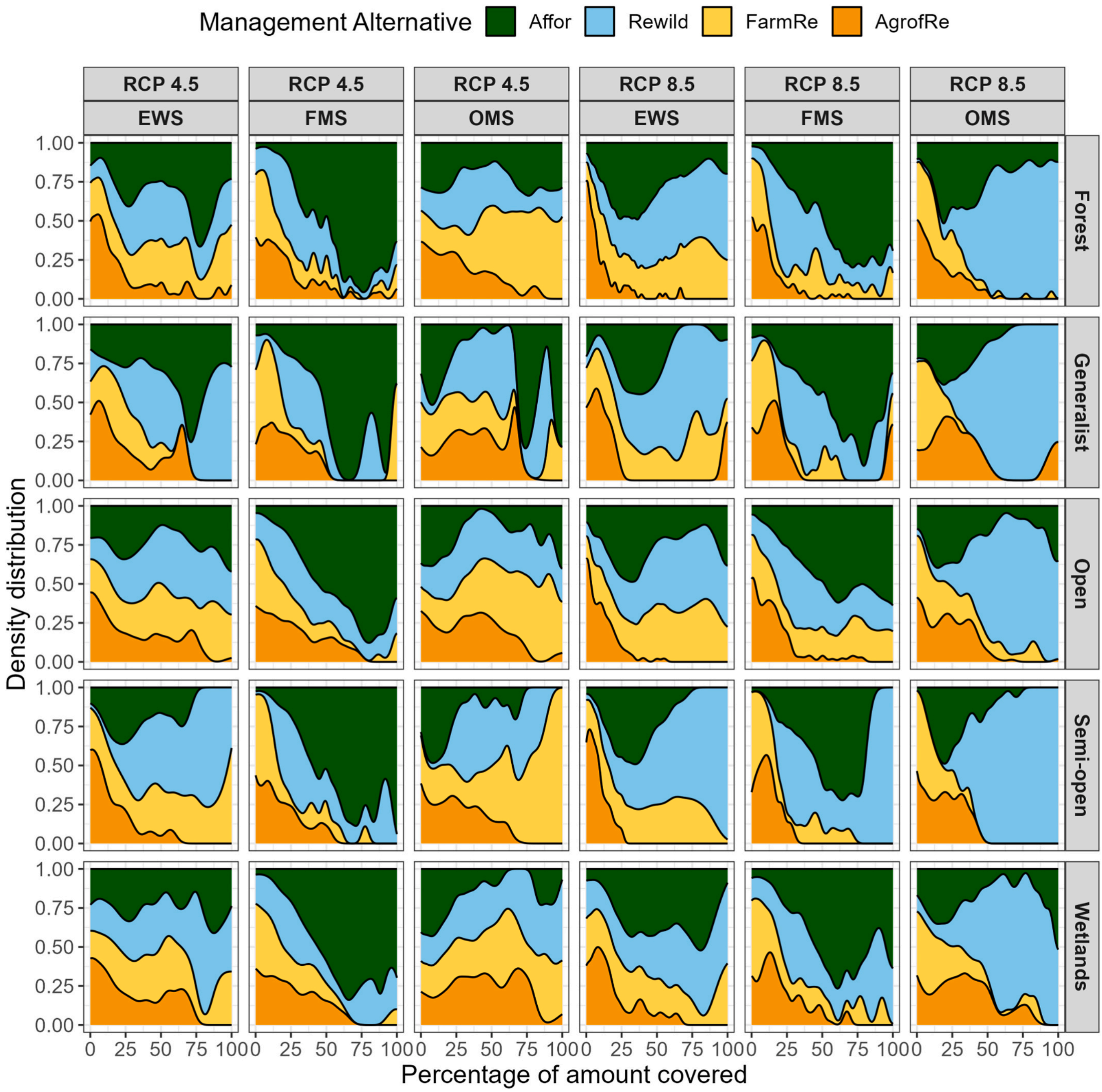

Fig. 8. Kernel density distribution plots representing density estimates associated with the percentage of species coverage by management strategies based on habitat preference. Data is grouped by habitat (rows) and Representative Concentration Pathways (RCP) and planning scenario (columns). "EWS": Equally Weighted Scenario; "FMS": Forest Maximising Scenario; "OMS": Open Maximising Scenario.

as climate change causes distributional shifts towards higher elevations for many species, habitat suitability may become a limiting factor (Kelly & Goulden, 2008; Tellería, 2020; Sillero, 2021). Maximising either forest or open habitat biodiversity and ES would lead to one or two management strategies dominating the landscape, increasing potential trade-offs with other management goals and potentially causing long term impacts. For example, previous afforestation trends in the area have focused on increasing coniferous forest cover, with *Pinus pinaster* as a dominating species, increasing the fire-proneness of forests, thus threatening forest biodiversity and the supply of ecosystem services provided by these ecosystems (Anderegg et al., 2020). Future management in the area should aim to reverse these trends by giving more importance to afforestation and conservation of sclerophyllous woodlands of *Quercus rotundifolia*, increasing landscape heterogeneity and decreasing fire spread potential (Sil et al. 2024). A focus on open habitats would also lead to long term risk derived from the fire proneness of dry shrublands, as well as the potential negative impacts of agriculture like soil degradation, increased water consumption and reduced habitat connectivity (Pereyra et al., 2020; Villarino et al., 2017). Biodiversity and services distribution under our scenarios highlight the need for integrated management practices that support diverse land cover types and habitats.

On a more technical aspect, our framework incorporates current advances and guidelines in conservation planning to provide quality

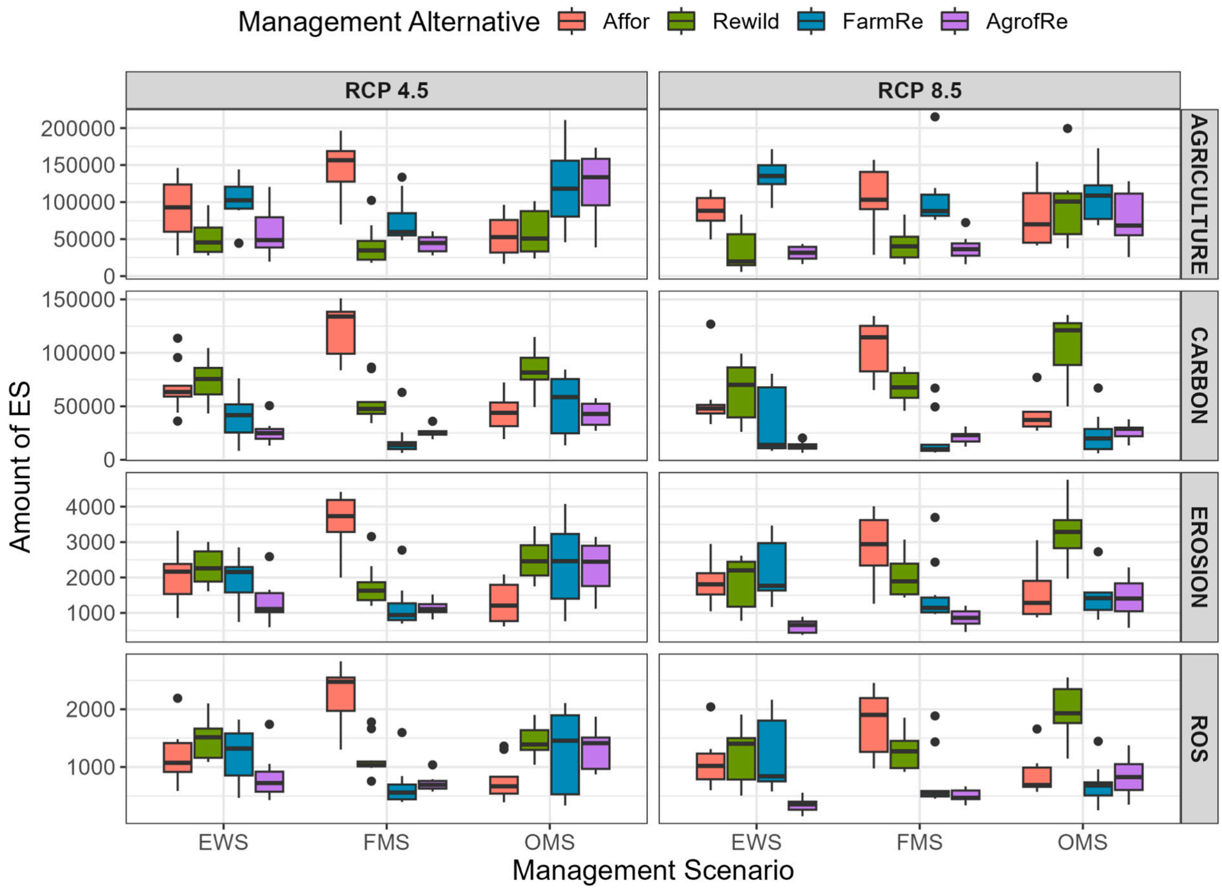

Fig. 9. Amounts of each ecosystem service (rows) distributed under each of the management strategies under each Representative Concentration Pathway (columns) and planning scenario (X-axis) "Affor": Afforestation; "Rewild": Rewilding; "FarmRe": Farmland Return; "AgrofRe": Agroforestry Return; "EWS": Equally Weighted Scenario; "FMS": Forest Maximising Scenario; "OMS": Open Maximising Scenario. Boxplots aggregate the results for the 10 replicates of each planning scenario and RCP. Lower and upper hinges of the boxplots correspond to the first and third quartiles (Q1 and Q3), while the horizontal line inside the box represents the median. Lower whisker represents data at Q1 − 1.5 * IQR and upper whisker represents data at Q3 + 1.5 * IQR. Data beyond that range are considered outliers and are represented individually with points.

information to decision-makers. To account for model variability and stochasticity, we addressed uncertainty at various levels by using ensemble models for biodiversity (Buisson et al., 2010, Beale & Lennon, 2012), replicates for the management strategies and ensembles of climate models (Thuiller et al., 2019). Acknowledging uncertainty enhances the utility of modelling data for identifying priority monitoring areas and gauging species distribution changes, facilitating adaptive and dynamic management (Grantham et al., 2010, Porfirio et al., 2014). Regarding our choice of planning tool, novel planning tools using exact solving methods such as the 'prioriactions' R package (Salgado-Rojas et al., 2023) can solve increasingly complex problems. 'Prioriactions' has been successfully applied to spatially prioritise management involving thousands of species and habitats ad hundreds of pressures at continental scale, enhancing the applicability and scalability of our approach (Hermoso et al., 2022).

Future applications could enhance the framework by including more features, such as additional taxonomic groups (e.g., mammals, plants, invertebrates, fungi), as well as a higher diversity of ecosystem services, ideally including an economic valuation. More provisioning ecosystem services, such as forest production, hunting or infrastructures for renewable energy sources would help better assess the trade-offs that would arise from securing a higher service supply in the area (Morán-Ordóñez et al., 2020). The impact of global change on ES would be better assessed by including the effects of climate change on ES provision and supply (Mooney et al., 2009, Weiskopf et al., 2020). The results presented here only aimed to demonstrate how to plan for integrated management at landscape scale. However, future applications would benefit from including additional constraints, not considered here for the sake of clarity, such as land tenureship, policy, or the pre-existence of management plans that already constrain the suitable management options (e.g., presence of protected areas with restrictive management plans), which would derive recommendations that better fit the management reality of each case. Finally, the successful implementation of management recommendations provided by decision support tools, such as 'Prioriactions', can be enhanced not only by better data but also a strong integration of decision-makers in the planning process, so that the limitations and opportunities presented by stakeholders are acknowledged throughout the whole planning process.

5. Conclusions

The present study develops a novel framework for spatial planning that allows the combination of scenarios that represent the implementation of different landscape management strategies. These management strategies are allocated to different areas according to where they would be most effective to meet management goals. Using this approach, we showed that the Meseta Ibérica Transboundary Biosphere Reserve can accommodate different management strategies to address different environmental and socioeconomic challenges while supporting biodiversity conservation and ecosystem services. The Reserve holds a variety of habitats that allow planning towards balanced conservation efforts between different groups of species and ecosystem services, but

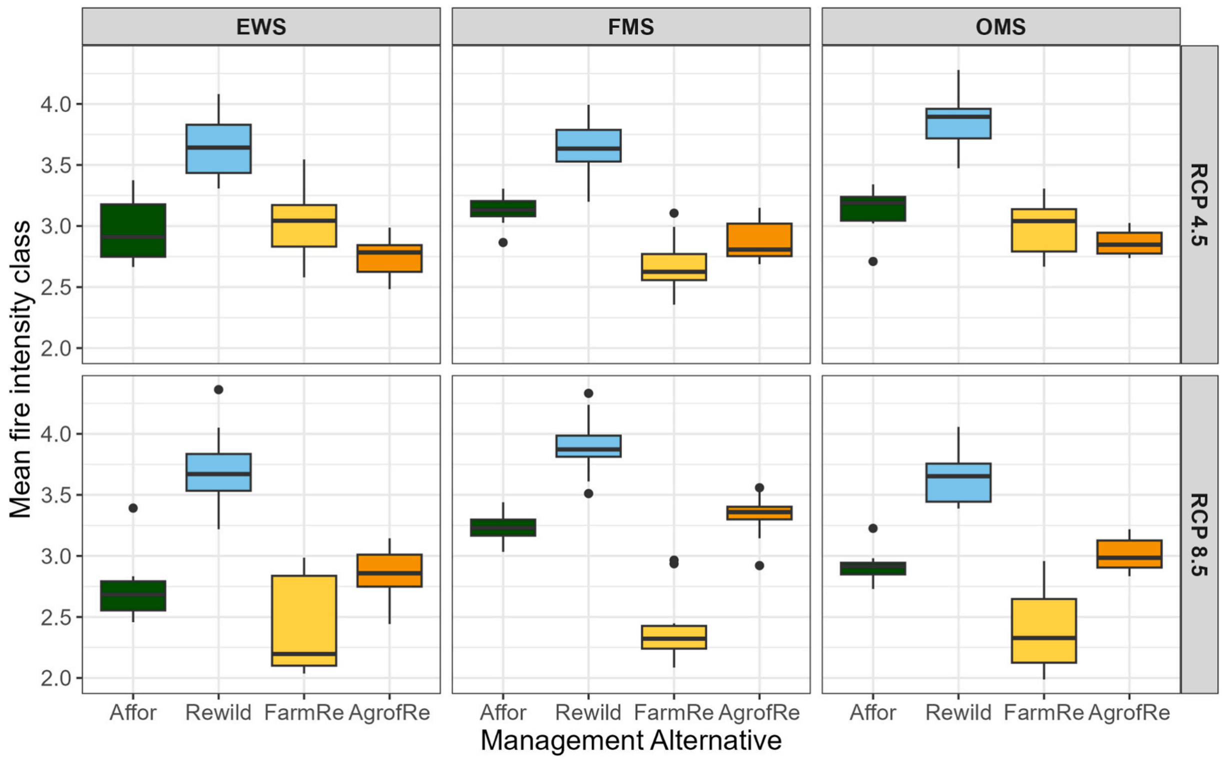

Fig. 10. Mean fire intensity in 1-km^2 planning units allocated to each management strategy across all 10 replicates per planning and climate (RCP) scenario. "Affor": Afforestation; "Rewild": Rewilding; "FarmRe": Farmland Return; "AgrofRe": Agroforestry Return; "EWS": Equally Weighted Scenario; "FMS": Forest Maximising Scenario; "OMS": Open Maximising Scenario. Boxplots aggregate results of 10 replicates per management strategy. Lower and upper hinges of the boxplots correspond to the first and third quartiles (Q1 and Q3), while the horizontal line inside the box represents the median. Lower whisker represents data at Q1 – 1.5 * IQR and upper whisker represents data at Q3 + 1.5 * IQR. Data beyond that range are considered outliers and are represented individually with points.

heavily prioritising certain species of ecosystem services might lead to conflicts. Adequate planning and careful implementation of management strategies are paramount to sustainably develop the Meseta Ibérica Transboundary Biosphere Reserve into a resilient landscape with high potential for socioeconomic development, climate regulation and biodiversity conservation, even under uncertain future climate conditions.

CRediT authorship contribution statement

Miguel Cánibe Iglesias: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Virgilio Hermoso:** Supervision, Conceptualization, Writing – original draft, Writing – review & editing. **João C. Azevedo:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **João C. Campos:** Writing – review & editing, Writing – original draft, Supervision. **José Salgado-Rojas:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Ângelo Sil:** Writing – review & editing, Methodology, Conceptualization. **Adrián Regos:** Supervision, Conceptualization, Writing – original draft, Writing – review & editing.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2025.101742.

Data availability

Data will be made available on request.

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