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Research article

Exploring the effects of protected area networks on the European land system

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ABSTRACT

The European Union's Biodiversity Strategy for 2030 seeks to protect 30% of land, with 10% under strict protection, while building a transnational nature network. We explore the effects of the Biodiversity Strategy targets for land use and ecosystem services across the European land system. To do so, we propose a novel approach, combining a methodological framework for improving green network connectivity with an EU-wide land system model. We identify an improved network of EU protected areas consistent with the 2030 targets, and explore its effects under different levels of protection and in a range of paired climatic and socio-economic scenarios. The existing network of protected areas is highly fragmented, with more than one third of its nodes being isolated. We find that prioritizing connectivity when implementing new protected areas could achieve the strategy's targets without compromising the future provision of ecosystem services, including food production, in Europe. However, we also find that EU-wide distributions of land uses and ecosystem services are influenced by the protected area network, and that this influence manifests differently in different climatic and socio-economic scenarios. Varying the strength of protection of the network had limited effects. Extractive services (food and timber production) decreased in protected areas, but non-extractive services increased, with compensatory changes occurring outside the network. Changes were small where competition for land was low and scenario conditions were benign, but became far larger and more extensive where competition was high and scenario conditions were challenging. Our findings highlight the apparent achievability of the EU's protected area targets, but also the need to account for adaptation in the wider land system and its consequences for spatial and temporal patterns of ecosystem services provision now and in the future.

1. Introduction

Protected Areas (PAs) are a key tool to address biodiversity loss. PAs are spatially defined and legally managed areas for the long-term conservation of nature with related ecosystem services and cultural values (Dudley, 2008). The main goals of PAs are to safeguard habitats and species, and to maintain essential ecological processes supporting life and the delivery of ecosystem services. PAs also play an increasing role in climate change policies and strategies, reflecting the strong links between ecosystem functioning, nature's contributions to people, and nature-based solutions (EEA, 2021). The EU's Biodiversity Strategy for 2030 set a target of protecting 30% of land, with 10% under strict protection that leaves natural processes essentially undisturbed (EC, 2020a). The 2022 UN Biodiversity Conference (COP15) adopted a similar target of protecting 30% of land by 2030 (UNEP, 2022).

However, the rapid continued loss of biodiversity despite increasing PA extent underlines the danger of assuming that protection alone is sufficient (Butchart et al., 2015; Kearney et al., 2020; Visconti et al.,

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2019). One of the main ways to improve PA effectiveness is through better connectivity (Hilty et al., 2020). The maintenance of intact, healthy, well-functioning and diverse ecosystems that support species and natural processes is severely impeded in fragmented environments (Damschen et al., 2019; Saura et al., 2014). The establishment of connections among PAs facilitates ecological flows and offers secure habitat refuges. Moreover, PAs that link across different spatial scales, have various dimensions, and are heterogeneously distributed, can bridge various network levels and play intermediate roles between local green networks and surrounding regional, national and international networks (Cumming et al., 2015; Langemeyer and Baró, 2021; Zulian et al., 2021). This also enables PAs to provide robust adaptation options as climate change shifts the distributions of species and habitats (Elsen et al., 2020).

Many policies now prioritise the connectedness of PAs for biodiversity conservation goals, ecosystem service provision, and climate change adaptation (CBD, 2021). The EU Biodiversity Strategy stresses the need for a coherent and resilient Trans-European Nature Network (EEA, 2020a). Together with PAs, Europe is investing in Green Infrastructure (GI) networks in the GI Strategy, the EU Green Deal, the Strategy for Sustainable Food Systems and research funding programs (EC, 2013, 2019; 2020b, 2021). GI networks link natural and semi-natural areas, and are strategically designed to deliver multiple ecosystem services, protect biodiversity, and enhance natural capital. Only around 7–10% of global protected land can be considered connected (Saura et al., 2017, 2018, 2019; UNEP-WCMC, 2020; Ward et al., 2020), but European PAs have relatively good connectivity, especially for long-distance dispersal and transboundary connections (Santini et al., 2016; Saura et al., 2017, 2018). This is mainly due to the Natura 2000 Network (N2000), within which most sites (80%) are connected by unprotected natural or semi-natural ecosystems, and 40% are fully connected by forests (EEA, 2020a), although the strictness of protection is very low in most cases.

As European PAs grow, they will compete with other land uses, especially where strong protection is enforced. Extractive services, such as food, fodder and timber production, might decline in these cases, leading to an intensification on remaining production-designated land or displacement of production elsewhere. Because protected areas are intended as long-term designations, these effects might also vary with time, especially under the impacts of global change. It is therefore necessary to analyse PA networks as embedded in the wider land system to ensure that ecosystem services are not unnecessarily compromised, whether directly or indirectly, and accounting for future uncertainty in climatic and socio-economic conditions. Addressing this challenge requires coherent cross-sectoral analyses that not only account for biophysical but also socio-economic conditions across a range of possible future scenarios (Chatzimentor et al., 2020). Such analyses have not yet been conducted.

In this paper, we bring together these requirements to investigate the potential impacts of a larger, better-connected PA network on the European land system. We develop such a network based on the EU Biodiversity Strategy 2030 targets and assess its effects across the EU in terms of ecosystem services and land use, under current and future climate change and socio-economic scenarios. To do this, we combine a methodology for network improvement with an EU-wide, integrated land system model and: i) analyse the current connectivity status of the EU's PA network; ii) identify potential improvements in this network to achieve the target of 30% of EU land protected and 10% strictly protected; iii) model land use and ecosystem service changes across different levels of protection and different pairs of climatic and socio-economic scenarios; and, iv) assess the possible impacts of the expanded PA network on ecosystem services across the EU in the future. We use results to assess the achievability and broad effects of an improved PA network in the EU, and also the value of cross-sectoral and cross-scenario studies of PA networks in general.

2. Data and methods

The analysis of the European network of PAs was based on a conceptual framework for GI Network development that combines methods and tools from landscape ecology, spatial planning, graph theory and network analysis (Staccione et al., 2022). We followed a three-step procedure to design the network: i) selecting network elements according to the scale, area, and purpose of the analysis (section 2.1); ii) mapping the existing network, identifying nodes and links and assessing connectivity (section 2.2); iii) constructing potential scenarios based on additional connectivity elements and distances between protected sites (section 2.3). We then applied climate and socio-economic change scenarios to the CRAFTY-EU agent-based model of European land use change (Brown et al., 2019, 2021), to assess the changes induced by the improved network configuration on the provision of a defined set of ecosystem services (section 2.4).

2.1. Case study areas

The analysis was undertaken at the European scale. The European Biodiversity Strategy for 2030 (EU BS 2030) identified around 26% of EU27 terrestrial land under protection, considering PAs under both the Natura 2000 (N2000) Network (18%) and national legislation systems (8%) (EEA, 2020a). We retained the focus on the EU27 domain (a land area of 4,131,745 km^2 (EEA, 2020b)) for the analysis of network improvement. To reach the 30% protection target, a further 4% of the EU's area must be protected, corresponding to 165,400 km^2. Strictly protecting 10% of land corresponds to an area of around 413,000 km^2. However, since connectivity does not necessarily respect administrative boundaries, we referred to a larger European scale to define network structure and status, including the UK, Norway, Switzerland, and the Balkans in the computation.

To be consistent with the EU BS 2030, we used data related to N2000 sites and national designated areas from the European Environment Agency (EEA) dataset (EEA, 2019b, 2019a). Following the EEA procedure to distinguish terrestrial and marine sites, we intersected PAs with the European coastline, filtering out sites that had less than 5% terrestrial area (Telletxea, 2014). Europe has almost 27,000 N00 terrestrial sites and more than 100,000 nationally designated areas on land, and these overlap one another in some cases (Fig. A1 in Annex A). The spatial extent of sites varies significantly, from a few square meters up to around 5000 km^2. The distribution of existing protected sites is shown in Fig. 1 (EPA – existing protected areas).

We also considered the level or strictness of protection. This is defined by the IUCN in eight categories according to PA management objectives, from the strictest protection level, where human presence is minimal, to the lowest, where human presence and use of resources sustainably coexist with nature (Dudley, 2008). This information is available in the EEA datasets only for the nationally-designated areas (EEA, 2019a). When overlapping, we attributed the same classification of national areas to the N2000 sites, and otherwise filled missing information with data from the UNEP World Protected Areas database (UNEP-WCMC, 2021). In Europe, most sites belong to the lower classes of protection strictness (Fig. 1 - EPA and Fig. A2 in Annex A).

2.2. Protected areas network analysis: map of the current status

To analyse connectivity in the existing PA network, we followed the methodological procedure of the GI Network framework: characterising first the network elements as nodes (i.e. core areas) and links (i.e. corridors) and then investigating the connectivity status of these together. The network characterisation is based on morphological spatial pattern analysis, which identifies the groups of pixels acting as nodes and links according to their shape and relative distances through mathematical morphology algorithms (Soille and Vogt, 2009). The GuidosToolbox software was used, fed by the European PAs raster with a resolution of

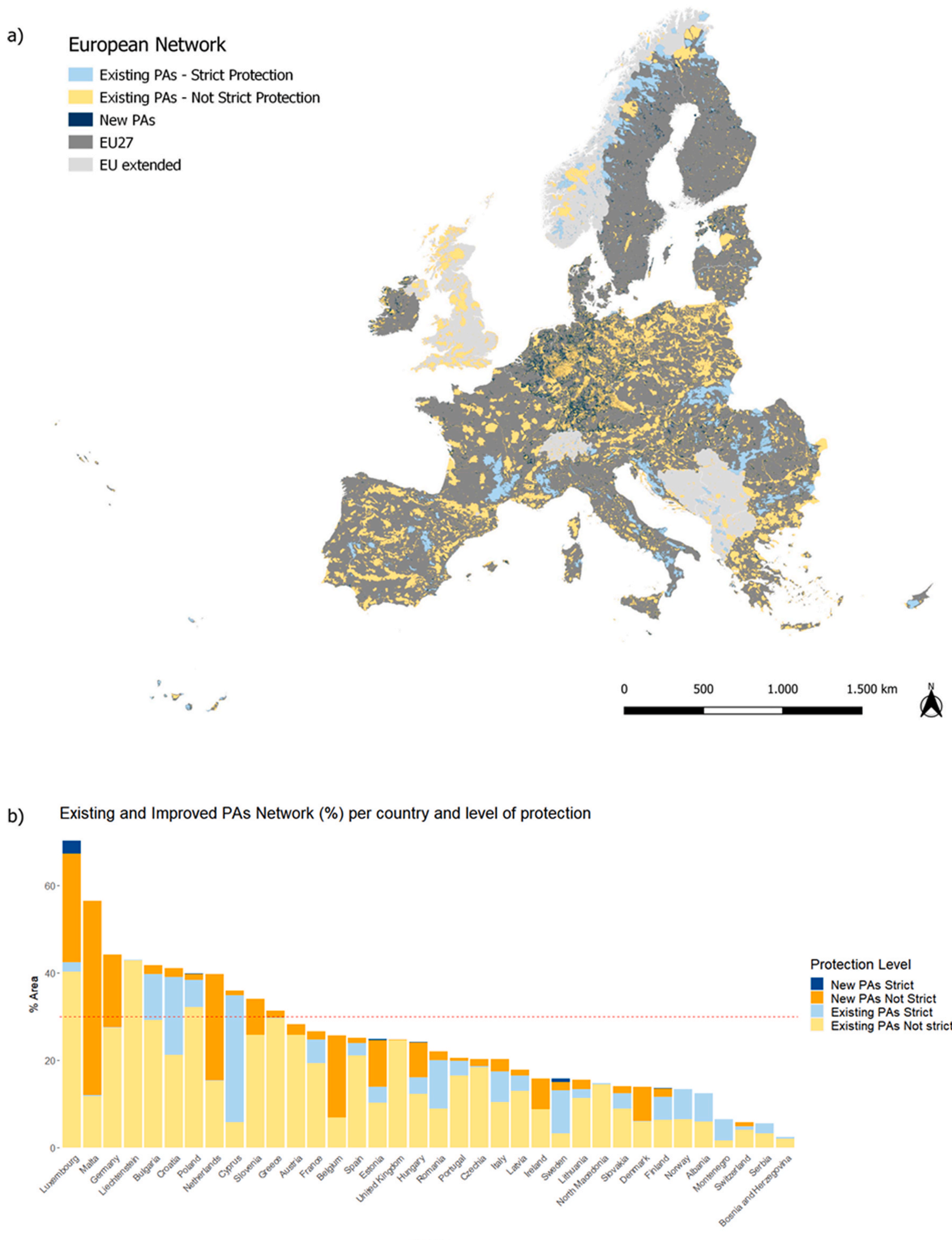

Fig. 1. Geographical distribution of the improved European Network of protected areas. a) The map shows the spatial distribution of existing PAs per level of protection (light yellow and blue) and the new corridors (dark blue). Level of protection of new corridors is not distinguished in the map. b) Bars show the percentage of areas under strict and not-strict protection per country: existing protected areas (light yellow – not strict and blue - strict) and the improvement associated with the new corridors (dark yellow – not strict and dark blue - strict). The level of protection of network improvement refers to the new protected area (NPA) configuration. In the Strict NPA configuration, the improvement is entirely classified as strictly protected. The dashed red line shows the 30% protection target of the EU Biodiversity Strategy 2030. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

200 m (Vogt and Riitters, 2017). Results were converted into a graph representation of the network, to highlight connected and isolated areas. To assess connectivity, we used the Integrated Index of Connectivity (IIC), which evaluates the overall structural connectivity, i.e. the physical links between landscape features, and ranks the contribution of each node to the network (Pascual-Hortal and Saura, 2006). This is a landscape connectivity index based on binary presence/absence of connections at node level, helping to simplify computation in large

network cases. The IIC ranges from 0 to 1, where 1 indicates a complete graph, i.e. all nodes are connected to each other. We computed the index with the R application of the Conefor software (Saura and Torné, 2009).

2.3. Protected areas network improvement: configuration for Biodiversity Strategy 2030

Here, we partly applied the GI Network framework, defining new links between existing areas rather than defining new areas, to account for the priority given to such new links and the far greater uncertainty involved in locating new areas. We used these new links to achieve the Biodiversity Strategy 2030 target (+4% of protected land to give 30% in total) as well as improving connectivity itself. We used cost-distance connectivity analysis considering the current network, distances among PAs, and existing land covers, refining the framework procedure proposed in Staccione et al. (2022). The analysis consists of three main steps.

1) We firstly identified all the possible connections among protected sites. Links between nodes longer than 10 km among the PA boundaries (edge-to-edge distance) were removed. We used this large distance threshold of 10 km in order to include more potential connections and ensure that the overall 30% protection target could be reached. The linear lengths of existing corridors suggest that longer connections are likely to be unfeasible (Annex A). In order to prioritise the connection of isolated sites, we also excluded already-connected pairs of nodes and pairs belonging to the same component, i.e. group of interconnected nodes.
2) Secondly, we defined the most feasible connections for the new network configuration. This was done by a least cost path analysis, using R's *gdistance* package (van Etten, 2017). We fed this analysis with a 'conductance' (the inverse of cost) raster in which PAs had a value of 1 (i.e. maximum conductance/no cost), unprotected areas had a value of 0.1 and built-up areas had a value of 0 (no conductance) (Annex A). This made it possible to exclude connections through built environments and favour connections minimising unprotected land requirements. The raster values were intended only to give a generic reflection of the ease of protecting land on the basis of area requirements, and we did not attempt to represent any ecological or connectivity value of different land types. For each cell we used the mean value of the 8 adjacent cells, assuming that cells adjacent to PAs are easier to connect through, and cells next to urban areas are more difficult.
3) Finally, we selected the connections to be added in the network configuration for the Biodiversity Strategy 2030 targets. We considered the corridors within the EU27 countries, even where these formed part of transboundary connections with non-EU countries. We ranked all the new feasible potential connections by cost (i.e. type of cells crossed) and length (i.e. linear distance between connected PAs), prioritizing links with lower costs and shorter length. This is based on the hypothesis that these could be more easily implemented. We then computed the cumulative area covered by the new corridors to identify those needed to reach the PA coverage target of 30%. We assumed a corridor width of 500 m, but also tested a width of 1000 m. The corridor width was defined from the literature as a feasible average value for the scale and distances of our analysis to support a wide range of ecological and wildlife needs without impinging too much on surrounding land uses (Ford et al., 2020; Loro et al., 2015; Samways and Pryke, 2016).

2.4. Protected areas network assessment

The network and improved configuration network maps were used as land use raster inputs in the CRAFTY-EU model (resolution of 10 Arcminutes; approximately 13 km in Europe) to assess their impacts on ecosystem services in different climate change and socio-economic scenarios. CRAFTY-EU is an application of the CRAFTY agent-based land use modelling framework to the EU27 countries plus Norway, Switzerland and the UK (Brown et al., 2019; Murray-Rust et al., 2014). The model simulates land use outcomes as a result of decision making and competition among individual agents representing land managers. A wide range of land uses and intensities is available to these agents, and each produces a set of provisioning, regulating, cultural and supporting ecosystem services. Ecosystem service provision is determined by the form of land use and by a range of capitals describing attributes of the land system at each modelled location (human, social, financial, manufactured and natural capitals). The model is driven by societal demands for ecosystem services, which agents compete to satisfy, and by scenario-based variation in capitals arising from climatic and socio-economic change. The model has 17 agent functional types (AFTs; Arneth et al., 2014) that capture the main forms of management and behaviour relevant to European land use change. The model is open-access and is described in detail in Brown et al. (2019, 2021).

We introduced four PA network configurations to this model, based on different protection levels for existing and new areas (Table 1). By assigning IUCN categories to PAs, we defined strict (IUCN cat. Ia, Ib, II) and not-strict (IUCN cat. III-VI) levels of protection for the existing PAs, and used these in the Existing Protected Area (EPA) network configuration. For new corridors, we then defined the links between two strict PAs and between strict and not-strict PAs as strictly protected, and the links between two not-strict PAs as not-strictly protected, in the Network Protected Area (NPA) configuration. We then re-defined all new corridors as strictly protected (Strict NPAs) and finally re-defined all existing PAs and new corridors as strictly protected (AllSs) (Table 1). Each configuration was imposed immediately in its respective model run.

In CRAFTY-EU, we interpreted the two levels of protection as constraining the potential production of extractive services (crops, livestock, and timber), i.e. reducing the ability of intensive forms of management to generate goods without precluding them altogether. For the strict level, all of the protected area was assigned as non-productive for extractive services to represent undisturbed natural processes as in the European Commission's definition of strict protection. For the not-strict level, we reduced the productivity by 50%, therefore allowing some production of extractive services in the PAs but less than outside of them. The 50% threshold was chosen as a transparent scaling factor in the absence of any 'known' value. We did not assume any other effects on ecosystem service provision or land management, but allowed these to emerge from simulated land use change.

The implementation of PAs therefore allowed land use change to occur freely (through simulated processes of competition and abandonment) in response to scenario conditions and changes in the PA network. In the absence of any such changes, the model was found to maintain the initial land use map, which incorporated the current European PA network. The model was also parameterised to prioritise food production over other ecosystem services, with food production receiving twice as much benefit per unit unmet demand.

We analysed the modelled changes in food crops, meat and timber production, carbon sequestration, recreation, and landscape diversity, as examples of provisioning, regulating and cultural ecosystem services. Food, meat and timber production levels were based on dedicated

Table 1
Network configurations used to assess ecosystem services impacts in the model.

Network configuration	Description
EPAs	Existing Protected Areas with current levels of protection (strict, not strict)
NPAs	EPAs + New corridors with levels of protection related to the PAs being connected
Strict NPAs	EPAs + New corridors all with strict level of protection
AllSs	EPAs all with new strict protection + New corridors all with strict protection

agricultural and forest models underpinning CRAFTY-EU, while carbon sequestration, recreation and landscape diversity were based on a land management ranking (both described in Brown et al., 2019). International trade in food and timber were accounted for in EU demand levels, meaning that only the appropriate levels of domestic production were modelled in each scenario (Brown et al., 2021). We did not vary demand levels across the protected area configurations, ensuring comparability but also potentially neglecting increased demand for regulating and cultural services that might be expected to motivate and occur alongside more extensive and stricter protection.

Protection of land affected productivity for food, meat and timber, with ultimate levels of service provision determined by agent dynamics and scenario-based capital changes. This model therefore accounted not only for direct effects of loss of production within the PA networks, but also indirect consequences including compensatory adjustments elsewhere in the land system. Because the model is agent-based and non-optimising, these indirect consequences can in principle be large, affecting agent decisions and competition for land across spatial and temporal extents; mirroring real-world land system change that is an emergent rather than imposed or optimised process at the EU scale.

The ecosystem service changes were assessed for each network configuration and level of protection under current climate conditions (2016 – baseline) and paired climatic (RCP) and socio-economic (SSP) scenarios: RCP2.6 – SSP1, which represents a 'green' and low-emission future with stringent climate policy; RCP4.5 – SSP3, representing an intermediate climate scenario characterized by political breakdown and lack of international cooperation; RCP8.5 – SSP5, characterising a high-emission future based on fossil-fuel use and rapid technological development (O'Neill et al., 2017, van Vuuren et al., 2011). The trends in the capitals and the main variables characterising the scenarios in the model are described in Tables 2 and 3. The timeframe of simulations covered the period from 2016 up to the mid-2080s, including the maximum period available for other CRAFTY-EU inputs. The long-term time horizon captured the full knock-on effects of PAs throughout the RCP-SSP scenarios. For each scenario (baseline and RCP-SSP pairs) and each level of protection configuration, we ran 10 different simulations to capture the effects of model stochasticity on results (40 runs per scenario, 160 in total), recording all model outputs on an annual basis.

3. Results

3.1. The EU PA network

3.1.1. The existing PA network

The existing European network of PAs (see Annex B) is characterized by many core areas (43,663 nodes), grouped in 21,647 components, and connected by 26,019 links. More than one third of the nodes are isolated (14,979 nodes), which indicates a low level of connectivity, confirmed also by the IIC index value (IIC = 0.0043). The low IIC value is also influenced by the large number of nodes, which exponentially increases the number of links needed to approach full connectivity, and by the presence of 'islands', which have very limited connections. The IIC index highlights some important nodes for the overall connectivity of the network, especially in Eastern Europe The distribution of PAs, both nodes and links, is not homogeneous across countries (Fig. 1 – EPA). There are countries that already have 30% of land protected (Belgium, Luxemburg, Lithuania, Poland, Cyprus, Greece, and Hungary), and others that are far from this target (especially the countries outside the EU27 domain). However, most existing PAs are not-strictly protected.

3.1.2. The improved network configuration for Biodiversity Strategy 2030

The improved network configuration includes more than 90,000 new pair connections, covering a total area of 167,527.5 km^2 (at 0.5 km corridor width), equal to 4.05% of EU27 land. Corridors span distances of between 1 and 10 km among PA boundaries, including across country borders (around 3000 connections, corresponding to around 4% of new protected areas). They also intersect and join each other, creating wider areas of protection that can act as stepping-stones among PAs or that can merge PAs. The results of the connectivity analysis for the new network shows an increase in IIC value from 0.0043 to 0.0071 (65% increase), a total number of 120,928 links and a substantial reduction of components (7,534).

The distribution of new corridors differs between countries (Fig. 1). The highest numbers are located in Central Europe (Germany, Belgium, Luxemburg, and the Netherlands), because there are many existing PAs close together in this area. Most of the new connections are between PAs that are not strictly protected, and so are themselves not strictly protected in the NPA configuration (Fig. 1b). In the Strict NPA configuration (where all new connections are strictly protected), strictly protected areas would cover 9.2% of EU land, close to the target of 10%.

Table 2
Trends of the capitals characterising the RCP-SSP scenarios in the land use modelling. These are general trends; spatio-temporal patterns may differ, especially for natural capitals. The trends are implemented through annual, cell-specific capital values that underpin the simulation of land use change; the table is based on and further explained in Brown et al. (2019, 2021).

	RCP2.6 – SSP1	RCP4.5 – SSP3	RCP8.5 – SSP5
Human capital	↗ Slight increase	↘ ↘ Large decrease	↗ Slight increase
Social capital	↗ Slight increase	↗ Slight increase	↗ ↗ Large increase
Financial capital	↗ ↗ Large increase	↘ ↘ Large decrease	↗ ↗ Large increase
Manufactured capital	↗ ↗ Large increase	↘ ↘ Large decrease	↗ ↗ Large increase
Natural capital (crops, forests, grassland productivities)	→ ↘ Highly variable decreases	→ ↘ Highly variable decreases	→ ↗ Variable but increasing

Table 3
Trends of main variables characterising RCP-SSP scenarios in the land use modelling. Supply and intensification are emergent outcomes of the model, while other variables are inputs (based on Brown et al., 2019, 2021).

		RCP2.6 – SSP1	RCP4.5 – SSP3	RCP8.5 – SSP5
Climate change/ climate impacts		↘ ↘ Very low	→ Intermediate	↗ High
Socio-economic change		↗ Economic growth, stable government, social cohesion, international cooperation	↘ Limited and ineffective political responses	↗ Social and economic development, fossil fuel exploitation, strong technology improvement
Land use change (intensification)		↗ Quite intensive land management	↘ Tendency to extensification and abandonment	↗ Large areas of intensive management, despite slight increase in extensification.
Supply	**Crops**	↘ Undersupply	↘ ↘ Large shortfalls	↗ Surplus
	Meat	↘ Undersupply	↘ ↘ Large shortfalls	↗ Surplus
	Timber	↘ Undersupply	↘ ↘ Large shortfalls	↗ Surplus
	Env. Services	↗ ↗ Large increase	↘ Decrease	→ Intermediate
Demand	**Crops**	↗ Increase	↘ Decrease	↗ Increase
	Meat	↘ ↘ Large decrease	→ ↗ Stable/slight increase	↗ ↗ Large increase
	Timber	↗ Increase	↘ ↘ Large decrease	→ Intermediate
	Env. Services	↗ Increase	↘ Decrease	↘ ↘
Population		→ Stable	↘ Decrease	↗ ↗ Large increase
Food imports		↘ Decrease	↘ → Slight decrease	↗ Increase

Therefore, Strict NPAs is the configuration that comes closest to achieving the Biodiversity Strategy 2030 targets for the protected area network.

3.2. The impacts of EU PAs network

To spatially report the impacts of the EU PA Network, we show here only the maps for the Strict NPA configuration, which closely matches the Biodiversity Strategy targets. Maps for the other network configurations are available in Annex B, and show similar changes with slightly varying magnitudes to those presented here.

3.2.1. Land use changes

The impacts of the enhanced PA network on land use changes vary significantly across scenarios (Fig. 2). In general, extensification and abandonment occur within PAs as a direct result of the imposition of the network, but also occur indirectly in other areas. Similarly, agricultural expansion and intensification occur not only in direct compensation for reduced production, but also in more widespread, complex and scenario-dependent forms. Slightly more consistent are the extent and broad locations of deforestation, afforestation and new management of existing forests (see North-eastern Europe in particular). Major changes in terms of intensification, extensification and agricultural expansion occur in unprotected and low-protection areas (where only small proportions of cells fall within the network). At higher levels of protection, conversely, changes are mostly related to abandonment. Fig. 3 shows these changes more in detail for Northern Europe and the Iberian Peninsula.

In the baseline conditions, minimal changes emerge between the 2080s land use maps with and without the network. When Strict NPAs are imposed in the baseline, we observe some agricultural expansion in southern Europe, mainly in Spain, and some abandonment in southern France. The NPA configuration shows similar results, while the AllS configuration produces more abandonment, also in eastern Europe, some intensification in the south and afforestation in the north (Figs. B1-2 in Annex B). RCP2.6-SSP1 is characterized by a balance of extensification and intensification in land use spread across the entire territory, except for higher latitudes where changes in forest management prevail. Similar but smaller changes are visible in RCP8.5-SSP5, where the model adapts to the imposition of the PA network with limited agricultural expansion (including into forests) and intensification compensating for abandonment and extensification elsewhere. RCP4.5-SSP3 shows the greatest changes; predominantly abandonment and agricultural expansion that are widespread across Europe even in marginally productive areas, with clear geographical trends only in

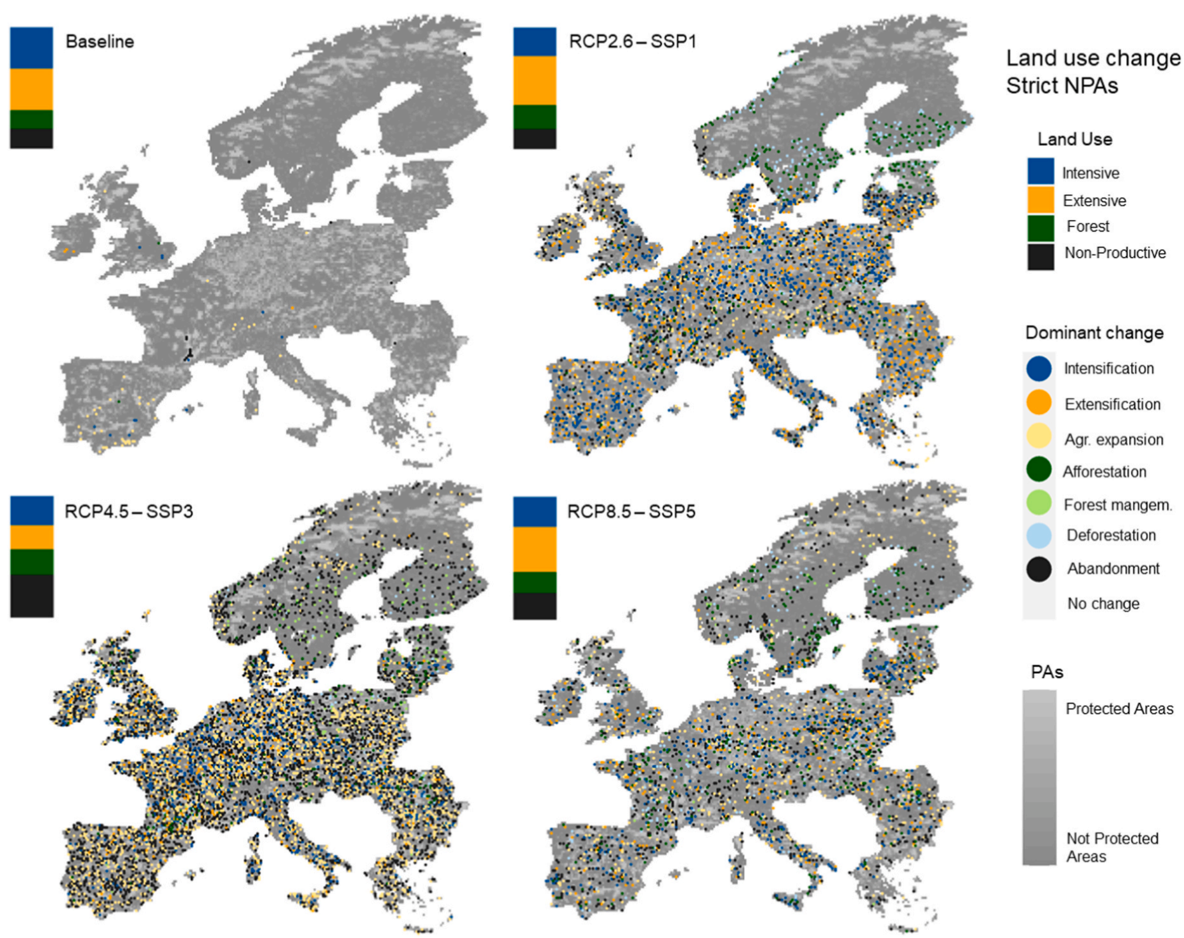

Fig. 2. Dominant land use changes in 2080s from enhanced network connectivity under the Strict NPA configuration, for baseline conditions and for three different future scenarios. Dominant changes are computed with respect to the EPA configuration in each scenario. Changes are classified as: Extensification – intensive land use changing to extensive, Intensification – extensive land use changing to intensive, Afforestation – forest on previously unforested land, Deforestation – forest changing to unforested land uses, Abandonment – active management of any sort changing to unmanaged, Agricultural expansion – non-agricultural use to intensive or extensive agriculture, Forest management – unmanaged or semi-natural forest to managed forest. The bar charts represent the final percentage of broad land cover types per scenario, grouped in four main categories: Intensive (intensive arable farming, intensive agroforestry mosaic, intensive farming, intensive pastoral farming), Extensive (mixed farming, mixed pastoral farming, extensive agroforestry mosaic, peri-urban, extensive pastoral farming, very extensive pastoral farming, multifunctional), Forest (managed forestry, mixed forest), Non-productive use (unmanaged land, unmanaged forest, minimal management, urban). Protected status is shown on a gradient as the proportion of grid cells under protection varies.

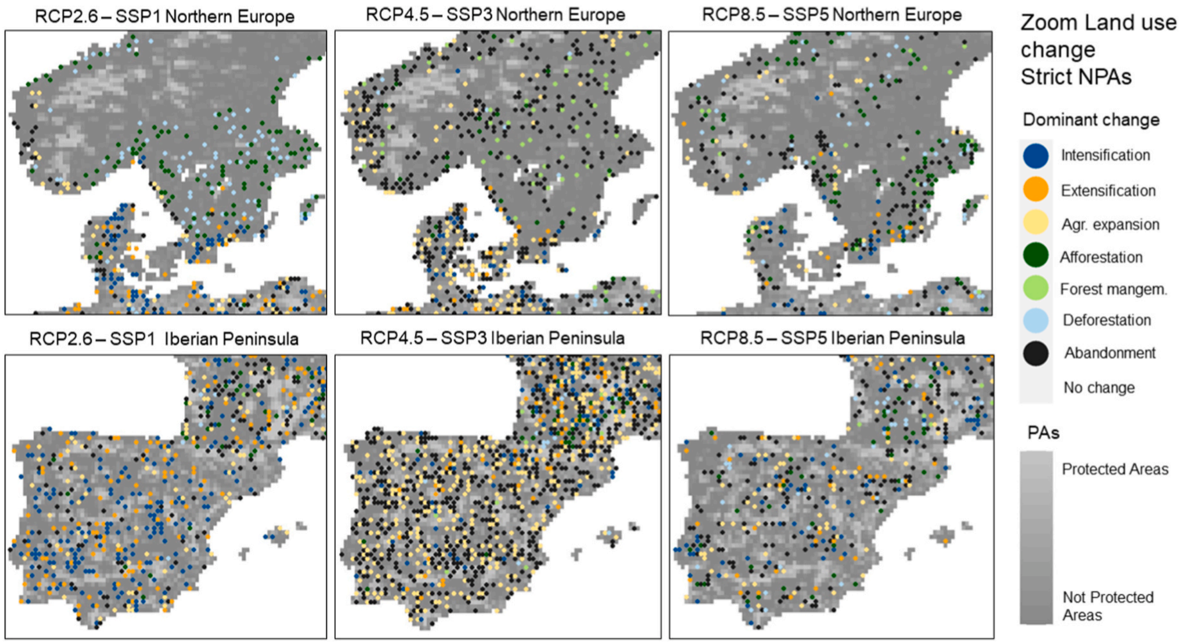

Fig. 3. Dominant changes occurring in Iberian Peninsula and Northern Europe.

forest management changes and agricultural intensification. These same general land use trends hold true for each scenario in the NPA and AllS configurations (Figs. B1-2 in Annex B). Increasing the level of protection, i.e. from NPAs to Strict NPAs to AllSs, amplifies but does not substantially alter the changes (Fig. B3 in Annex B).

3.2.2. Ecosystem service changes

Increasing the extent or protection level of PAs generally did not undermine the EU-wide supply of ecosystem services. The supply of services continues to meet demand up to the end of the century for all the network configurations and scenarios, except in the case of timber production in RCP2.6-SSP1, where shortfalls were nevertheless almost identical across PA network configurations (Fig. 4). This scenario is characterized by an extensification of land management that increases recreational amenity but also competition for land, leading to a lack of timber production. While there are large changes in absolute values of demand and supply in all scenarios (service supply and demand trends are reported in Annex B (Figs. B4-5)), the ratio of supply to demand is relatively stable in most cases.

Comparing the extractive services (crops, meat and timber production) and non-extractive services (carbon sequestration, recreation and landscape diversity) spatially reveals that the supply-demand balances shown in Fig. 4 are produced in quite different ways with and without the PA network. Changes in extractive services occur in aggregated areas, decreasing within the PA network and increasing in unprotected by productive land, while non-extractive service changes are more widespread (Figs. 5 and 6, Annex B Figs. B.6-9). Geographical patterns are apparent, however. Extractive services increase especially in southern Europe, while losses in production are more concentrated in central and northern Europe within PAs. Non-extractive services mostly increase within PAs across the entire territory, with a resulting decline outside PAs, especially in the south.

The patterns of changes in crop production and recreation provision when the Strict NPA configuration is imposed are shown in Figs. 5 and 6. In the baseline conditions, crop production increases most in southern Europe and in the UK, with declines in central Europe where PA densities are highest. The opposite occurs for recreation, with major losses in the south (Spain, Greece and the Alps) and to some extent in the north of Europe. These service-level changes often occur without transitions between broad land use classes (Fig. 2), but reveal within-class adaptions to the PA network.

RCP2.6-SSP1 is characterized by larger increases in crop production in southern Europe, alongside some PA-related losses in the same area. In this scenario, recreation declines are concentrated in areas of increased crop production, but increases are distributed across the entire EU, except for Scandinavian countries. Similar patterns of recreation change can be observed in both scenarios RCP 4.5-SSP3 and RCP8.5-SSP5. In the first, more widespread land use change means that recreation changes occur also at higher latitudes and are less concentrated in the south. Crop production changes in RCP4.5-SSP3 are mainly located in western-central Europe, Italy and the UK, in terms of both gains and losses. RCP8.5-SSP5 is the scenario with the smallest changes in crop production between NPA configurations, and these are mostly located in Spain and Italy.

4. Discussion

We find scenario-specific effects of a new EU protected area network meeting the Biodiversity Strategy's targets. In the RCP2.6-SSP1 scenario, the imposition of a PA network leads to extensification of land use (primarily inside the network) and intensification (primarily outside the network). Competition for land is strong (timber is under-supplied in this scenario with or without the PA network), and so land use changes in response to the PA network have knock-on effects in many areas. Knock-on effects are far larger in RCP4.5-SSP3, however, which displays massive agricultural expansion and, conversely, abandonment, despite lower demand levels overall. Impacts of the network were smallest in RCP8.5-SSP5, with some abandonment and afforestation but little intensification or extensification.

The politically and socially dysfunctional nature of SSP3 severely limits options for agricultural production and intensification, with manufactured, human and financial resources all becoming very low during the scenario (Brown et al., 2019). As a result, the PA network causes expansion of agriculture rather than intensification, and this occurs over very large areas because the production benefits are so small. In happening over large areas, it also produces successive waves of extensification and abandonment across Europe. While these have minor net effects on ecosystem services as simulated here, there is clear potential for major gross impacts depending on the locations affected and their precise ecosystem service dynamics. RCP8.5-SSP5, in contrast,

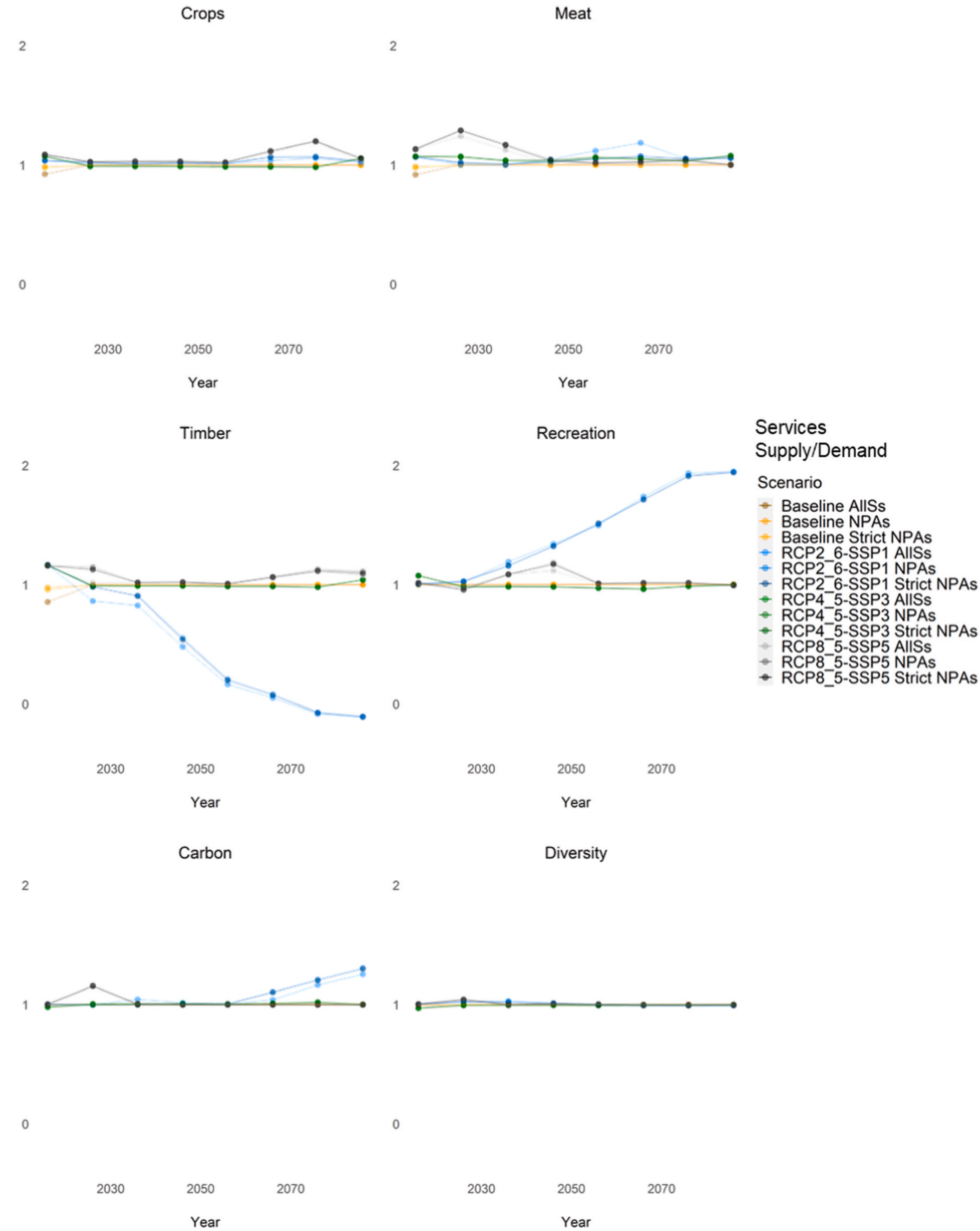

Fig. 4. Trends of services supply/demand for each network configuration in climatic and socio-economic scenarios. The y axis reports the ratio between supply and demand scaled by the size of demand: positive values indicate that supply is equal to or greater than demand.

has high capital levels despite large climate impacts on natural productivity, low competition for land, and many viable options for changing production methods and technological development. This results in the network causing a small amount of change mainly in the form of intensification compensating for PA-associated loss of production. In other words, SSP5 can be seen as more resilient and flexible, despite the pairing with the high-end RCP8.5 climate scenario (in which some possible impacts such as extreme meteorological events are not modelled), while SSP3 is more unstable and fragile. These scenario-dependent forms of adaptation to the imposition of the PA network are analogous to land change archetypes that have been identified around the world, where biophysical and socio-economic context changes the dominant form of land use change (Dornelles et al., 2022).

In contrast to the strong scenario differences, we find that alternative network protection levels have limited influence on the forms or distribution of land use changes. Instead, protection levels influence the

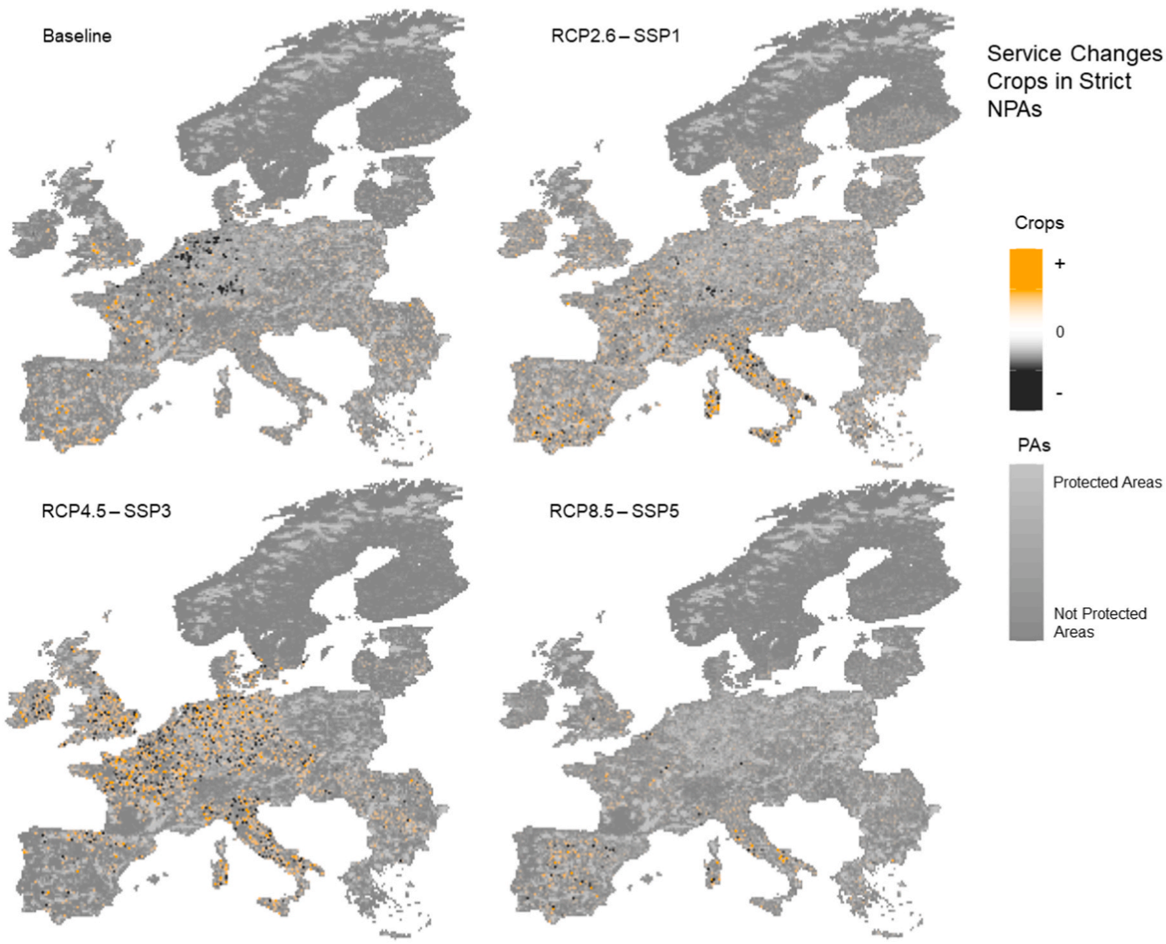

Fig. 5. Changes in crop production across Europe in 2080s in each scenario, with the Strict NPA configuration compared to the EPA configuration (change values are ratios of production within each cell). Yellow dots represent gains (+), while black dots represent losses (−) in production. PAs are represented as a share of areas in the cells. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

'intensity' of changes, increasing the extent of dominant forms of change. This indicates that the reduced level of production imposed by the PA network has consistent effects within scenario contexts.

Other studies investigating European PA networks have highlighted their potential in supporting ecosystem services provision and biodiversity conservation. EEA (2020a) found that within PAs the provision of multiple services is 4% (6% for at least one service) larger compared to unprotected and disconnected landscape elements, showing also less pressures for services within the network. Hermoso et al. (2020) assessed an EU GI network to improve connectivity among conservation areas and maintain ecosystem services, finding greater capacity in the network to provide services compared to conservation-only zones, especially at the EU-level rather than at the country-level. However, the wider land system context and demands for multiple services are not fully considered in these studies, and the effects of potential future conditions are not assessed. We attempt to provide a more comprehensive view by modelling a representative range of land uses, ecosystem services and future scenarios across the EU. The impacts we find are, in practice, barely observable in total supply levels, largely hidden in land cover summaries, but progressively clearer as we look further into the details of land management and ecosystem service provision. This demonstrates the need to use detailed and integrated land system models to investigate the complex reality of possible impacts, which would be missed in more traditional land cover models (Verburg et al., 2019).

By the same token, our specific findings are dependent on our assumptions and approaches. In this study, network connectivity improvement is influenced by design criteria such as the distances among existing PAs, size and number of sites, but not by protection needs from a biodiversity and habitats perspective. Therefore, parts of Europe with particularly few or isolated PAs are not included in the network we assess, even though they might have substantial ecological value. Further research is needed into alternative network designs, which could include different distance thresholds, corridor widths, or entirely different placement of protected areas and buffer zones. This would be particularly useful to combine diverse national contributions to the EU targets, optimize new corridors across countries, maximize benefits, or balance trade-offs in terms of specific services. These alternative network designs would also require detailed treatment of land ownership and use. Corridors could also be designed to be compatible with the European Common Agricultural Policy (CAP) (EC, 2023). For example, they could align with a shift towards more sustainable agriculture or provide compensation for converting the use of land through subsidies or funds from EU CAP or national Rural Development Programs, including via ecosystem services mechanisms (EC, 2023; Pistocchi, 2022; Schirpke et al., 2017; Staccione et al., 2021). CRAFTY-EU does not include any directed or optimised response to the PA network either. As an agent-based model, it allows us to consider various socio-economic characteristics of the land system and scenarios, but its results are dependent on a set of behavioural assumptions (set out in Brown et al., 2021) rather than a single objective function. Exploring network effects under different modelling approaches for social and ecological components of the land system would allow us to draw firmer conclusions.

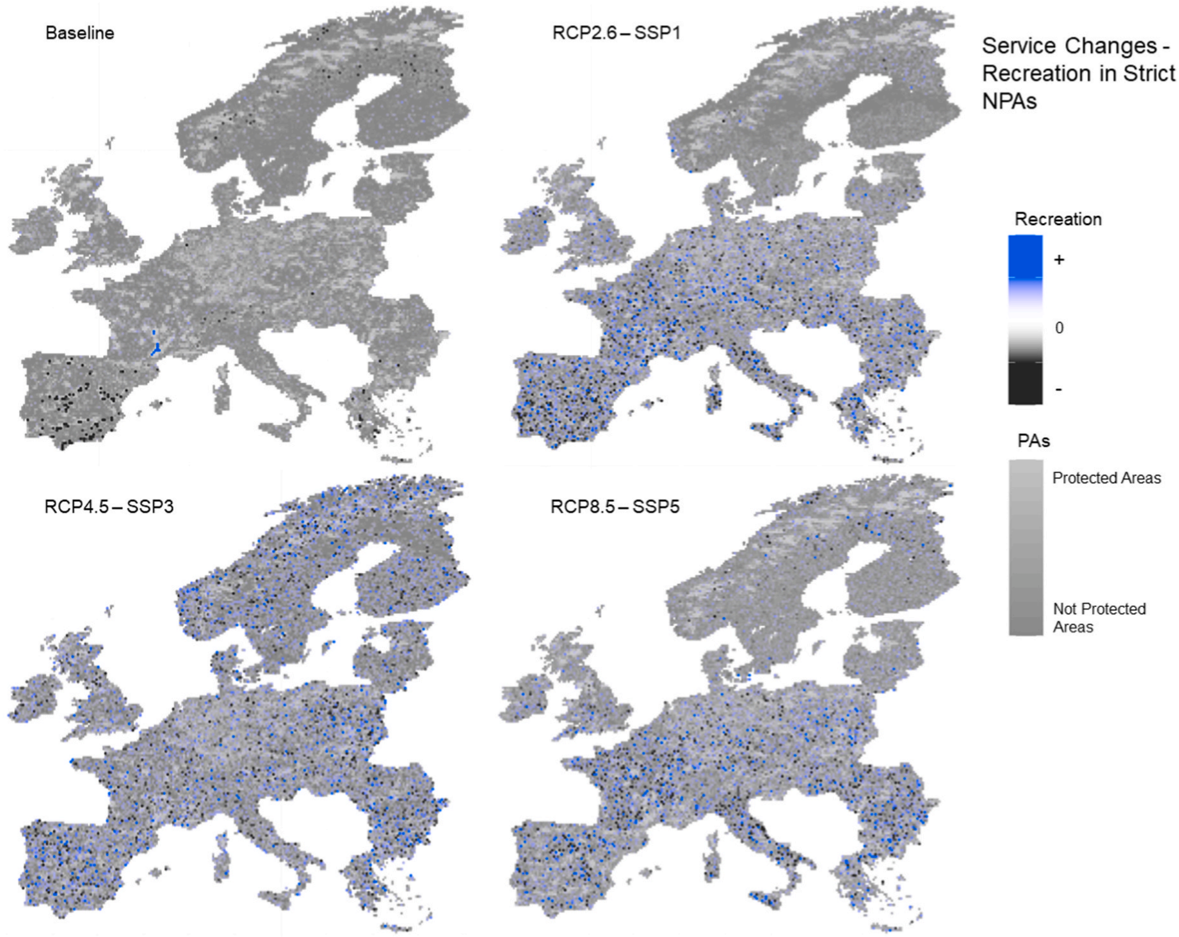

Fig. 6. Changes in recreational service across Europe in 2080s in each scenario, with the Strict NPA configuration compared to the EPA configuration (change values are ratios of provision within each cell). Blue dots represent gains (+), while black dots represent losses (−) of recreation. PAs are represented as a share of areas in the cells. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Conclusion

We found substantial changes in the distributions of land uses and ecosystem services within Europe in response to changes in PA network configurations, with the nature of these effects being strongly influenced by climatic and socio-economic conditions. While our findings therefore imply that a PA network covering 30% of EU land with 10% under strict protection, as called for by the EU biodiversity strategy, is an achievable goal, it is also one that would require careful implementation to avoid negative externalities in the rest of the land system, including effects not modelled here such as agricultural pollution or socio-cultural impacts.

Working at a large, continental scale showed the relevance of cross-border connections to reach protection goals and to effectively build the PA network, making trans-national cooperation fundamental as advocated by the EU Biodiversity Strategy 2030 (EEA, 2020a). Large scale connectivity can also inform and drive actions at smaller scales: to integrate and better plan regional and local network management to contribute to European targets, and to connect and upscale local projects and goals to the regional and international context. In the analysis presented here, strict protection of new corridors better matched the policy goals, and can also be expected to improve service provision, material and species flows within the network. New corridors generally linked areas with less strict protection, especially in central Europe, and the network potentially makes important contributions to nature conservation in those areas. Conversely, network improvement is limited around larger strictly protected areas. In the policy context, it would be relevant to investigate the effects of protection strictness on biodiversity, ecosystem services and climate change mitigation and adaptation. Finally, it is clearly necessary for policy to account for possible future conditions in which a PA network will operate, and so to maximize its contribution to the long-term sustainability of the EU land system.

CRediT author statement

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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.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117741.

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