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Using the Nature Futures Framework as a lens for developing plural land use scenarios for Europe for 2050

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ABSTRACT

Ambitious international targets are being developed to protect and restore biodiversity under the Convention on Biological Diversity's post-2020 Global Biodiversity Framework and the European Union's Green Deal. Yet, the land system consequences of meeting such targets are unclear, as multiple pathways may be able to deliver on the set targets. This paper introduces a novel scenario approach assessing the plural implementations of these targets. The Nature Futures Framework (NFF) developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services aims to illustrate the different, positive ways in which society can value nature. It therefore offers a lens through which the spatial implementation of sustainability targets may be envisioned. We used CLUMondo, a spatially explicit model, to simulate plural land system scenarios for Europe for 2050. The model builds on current land system representations of Europe and explores how and where sustainability targets can be implemented under projected population trends and commodity demands. We created three different scenarios in which the sustainability targets are met, each representing an alternative, normative view on nature as represented by the NFF, favoring land systems providing strong climate regulation (Nature for Society), species conservation (Nature for Nature), or agricultural heritage features (Nature as Culture). Our results show that, irrespective of the NFF view, meeting sustainability targets will require European land systems to drastically change, as natural grasslands and forests are forecast to expand while productive areas are projected to undergo a dual intensification and diversification trajectory. Despite each NFF perspective showcasing a similar direction of change, 20% of Europe's land area will differ based on the adopted NFF perspective, with hotspots of disagreement identified in eastern and western Europe. These simulations go beyond existing scenario approaches by not only depicting broad societal developments for Europe, but also by quantifying the land system synergies and trade-offs associated with alternative, archetypal, interpretations and values of how nature may be managed for sustainability. This quantification exemplifies a means towards constructive dialogue, on the one hand by acknowledging areas of contention, and bringing such issues to the fore, and on the other by highlighting points of convergence in a vision for a sustainable Europe.

1. Introduction

Biodiversity loss is one of the major problems that society needs to urgently tackle. Human activities, including resource harvesting and extraction, have caused land cover change, habitat fragmentation and land degradation, casting increasing pressure on biodiversity (Kehoe et al., 2017; Newbold et al., 2015; Winkler et al., 2021). In response to these trends, scientists, policymakers, and practitioners are working to set ambitious targets at all scales, from national, to regional and international levels (Maron et al., 2021; Pattberg et al., 2019). For example,

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the Post-2020 Global Biodiversity Framework (GBF) and the European Union's (EU) Green Deal are aiming to establish transformative targets relating to no-net-loss of natural areas, the extension of protected areas and forested lands, and the reduction of nitrogen use.

These targets imply a need for drastic reconfiguration of the way our land is currently used and managed (Díaz et al., 2019). However, attaining these environmental targets is challenging due to projected changes to societal development and economic growth which foresee an increase in further land cover change and the intensification of current land use management (Beckmann et al., 2019; Gonçalves-Souza et al., 2020; Horák et al., 2019; Hu et al., 2020; Kehoe et al., 2017; Newbold et al., 2015; Powers and Jetz, 2019; Zabel et al., 2019). For example, the Shared Socio-economic Pathways projections (SSPs) estimate a 20 % increase in the need for wood products from forests in the EU by 2050, mostly resulting from intensively managed forest plantations (Lauri et al., 2019). Existing land use projections also indicate that intensification of croplands will likely replace the multi-functional agro-silvo-pastoral mosaics which characterize traditional Mediterranean landscapes (Malek et al., 2018). Such land system changes will inevitably affect Nature's Contributions to People (NCPs) (Ellis et al., 2019; O'Connor et al., 2021), for example by altering the regulation of water quality and quantity, or by affecting agricultural systems functioning through pollination and pest control.

How, and especially where, to implement land system changes to meet projected commodity demands alongside sustainability targets is therefore dependent on the land-based services we choose to value and prioritize as a society (Meyfroidt et al., 2022). Scientists have tried to map key areas for nature protection and restoration based on different priorities. For instance, Strassburg et al. (2020) identified global priority areas using multiple criteria including biodiversity conservation, carbon sequestration, and cost minimization. Their results illustrate a wide variation in spatial patterns, as areas optimized for one criterion may not perform well for other priorities. At the European scale, O'Connor et al. (2021) identified areas that can lead to maximized nature conservation outcomes when considering three alternative objectives: species conservation, the cultural value of landscapes, and regulating services provided by nature. In this study also, areas of preference for conservation action largely differed depending on the objective under consideration. Even when considering only one overarching objective, the multiple ways in which such an objective can be operationalized can lead to substantially different land use patterns, as shown by a simulation study that used land degradation neutrality as a goal (Schulze et al., 2021).

While these studies address the importance of accounting for multiple target interpretations or criteria in land use decision-making, they do not explicitly state the underlying societal values which may frame such diverging implementations. The Nature Futures Framework (NFF), developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), is a heuristic tool illustrating the diverse ways in which society can positively value nature (Kim et al., submitted). The NFF places human-nature relationships at its core and distinguishes three primary perspectives addressing people's relations to nature. These have been termed "Nature for Nature", "Nature as Culture" and "Nature for Society", respectively building on intrinsic, relational, and instrumental values for nature. This framework has been used to engage stakeholders to explore and co-design plausible futures for protected areas (Kuiper et al., 2022; Palacios-Abrantes et al., 2022) and can be used as a tool to elaborate plural desirable scenarios for representation within a modelling environment (Kim et al., 2023; Pereira et al., 2020). The explicit acknowledgement of common or diverging values held by a wide range of stakeholders is presented by the NFF as an essential means toward constructive dialogue, and the attainment of desirable futures (Pereira et al. 2020).

In this paper, we develop a novel scenario and simulation approach in which we use the NFF as a lens to illustrate how different value perspectives on nature can guide the implementation and attainment of sustainability targets across Europe. As such, we enable the identification of land system synergies and trade-offs which emerge from different value perspectives. We make use of a land system change model to first simulate a reference scenario based on a global scale assessment of projected commodity and demographic changes for 2050 under the SSP1 "Taking the Green Road" scenario. To assess the role of different visions of nature we then compare the outcomes of this reference scenario with the results of three further model simulations where sustainability targets, as defined by the EU Green Deal and post-2020 GBF, are attained on top of the macro-economic assessment of commodity demands in the SSP1 scenario. Each of these three target scenarios reflects a different NFF perspective, whereby different nature values are prioritized. Section 2.1 briefly introduces the CLUMondo land system change model, while Section 2.2. illustrates how the SSP1 and NFF sustainability target scenarios have been defined and translated in respective model simulations. These newly developed plural land system scenarios for Europe are then presented in Section 3, and their potential and implications are discussed in Section 4.

2. Methods

2.1. The CLUMondo land system change model

CLUMondo is a dynamic and spatially explicit model designed to simulate changes in the spatial allocation of land systems (Malek et al., 2018; Schulze et al., 2021; Van Asselen and Verburg, 2013; Wolff et al., 2018). The allocation procedure is on the one hand driven by demands for goods and services provided by different land systems, and on the other by the prioritizaiton of locations with the highest land system-specific suitabilities. In addition, the allocation accounts for rules establishing the land system conversions which are allowed to take place (alongside their timing and location), and rules determining the competitive advantage of each land system in fulfilling each demand (Fig. 1). One specific characteristic of the modelling approach is that each land system can supply multiple demands for goods and services, thus explicitly representing the multifunctionality of land systems. The simulation starts from a recent European land system classification developed by Dou et al. (2021), representing the baseline year 2015 at a spatial resolution of 1 km^2. The land systems in this classification provide goods and services in the form of shelter, annual and perennial crops, livestock, and wood products (see Supplementary Information (SI)), allowing one land use system to provide contributions to multiple goods and services. The spatial suitability of the different land systems is defined by soil characteristics, five bioclimatic variables (annual mean temperature, mean diurnal range, temperature seasonality, annual precipitation, precipitation seasonality), and socio-economic conditions, resulting in a total of 18 variables (SI). At each time step, the model updates the spatial suitability calculated based on the (changes in some of these) 18 variables for each land system, and allocates different land systems in response to the demands for various services and goods until every demand is met, while considering any conversion restrictions which may be in place. The effect of changing policies under the NFF sustainability targets scenarios is implemented in the CLUMondo simulations by changing or adding demands for certain products and services, and by regulating the land system conversions which are allowed to take place, as well as their preferred locations (see Section 2.2.3). In this study, CLUMondo models were parameterized and run for four regions of Europe, to reflect specific regional characteristics and reduce computational requirements (an overview of countries in each region is provided in the SI). Further methodological details on the CLUMondo model (e.g., allocation process and parameters) can be found in the SI.

2.2. Scenario definition

2.2.1. The SSP1 reference scenario

We first developed one reference scenario based on SSP1 "Taking the

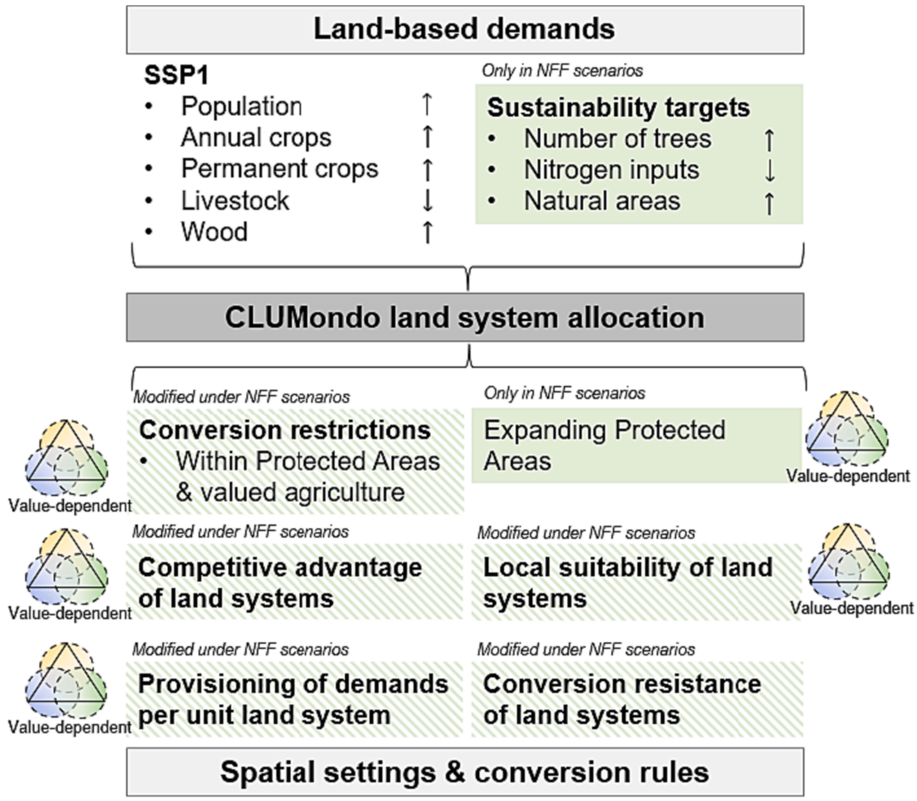

Fig. 1. Overview of main parameters involved in the CLUMondo model land system allocation procedure, and illustration of how these were configured in the Nature Future Framework (NFF) scenarios by either adding complementary rules to the reference SSP1 scenario (i.e., new sustainability demands and protected area expansion rules), or by modifying the reference SSP1 parameter values. The demands set by the sustainability targets are equal across each of the three NFF scenarios, while their implementation varies according to each perspective (see details in Table 2).

Green Road" (Table 1). As this CLUMondo model application focuses on Europe alone, and demands for land use related goods are largely determined by changes in global demographic and economic trends, we based our overall required demands for goods and services on the outcomes of the GLOBIOM Integrated Assessment Model (Havlík et al., 2011; Lauri et al., 2019) (Table 1). More specifically, we used the projections of the SUSFANS project (Frank et al. 2018), which elaborated scenarios for Europe, alongside food and agricultural projections (Food and Agriculture Organization of the United Nations, 2018). For the whole study area, these SSP1 projections foresee a population increase of 6 %, from 540.4 million to 574.7 million, by 2050 and an increase in the demands for most goods and services (e.g., crop production is forecast to increase by 2 % and reach 1079.6 million tons) with the exception of livestock products (Table 1 and Table S4). Each European region, although following the general storyline of the scenario, additionally had some distinct assumptions to account for respective specificities in land use. In contrast to the GLOBIOM simulations, we separated demand for annual crops (e.g., wheat, rice, maize, barley) and permanent crops (e.g., olives, grapes, fruits), as these differ in terms of spatial land suitability, their role in diets, and importance to biodiversity. These quantities were further supplemented with our interpretations of the SSP1 storyline in terms of land use conversion rules and other spatial model settings (Table 1 and SI). The corresponding climate projection of the SSP1 scenario, namely the Representative Concentration Pathway (RCP) 2.6, forecast to represent increases of 1.2–3.4 °C in Europe (European Environment Agency, 2023), was used to account for changing yearly climatic conditions by updating the five bioclimatic variables which determine land system suitability (section 2.1) (Engström et al., 2016; Brown et al., 2019). This projected climate data was obtained from the CHELSA database, which provides statistically downscaled data from the Coupled Model Intercomparison Project (CMIP6) to 30 arcsec, ~1 km resolution (Karger et al., 2017). Climate change impacts were furthermore accounted for in the crop yield estimations sourced from the GLOBIOM model and reflected in the amount of crops each land system provides throughout the simulated time period. Further details on the interpretation and parameterization of the reference scenario are documented in the SI.

2.2.2. *Identification of sustainability targets for 2050*

The post-2020 GBF of the Convention on Biological Diversity and the EU's Green Deal are working to set ambitious plans to overcome the twin challenges of climate change and environmental degradation. While the post-2020 GBF represents a comprehensive consultation process to shape global policy action on biodiversity until 2050, the EU Green Deal involves a broader set of actions and legislation to achieve climate neutrality across the EU within the same time frame. We hereby focus on the goals and targets set out by both frameworks which relate to spatial (area-based) sustainability measures addressing biodiversity and climate objectives. The identified targets for the EU Green Deal are therefore primarily laid out in the EU Biodiversity Strategy for 2030, and related Forest Strategy and Farm to Fork Strategy (European Commission, 2020; Working group of Convention on Biological Diversity, 2021). We reviewed and compiled respective policy targets and translated them to parameterizations of the land use simulations (Table 2). For targets designed with a timeline to 2030, we assumed gradual increases in the target objectives to the year 2050, reflecting an ambition to progressively increase environmental protection and restoration in the long-term (European Commission, 2020, 2018; Working group of Convention on Biological Diversity, 2021). According to the policy documents, most of these goals should be attained at the global or European level, leaving implementations at the member state level unspecified. Our simulations therefore assumed a middle ground in which a share of the

Table 1
Storyline for the SSP1 reference scenario and respective parameterization in the CLUMondo reference model.

	SSP1 GLOBIOM trend (2050)	CLUMondo scenario implementation
Overall population & commodity demands	-A slight increase is assumed for both Europe's population and economic development -A stagnating household income and high agricultural production from the rest of the world only increase Europe's agricultural demand modestly (3 %) -The shifting social norm to consume less meat contributes to an overall reduction of livestock products and higher overall demand for permanent crops -There is a high demand for wood production caused by increased biofuel demands	-Changing demand trends as predicted by GLOBIOM are assumed for each of the CLUMondo simulated regions
Regional population & commodity demands	-Population declines in the east region (−8%) while elsewhere it increases (especially in the north) -Annual crop demands decline in the south (−25 %) but increase elsewhere -Demand for livestock products declines in the south and west regions (−19 % and −9%), while it increases in the north and east -Demand for wood products and permanent crops increases in all regions	-Changing demand trends as predicted by GLOBIOM are assumed for each of the CLUMondo simulated regions
Urban development	-There is a lifestyle preference for residing in villages and peri-urban areas -Environmental protection results in strict rules for where urbanization is or is not allowed	-Villages and peri-urban areas are promoted by contributing to a number of agricultural demands beyond shelter provisioning -Strict conversion rules in place for urbanization expansion
Agricultural development	-Reduced agricultural profits are compensated by transitioning from industrial farming and grazing systems to more diversified and multi-functional systems balancing product quality, quantity, and environmental impacts, and by allowing agricultural systems to be converted to non-agricultural uses (e.g., natural areas) -Innovative and sustainable forms of production are incentivized as part of sustainable intensification efforts, yet yields are also affected by changes to climate and ecosystem services and may regionally decline	-Crop and livestock production are promoted in a variety of land systems, particularly mosaic systems containing forest/shrubs with cropland, and agricultural mosaics of cropland and grassland, instead of focusing solely on specialized cropland or grassland systems -Gradual increases to productivity are implemented within medium and high-intensity agricultural land systems (except for the south region, where crop productivity declines alongside declining demands for annual crops), and grassland systems for the south and west regions (while productivity declines take place in the north). Low intensity systems do not see increases in productivity as technology development is infrequently implemented in these more extensive and marginal systems

targets needs to be reached by each of the four simulated European regions (North, South, West, and East regions of Europe), while the contributions of the member states within each region may differ and are not imposed in the model parameterization. The share of targets that needs to be reached by each region is determined based on total regional land area and/or total agricultural land area depending on the specific target (i.e., larger regions are required to implement a proportionally greater share of the target). Non-EU countries within each region are assumed to contribute to the same targets and were subject to the same model settings as EU countries, assuming these would follow similar policies.

We summarized compatible policies from the EU Green Deal and post-2020 GBF within three main policy domains: *nature protection and restoration*, *sustainable agriculture*, and *increased tree cover*. If a specific target has not been mentioned in (one of) the two policy statements, we used targets from the other policy, or assumed a value in line with the overall description in the policy documents. The action points regarding nature protection and restoration, derived from both the GBF and EU Green Deal, refer to expanding current protected areas under the Natura 2000 network from 18 to 30 % of European land by 2030 and to implement a "no-net-loss" policy for all natural ecosystems, meaning that nature outside protected areas may be converted to a different use, but only if compensated by increases in natural area elsewhere in the region. After 2030, we assumed an annual 1 % increase in natural areas until 2050 as a result of ecosystem restoration or rewilding. Natural areas were defined by land system classes referring to low-intensity forest or grassland systems (thereby also including land comprised by the low-intensity agricultural mosaics class). Hereafter, any reference to simulated "natural" land systems or areas will therefore be referring exclusively to these three land systems. The expansion of natural areas was calculated based on the 2015 extent of low-intensity forests.

For sustainable agriculture, we focused on the policy that aims at reducing the excessive use of nitrogen. According to the EU Green Deal, the total use of nitrogen in agricultural production should be reduced by 20 % by 2030, compared to 2015. We extended this reduction target to 30 % by 2050. Europe additionally plans to plant 3 billion new trees by 2030 according to the Green Deal. This target was implemented in the scenarios and extended by an additional 2 billion trees to be planted between 2030 and 2050. In addition to these targets, we implemented specific rules addressing the process of *urbanization*. These rules vary according to the NFF scenario to reflect different perspectives on nature appreciation (e.g., greater urban density to allow for land sparing for nature, vs. lower urban density to increase access to green and blue spaces within cities – see Section 2.2.3).

2.2.3. The NFF scenarios: different pathways to achieving sustainability targets in Europe

Land system scientists have called for stronger engagement by the community with normative questions (Nielsen et al. 2019, Meyfroidt et al. 2022). Achieving sustainability and biodiversity goals requires joint efforts from people and stakeholders who may have fundamentally different relationships with nature. To represent these different relationships, we applied the NFF as a tool to explore how different values may guide the implementation of the identified sustainability targets. This resulted in the development of three additional scenarios (one for each NFF perspective) whereby land systems are required to meet the sustainability targets in addition to the demands for food, wood, and shelter envisaged under the SSP1 reference scenario. The three NFF scenarios were developed and implemented as follows:

From the *Nature for Nature* perspective, priority is given to preserving the intrinsic value of nature and species conservation. To identify where additional protected areas should be implemented within this scenario, we therefore prioritized regions based on the distribution of all vertebrate species known to occur within Europe (Maiorano et al., 2013; O'Connor et al., 2021). Top priorities are areas that are diverse, irreplaceable and complementary to the existing protected area network, and optimize the representation of terrestrial vertebrate species. As existing protected areas, we considered Natura 2000 for EU28 countries, and national parks for non-EU countries in the study area (European Environment Agency, 2022; UNEP-WCMC and IUCN, 2023). The prioritization was performed using Zonation software (Lehtomäki and Moilanen, 2013). We applied the same methodology as the prioritization

Table 2
Implementation of sustainability policy targets in the CLUMondo model according to the three Nature Futures Framework perspectives.

			CLUMondo scenario implementation		
Policy domain	**EU Green Deal target**	**Post-2020 GBF target**	**Nature for Nature (NfN)**	**Nature as Culture (NaC)**	**Nature for Society (NfS)**
Protected areas	Protect 30 % of land in Europe by 2030	By 2030, protect and conserve at least 30 % of the planet, prioritizing important areas for biodiversity	The expansion of protected area focusses on priority areas for terrestrial vertebrates	The expansion of protected area focusses on culturally valued agricultural landscapes	The expansion of protected area focusses on priority areas for regulating NCPs (carbon accumulation)
No-net-loss and restoration of nature	Restore degraded ecosystems	Increase the extent of natural ecosystems by at least 15 % by 2050	No-net-loss of natural areas (natural grasslands and forests) by 2030, and annual 1 % increase after 2030		
			The restoration of forests focuses on areas with high conservation value for vertebrate species	The restoration of forests does not come at a cost for culturally valued agricultural landscapes	The restoration of forests focuses on areas with high carbon accumulation potential
Sustainable agriculture	Reduce use of fertilizers by at least 20 % by 2030	By 2030, reduce pollution from all sources by 40 %, including excess nutrients	Total nitrogen application from all cropland and grassland systems to be reduced by 10 %, and applications from high-intensity cropland to be reduced by 10 % by 2030. By 2050, achieve an additional 10 % decrease in nitrogen application		
Increased tree cover	Plant 3 billion new trees by 2030	Increase secondary natural forest cover	Plant 3 billion new trees by 2030, followed by an additional 2 billion new trees by 2050		
			Increase tree density in urban and low-intensity agricultural systems and push for expansion of forest and shrub (favoring areas with high species conservation value)	Increase tree density in urban and low-intensity agricultural systems and prevent expansion of forests within culturally valued agricultural landscapes	Increase tree density in urban and low-intensity agricultural systems and push for expansion of forest and shrub (favoring areas with high carbon accumulation potentials)
Urban land take		By 2030, increase benefits from biodiversity and green/blue spaces for human wellbeing, including the share of people with access to such spaces by at least 100 %, especially for urban dwellers	Gradual increase of the population density in all urban classes	Preference for village expansion over peri-urban areas to allow more human-nature interactions	Gradual decrease of population density in cities

for terrestrial vertebrates in O'Connor et al. (2021), but by contrast, the study area was broader and included non-EU countries. Areas with higher potential gains for the protection of terrestrial vertebrates were gradually designated as protected areas (5 % expansion every five years), meaning that land systems present within these newly established areas could no longer be converted to high-intensity land uses. The tree planting target instead involved (1) increasing the density of trees in urban areas and low-intensity agricultural systems, representing an increase in urban parks and (linear) landscape elements in low-intensity agricultural systems, and (2) favoring the expansion of forest and shrub systems. The target relating to no-net-loss and restoration of natural land systems referred to the preservation and expansion of low-intensity forest and grassland system classes. As part of this NFF perspective, all forests, forest/shrub mosaics, and shrublands are specifically promoted within areas of high conservation value for terrestrial vertebrates. In addition to the sustainability targets, population density in all three settlement systems was increased over time to represent compact residential areas and permit land sparing to make more land available to nature.

The *Nature as Culture* perspective focuses on the cultural context and highlights Nature's non-material Contributions to People. Therefore, when identifying the preferential areas for expansion of protected areas, regions with a high capacity for cultural services were prioritized and determined by the location of agricultural landscapes of the greatest known cultural value in Europe (Tieskens et al., 2017). The tree planting, no-net-loss, and nature restoration targets addressed the same land systems as under a Nature for Nature scenario, yet in a Nature as Culture scenario, forest and shrubland systems were not promoted within preferential areas for habitat suitability, and re/afforestation was prohibited within the most culturally valued agricultural landscapes in order to preserve their character. We assumed that current trends towards urbanization would be changing due to a preference for residing in villages; this land system was therefore indicated as a priority system to meet residential demands.

The *Nature for Society* perspective highlights the benefits that nature provides to people and society. We acknowledge that under this perspective, a wide range of NCPs should be considered. In this scenario, we however focus on the exploration of NCP delivery to the mitigation of climate change, identifying this as one of the most important societal functions to be achieved under the sustainability targets. Under this scenario, the expansion of protected areas is focused on prioritizing areas with high above-ground carbon accumulation potentials (Cook-Patton et al., 2020). While the tree planting, no-net-loss, and nature restoration targets address the same land systems as in the other NFF scenarios, under a Nature for Society perspective all forests, forest/shrub mosaics and shrubland systems are specifically promoted in areas with high carbon accumulation potential values (Cook-Patton et al., 2020). To represent the ambition to locally supply NCPs, we assumed that population density in cities gradually decreases, allowing for more green space to provide these benefits.

For the final sustainability target, relating to the reduction of nitrogen applications, we assumed that half of the reduction goal is fulfilled by substituting nitrogen-intensive land systems with less intensive systems, while the other half is fulfilled by gradually lowering the unit nitrogen input in all grassland and cropland systems. Improving nitrogen-use efficiency can be attained through strategic choices such as improved genotypes, changed timing of application, site-specific changes to nitrogen and water supply applications, and improved cropping systems (Spiertz, 2009). For example, intercropping of sugarcane/soybean can give a larger positive yield gain than the increase of nitrogen inputs (Luo et al., 2016). This target is implemented in the same way in each of the three NFF scenarios. Across each scenario, conversion rules were further parameterized to ensure that natural land systems could not be replaced by non-nature land systems (within protected areas), but also not by one another (e.g., low-intensity forests could not replace low-intensity grasslands, and vice-versa). The parameterization further discouraged new natural areas from replacing forest/shrub mosaics, as these areas are also likely to retain patches of value to biodiversity, despite not being considered as natural land systems contributing to the nature restoration target.

All specific targets were implemented in CLUMondo by either: (1) introducing new "target goods and services" to be delivered by different land systems (notably for trees, nature areas, and nitrogen use), or (2) by changing land system preferences or conversion rules. To calculate the amount of goods and services each land system class can provide (for population, livestock, wood production, tree density, and nitrogen specifically), we overlayed our present-day land system map with maps representing spatial proxies for each of these demanded goods and services, and then extracted respective average values for each region. Comprehensive details on the parameterization of the targets can be found in the SI.

3. Results

3.1. Substantial changes in land use are needed to meet sustainability targets and projected population and commodity demands

Each land system category (forest, grassland, cropland, mosaic, and urban systems) will undergo marked and distinct changes to meet projected population and commodity demands alongside sustainability targets, as 25–28 % of European land systems are forecast to witness a conversion by 2050 under the explored scenarios (Figs. 3, SI). Forest areas are projected to increase under the SSP1 reference scenario (Fig. 2), however these increases will primarily be characterized by mid- to high-intensity forests, while the extent of low-intensity forests is expected to decline by 4 % by 2050. By aiming to conserve and expand

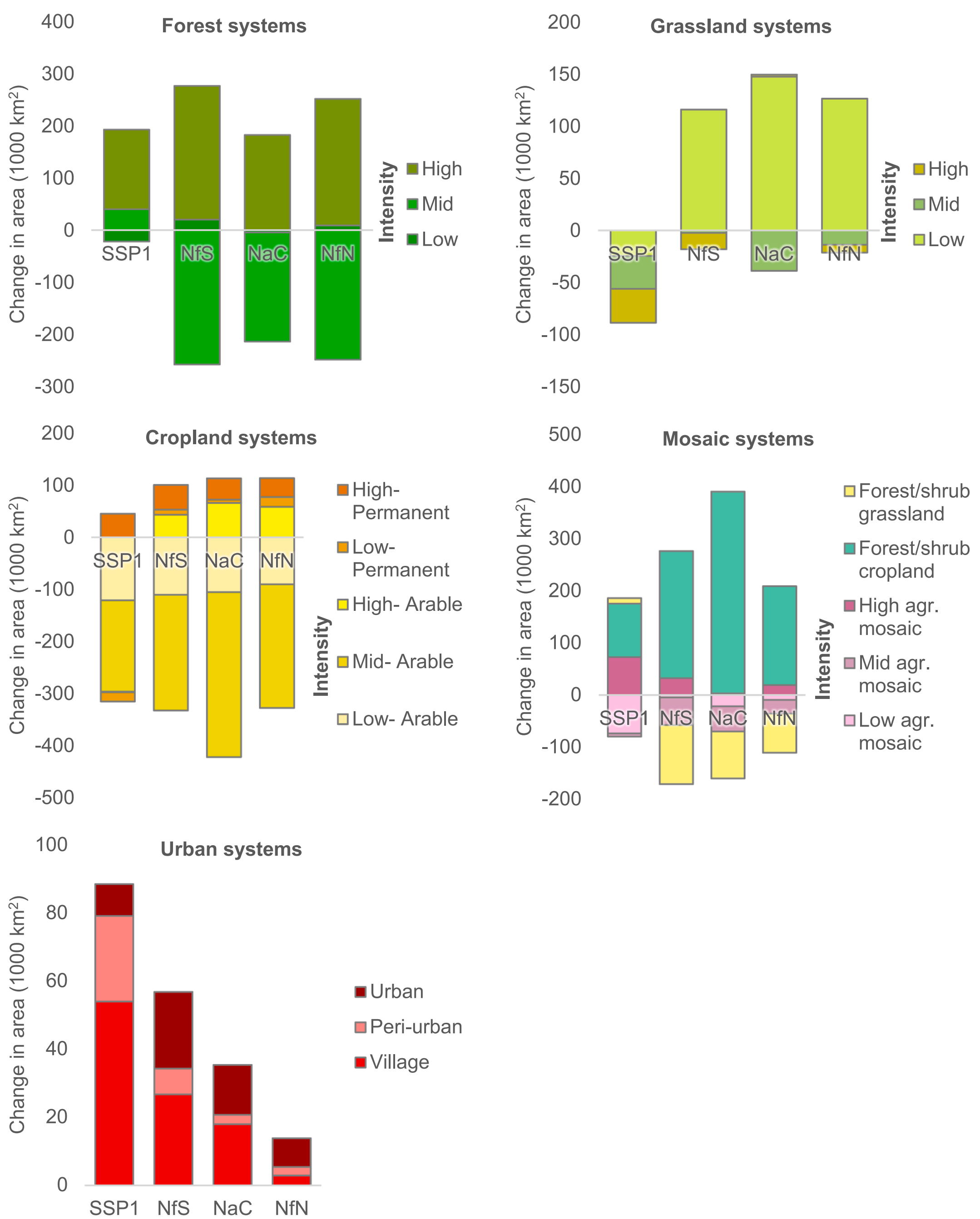

Fig. 2. Amount of land system changes between 2015 and 2050 according to the reference SSP1 scenario and the three NFF scenarios.

natural areas under the area restoration target, two of the three NFF scenarios simulating the impacts of sustainability targets instead see a slight increase in the area of low-intensity forests, notably of 2 % in the Nature for Nature scenario and of 4 % in the Nature for Society Scenario, while under a Nature as Culture scenario a −1% decline in low-intensity forests is foreseen. Increases in low-intensity forest areas are for the most part achieved through conversions from cropland and agricultural mosaics. When compared to the reference SSP1 scenario, the NFF scenarios all additionally see a more substantial intensification (i.e., replacement of mid-intensity forests with high-intensity forests) to achieve wood harvesting demands in light of greater co-occurring de-intensification (Figs. 2, S9).

The difference between the SSP1 and NFF scenarios is more pronounced for grassland systems. In the SSP1 scenario, all grassland areas decline, with the most substantial changes occurring for high-intensity grasslands (−40 %). In the NFF scenarios, low-intensity grasslands instead expand, while the remaining grassland systems are generally subject to smaller reductions. The Nature as Culture scenario has the largest low-intensity grassland area by 2050 (107 % increase from 2015). Similarly to low-intensity forests, the increased preservation of low-intensity grassland areas in the NFF scenarios is the result of the explicit sustainability target of no-net-loss and restoration of nature, which includes low-intensity grassland systems. Unlike low-intensity forests however, new low-intensity grassland is often converted from forest/shrub and grassland mosaics (e.g., 12 % of new low-intensity grassland area in the Nature as Culture scenario, Fig. S9) and mid-intensity agricultural mosaics, representing cases of land system specialization (as mixed-use land systems are replaced), alongside de-intensification from higher intensity grassland classes.

All annual cropland areas decrease in the SSP1 scenario and especially within the low- and medium-intensity classes. These croplands primarily undergo a process of diversification and are converted to forest/shrub and cropland mosaics. The three NFF scenarios show a different pattern of intensification compared to the SSP1 scenario, as high-intensity croplands increase (by up to 27 % in a Nature as Culture scenario) and primarily replace medium-intensity cropland, followed by high-intensity forest and forest/shrub and cropland mosaics (Fig. S9). Simultaneously, large quantities of medium-intensity cropland are also converted into forest/shrub and cropland mosaics in all three NFF scenarios, leading to greater increases of this latter land system when compared to the SSP1 scenario (e.g., in Slovakia, Fig. 3). The spatial coverage of this multi-functional land system is highest and more than doubles (129 % increase) in the Nature as Culture scenario, a change that is twice bigger than in the Nature for Nature scenario (Fig. 2). It is furthermore driven by the substitution of forest/shrub and grassland mosaics and low-intensity agricultural mosaics. Across the NFF scenarios, annual crop production therefore becomes either highly intensively managed or undergoes a diversification process and becomes characterized by a more multi-functional forest/shrub mosaic. Increases in high-intensity permanent crops are fairly consistent across SSP1 and NFF scenario results (ranging from 80 % to 104 % increases), while low-intensity permanent crops are forecast to decline in SSP1 and to increase under the NFF scenarios, primarily replacing annual cropland or forest/shrub mosaics. Out of the three cropland and grassland mosaic classes, only the high-intensity mosaics are forecast to increase under all scenarios and to primarily replace mid-intensity annual croplands.

For urban land systems, the greatest increase in urbanization takes place in the SSP1 reference scenario and is for the most part characterized by the expansion of villages. While increased urbanization also occurs in each NFF scenario, this is more restricted under a Nature for Nature scenario (4 % increase in urban land systems), and most substantial under a Nature for Society scenario (16 % increase), as the decrease in urban population density under this perspective is compensated for by greater urban expansion. Due to greater demands on land systems under the NFF perspectives, cities are forecast to witness greater expansion than under the SSP1 scenario. Especially in a Nature for Nature scenario, the expansion of villages is very limited. Altogether, these trends for each land system category show that the sustainability targets push for a similar direction of change across each of the NFF scenarios when compared to the reference SSP1 scenario, yet the magnitude of change differs according to each perspective, being particularly distinct in the Nature as Culture scenario which favors increases in mosaics and grasslands at the expense of forests.

3.2. East and west Europe are consistently identified as hotspots of land system change

Most of the changes in land systems across the explored scenarios consistently occur in the west and east of Europe, where respectively 27 % and 38 % of national land area, on average, is subject to conversions within the simulated time frame (Figs. 3, 4). Across both regions, present-day high-intensity grassland systems, low-intensity croplands, and mid-intensity agricultural mosaics are undergoing the greatest relative national-level changes, as at least 75 % of their areas, on average, are forecast to change. In the NFF scenarios, these systems are often replaced by the natural land system classes, as these two regions were parameterized to fulfill the nature restoration targets due to their larger extents and smaller relative present-day natural land cover. While new natural areas are most often generated via trajectories of land system specialization in the east (i.e., by replacing mosaics classes), in the west, new nature systems are most often attained through de-intensification processes (Fig. 4). In the east, mid-intensity grasslands, forest/shrub and grassland mosaics, and high-intensity agricultural mosaics represent additional systems which undergo important conversion shares in the NFF scenarios, while in the west, additional systems undergoing widespread relative change are primarily characterized by permanent crops and shrublands. In both regions, these systems are either also most often replaced by natural land systems, or by high-intensity systems (i.e., high-intensity cropland and forest) and forest/shrub and cropland mosaics to compensate for the reduced production of cropland and wood in newly established nature areas.

In addition to urban systems and bare land, only low-intensity grasslands are consistently forecast to maintain the majority of their current coverage (>75 %) in the future in both the east and west regions across the NFF scenarios (e.g., within Austria and Ireland). In the west, present-day low-intensity forests are additionally stable, with change occurring on only 11 % of their initial area. In the north and south regions, where a greater share (82 % on average) of national land systems are forecast to remain the same, high-intensity croplands represent an additional uniformly stable system, with an average of only 10 % of its initial area being forecast to change. These stable systems are the product of the scenario parameterizations reflecting either a difficulty (e.g., in the case of urban systems) or undesirability (e.g., in the case of natural areas) of system conversion. Like in the east and west regions, also the north and south see a significant share of present-day land system areas (>75 %) instead undergo conversions within high-intensity grassland and low-intensity cropland systems, alongside mid-intensity grasslands. Especially in the south, these are largely converted to mosaics, providing mixed agricultural products and wood provisioning, and to a lesser extent to cropland areas and natural systems.

3.3. Twenty percent of European areas show a divergent development based on different valuations of nature

Consistent trends displayed either through land systems remaining unchanged throughout the simulation period, or engaging in the same conversion processes, can be identified in a majority of cases for all scenario comparisons. On average, each of the NFF scenarios has a 69–70 % 2050 land system allocation agreement with the SSP1 reference scenario, while amongst themselves, the NFF scenarios agree on the allocation of 80 % of land systems in Europe (SI). The share of scenario agreement is consistently higher in the north and south regions, where

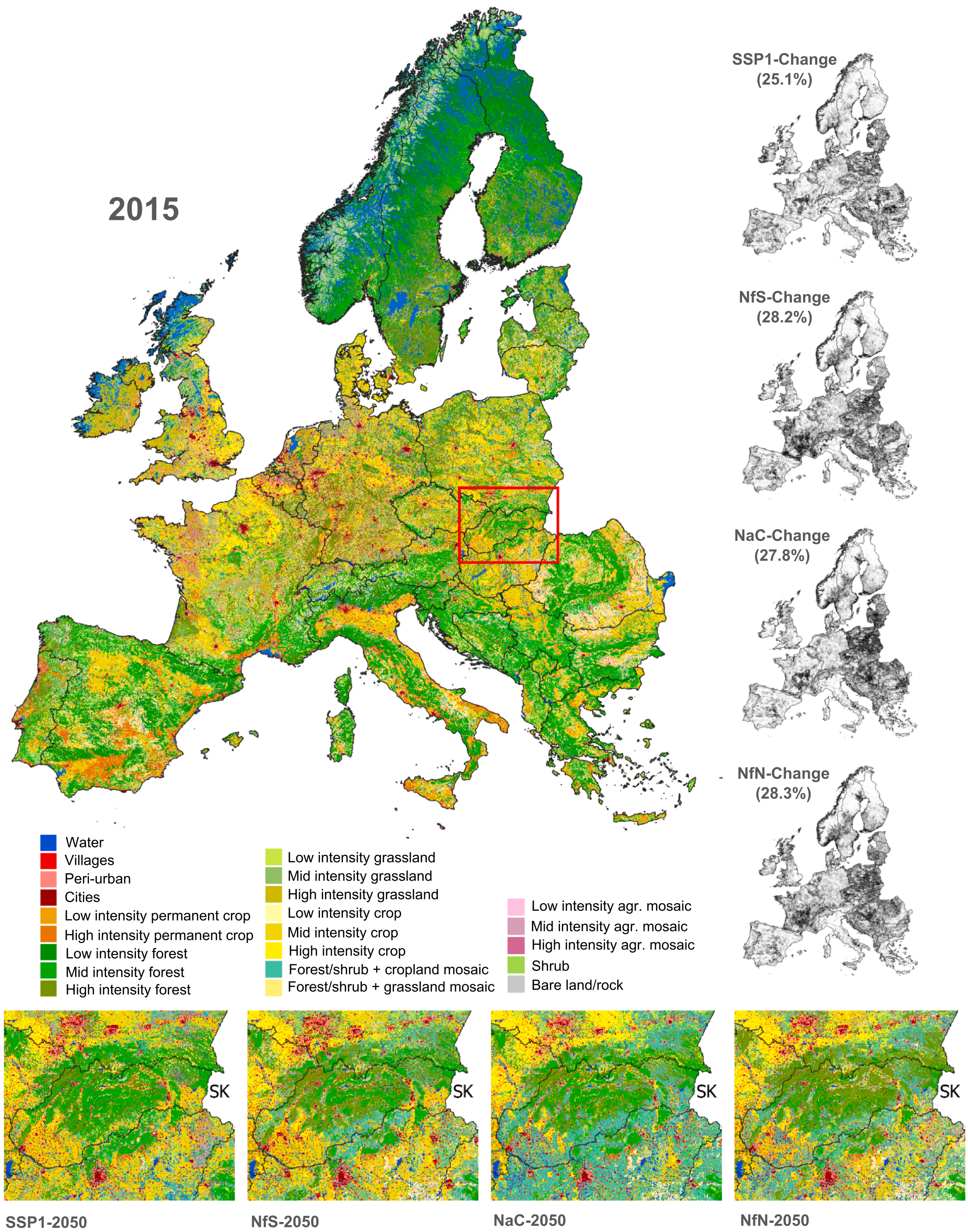

Fig. 3. Areas undergoing land system changes between 2015 and 2050 according to the reference SSP1 and three NFF scenarios. % values refer to the share of European land area undergoing change in each scenario.

the fewest land system conversions occur, and conversely lowest in the east (57 % agreement for this region in an SSP1 vs. Nature for Nature scenario) (Fig. 4, SI). With the exception of mid-intensity forest systems, the land systems showing the greatest consistency across scenarios (>75 % agreement) are also those most likely to remain unchanged throughout the simulation period (section 3.2.1), suggesting an agreement is most likely associated with stability rather than with a limited conversion possibility space.

On approximately 20 % of European land, our NFF scenario results therefore show divergent land conversion pathways that are likely to be promoted by different nature value perspectives. The results show the lowest agreement in the final distribution of high-intensity permanent crops and high-intensity agricultural mosaics (as expanding systems), alongside mid- and high-intensity grasslands, low-intensity crops, and low- and mid-intensity agricultural mosaics (as declining systems). The expansion of high-intensity permanent crops and agricultural mosaics primarily represents an intensification trajectory, as these systems replace low- and mid-intensity annual crops. Conversely, declining systems give way to new nature (frequently via de-intensification of grassland), and new forest/shrub mosaic systems. The expansion of mosaic systems is almost twice as extensive in the east region in a Nature as Culture scenario than in a Nature for Society or Nature for Nature scenario. In Slovakia, 28 % of land is comprised by new mosaics in a Nature for Culture scenario, a value which declines to 12 % in a Nature for Society scenario (Fig. 2). The expansion of mosaics is comparatively lower in the west region, as is the transition away from the mosaics class (Fig. 4). Cases of intensification similarly vary across the west and east regions, with the most cases occurring in the east region in a Nature for

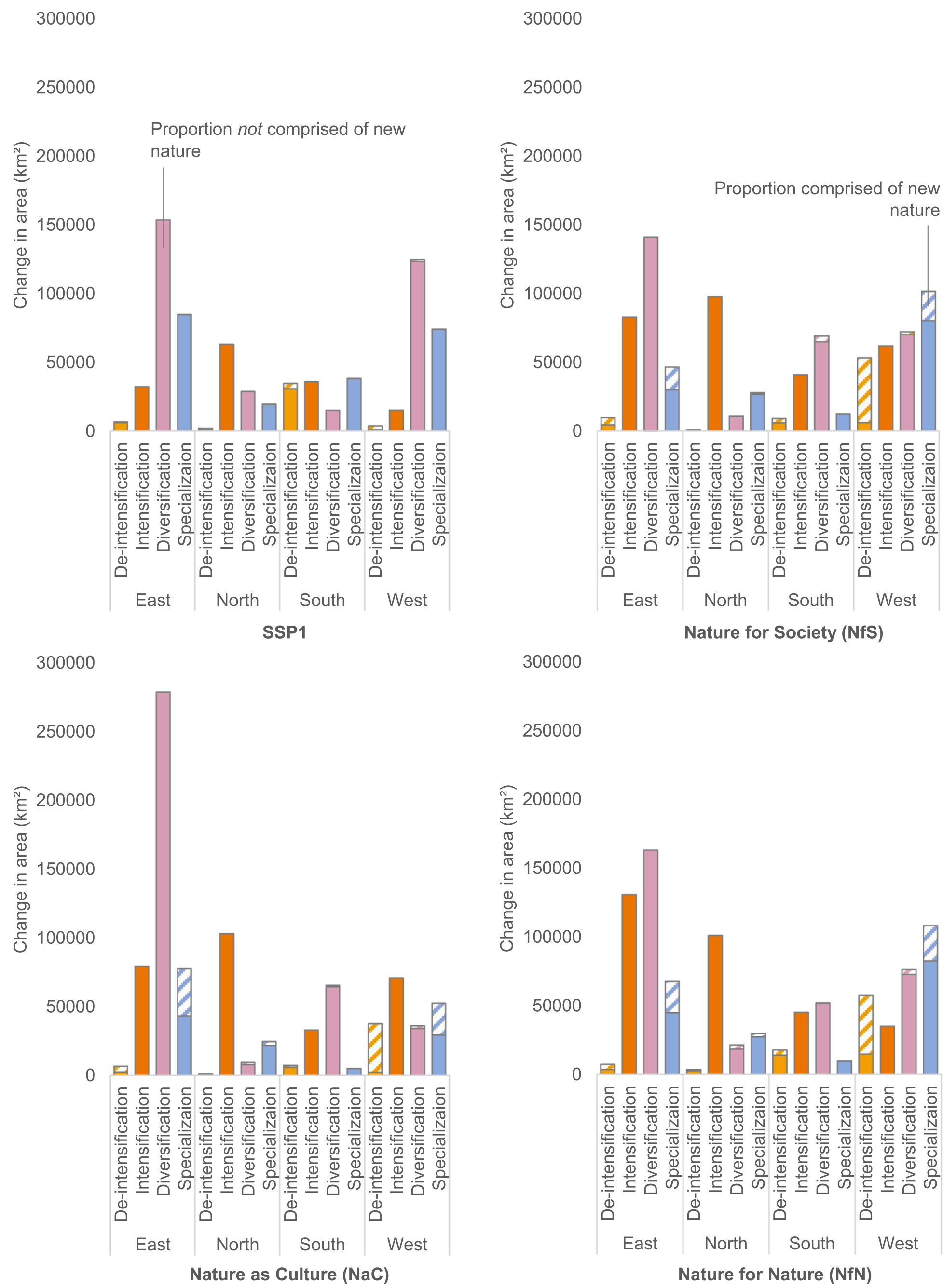

Fig. 4. Amount of land area undergoing an intensification (e.g., from the “low” to “high” intensity forest class), de-intensification, diversification (i.e., transitioning to a mosaics class), or specialization (i.e., transitioning away from a mosaics class) trajectory in each European region between 2015 and 2050 according to the reference SSP1 and three NFF scenarios. The proportion of area undergoing each trajectory and comprising a case of “new nature” creation is furthermore illustrated (i.e., transitions to the low-intensity forest, low-intensity grassland, or low-intensity agricultural mosaics classes from any other land system class).

Nature scenario, while the other scenarios see greater intensification occurring in the west.

4. Discussion

4.1. Meeting sustainability targets within an SSP1 scenario

Sustainability targets established under the Convention on Biological Diversity and the European Union’s Green Deal imply a structural reconfiguration of Europe’s current land systems. In this study, we investigated if and where future land system changes can take place to deliver all targets, as well as projected changes in population and commodity demands. We compared land system changes taking place in an SSP1 reference scenario, with additional changes taking place as a result of the implementation of sustainability targets, guided by three different perspectives on nature management aligned with the NFF. The most striking effects of the sustainability targets are found for grassland systems. Without the implementation of the “no-net-loss” and nature “restoration” targets, Europe would lose approximately one-third of its grasslands due to the declining demand for livestock and growing demand for wood and crop production foreseen by the SSP1 scenario. In the model simulation, the preservation and increase in low-intensity grasslands was achieved in part by directly increasing demands for these systems to meet the nature restoration target, but also by altering their competitive advantage towards meeting other goods and services. This implementation could represent explicit policy targets and incentives, such as payments to land owners, to foster such development. Similar patterns also appear in low-intensity forests in the NFF scenarios, as the implementation of sustainability targets pushes for the expansion of both low-intensity forests, serving as natural habitats for species, and productive forest plantations to fulfill increasing wood production demands (Chaudhary et al., 2016; Horák et al., 2019).

Besides forests and grassland systems, the implementation of sustainability targets also transforms European croplands substantially. This is partly caused directly by the target on the reduction of nitrogen use implemented in the NFF model settings, pushing for the replacement of medium with high-intensity croplands with higher productivity per unit of nitrogen requirement. In addition, our modelling results reveal this target will lead to the more indirect result of medium-intensity croplands being converted to multi-functional forest/shrub and cropland mosaic systems in order to deliver additional services beyond food. The trend of increased diversification is clearly exemplified in Slovakia (Fig. 3), where under the NFF scenarios approximately 20 % of the country's land, on average, will be characterized by new mosaics, vs. only 6 % in an SSP1 scenario. These transitions are likely to also be the indirect effect of the preservation and expansion of natural forests and grasslands, which require the implementation of both land sparing (through higher intensity cropland) and land sharing (by achieving synergies through multi-functional mosaics) approaches. Our results under the NFF scenarios are likely to lead to greater provisioning of a range of NCP (from habitat provisioning to carbon sequestration) due to the greater extent and targeted allocation of natural systems when compared to the reference SSP1 scenario, showing the value of implementing specific sustainability targets in addition to sustainable commodity demands.

4.2. *Alternative futures when prioritizing different values*

Scenario studies represent useful tools to demonstrate how different development, emissions, and policy choices can lead to alternative futures. However, most scenario studies describe and compare these choices without acknowledging their normative dimensions (Doelman et al., 2018; Malek and Verburg, 2021; Prestele et al., 2016; Sun et al., 2012; Wolff et al., 2018). Often, the way policy targets are implemented is implicit to the model assumptions or a choice of the researcher implementing the scenario into the model. Even in our own modelling study some normative choices remain implicit to the model's functionalities, e.g., by not changing the basic competitive functioning of the land allocation mechanism in the model, we implicitly assume that the scenarios will not change the current land market mechanisms. The different land use change pathways simulated by our scenarios by following the perspectives of the Nature Futures Framework underscore the importance of articulating differences in normative positions in modeling and scenario studies (Metzger et al., 2010; Meyfroidt et al., 2022; Nielsen et al., 2019), as considerable spatial tradeoffs were identified, especially within the west and east European regions where an average of 20 and 29 % of land systems respectively were found to differ. This plurality underlying spatial prioritization is, to the best of our knowledge, the first among land system scenario studies.

These results call for more explicit societal debate on nature management and the implementation of sustainability targets. According to a recent review (Pascual et al., 2023), only half of scenario planning studies that incorporate conservation planning explicitly mentioned values; with the majority of these being instrumental values. Our approach and results go beyond the often-used instrumental values of nature to cover intrinsic values and relational values. Comprehensively identifying and communicating these multiple values and their implications to a wide and varied public is necessary for ensuring land-based policies, which are often contentious, can be equitably designed and thus hope for successful implementations. By identifying potential areas of agreement or contention, our results highlight potential strategies policymakers can employ. For example, particularly within the north and south of Europe, the expansion of protected areas may largely be implemented in areas prioritized by all of the NFF scenarios to maximize the delivery of valued land-based services by different stakeholder groups. Even in the east some areas of agreement are found, as three-quarters of the expanded protected areas share high prioritization values for both species conservation and carbon sequestration. Alternatively, policymakers will need to evaluate the benefits and losses associated with the different land system change trajectories presented by different valuations of nature. Examples of participatory processes successfully navigating conservation planning by making use of the NFF are encouragingly being developed (Kuiper et al., 2022).

4.3. *Feasibility of sustainability targets across regions and scales*

Our simulation study shows that European land systems can deliver upon sustainability targets for 2050 while also meeting societal demands for shelter, crops, timber, and livestock as projected by the SSP1 scenario (which implies shifts towards more sustainable consumption). Meeting these sustainability targets and societal demands will induce a conversion in 27–28 % of European land systems, only marginally larger than the 25 % result for an SSP1 scenario without additional sustainability targets. When compared to historical trends over the 1990–2016 period for the EU-27, where approximately 43 % of land systems witnessed a transition (Levers et al., 2018), our simulation thus foresees levels of change that are certainly not unprecedented (although these values do not account for within-class changes, e.g., in productivity). This is in part due to increased intensification over the recent period, which limits possibilities for future conversions, but also due to future policies deliberately aiming to stabilize some systems (e.g., natural systems) while limiting or witnessing declining demands for others (e.g., reduced livestock). It also undoubtedly reflects a discrepancy between real-world processes and simulations representing optimized allocations. Nonetheless, this comparison highlights that while our results foresee substantial changes to Europe's land systems, these are also in line with the magnitude of change that Europe has witnessed in its recent past.

Under the NFF scenarios, for example, areas undergoing annual cropland intensification represent on average 0.8 % of Europe's land area, in contrast to the 3 % identified over the 1990–2016 period (Levers et al., 2018). This is over two times as much land area in comparison to the reference SSP1 scenario. In addition to increased cropland intensification, the sustainability targets will further transform Europe's land systems by increased land sharing (Fischer et al. 2014), as diversification of cropland (e.g., transitions to the forest/shrub and cropland mosaics class) is also more prominent in the NFF scenarios, representing 4.5 % of Europe's land area, on average, compared to 3 % under SSP1. This trend is aligned with findings from other simulation studies which also find a slight preference for land sharing (Karner et al., 2019). At the same time, it shows that in realistic land use developments, different pathways of change are likely to happen alongside one another, depending on the local comparative advantage of these pathways.

Certain targets could, on the other hand, not be completely met in some regions due to greater pressure on these regional land systems. The target of reducing nitrogen applications by 40 % in 2050 was relaxed to 30 % in the south region, resulting in 1.2 million kilograms higher nitrogen input than the original target. However, the total nitrogen application rate in the south remains low and is less than a fifth of the nitrogen use in the west in 2050. Similarly, the productivity of mid- and high-intensity forests for wood production was increased in order to meet demands for wood in NFF scenarios in the east and west regions, as projected increases in demand outstrip the possibility of expansion of productive forests. This means that our projected trends for forest intensification are more widespread than what has been witnessed during the 1990–2016 period (Levers et al., 2018). While timber yield increases in the forestry sector are possible, these are increasingly challenged by climatic changes (Hanewinkel et al., 2013). This competition for land resources is likely to dominate land use issues in Europe in the future. Only when consumption is sufficiently lowered (as already assumed under the SSP1 scenario) it is feasible to meet sustainability targets. Under higher demands for agriculture and wood products, it is unlikely that sustainability targets can be achieved.

How these sustainability targets will be implemented in practice needs to address equity considerations and account for regional differences. In this scenario study, we divided the sustainability targets based on the baseline characteristics of four different European regions. However, we acknowledge that this approach is relatively simple and crude, as targets will likely need to be implemented at finer scales, for example at national or sub-national levels (Mehrabi et al., 2018). National level implementations of sustainability targets may perhaps have yielded meaningful results to policymaking, yet national sustainability plans are not always available. In their absence, our regionalized approach offered the advantage of representing some of the existing variation in baseline conditions across Europe, while simultaneously presenting an equitable approach to target contributions, as countries more constrained in their land system conversions were required to make fewer changes than countries with greater flexibility. Furthermore, a regionalized approach may be more suited to sustainability targets addressing the expansion and restoration of nature – as these are likely to address transboundary areas and ecological corridors in Europe which are sometimes specified by biome or region rather than at the national level. Importantly, altering the scale of implementation will result in different land system outcomes. Evaluating the influence of scale (whether at national, sub-national, or (eco)regional levels, as investigated by (Mehrabi et al. 2018)) is therefore important. Additional reflection is similarly required on our use of a single variable to capture the normative value guiding nature management in each NFF perspective (e.g., carbon sequestration was used to guide the prioritization of protected area expansion, representing the valued delivery of ecosystem services in a Nature for Society scenario), while multiple value criteria can (and likely would be) used to guide the implementation of sustainability targets following a participatory process (Quintero-Uribe et al., 2022).

4.4. Methodological limitations

Our translation of ambitious sustainability targets into the CLUMondo models has some limitations. We did not, for example, account for how different land systems will respond to the per-unit nitrogen reduction target in terms of changes to crop yields (Mueller et al., 2012), instead assuming that management and technological advancements will be able to compensate for any losses and maintain the same yield increases foreseen by the SSP1 outlook. We also lacked data on nitrogen inputs of permanent crops, and hence did not account for their nitrogen contributions. For the no-net-loss and nature restoration targets, we categorized all low-intensity grassland and forest systems as natural systems, yet these may not always reconcile with natural ecosystems, while other semi-natural classes (such as the forest/shrub mosaic classes) may on the other hand incorporate significant natural patches of value to biodiversity (Lindenmayer, 2019). This is especially relevant as the expansion of low-intensity grasslands in the NFF scenarios could in some models only be met through the replacement of areas of forest/shrub mosaic – yet determining whether this conversion is truly desirable from a biodiversity perspective would require a more careful evaluation. This could be achieved by accounting for natural elements in different systems, rather than the presence/absence of natural land system classes (Schulze et al., 2021), alongside a more detailed representation of restoration processes and timescales. Ultimately, determining which systems and characteristics will define the natural areas to be protected and restored under sustainability targets will also involve stakeholder deliberation and careful investigation of the repercussions of different value-laden definitions of nature on the provisioning of ecosystem services.

5. Conclusion

Using a land system simulation approach, we implement a novel scenario perspective to explore the potential for sustainable land use futures in Europe. In particular, our study highlights how different implementations of sustainability targets make a difference, even within a Shared Socioeconomic Pathway reference scenario of sustainable consumption. The comparison with the reference scenario shows how the targets established under the Global Biodiversity Framework and the European Union's Green Deal make an important contribution to nature conservation. Without these, Europe would further lose its already at-risk low-intensity forest and grassland ecosystems by 2050. Our results further illustrate that multiple implementation pathways are possible to achieve the desired targets, especially within eastern and western Europe, reflecting different perspectives on nature management aligned with the Nature Futures Framework. This plural and normative framing around target implementation can prove pivotal to the identification of synergies and trade-offs, paving the way for more effective decision-making.

CRediT authorship contribution statement

Yue Dou: Conceptualization, Methodology, Data curation, Writing – original draft. **Cecilia Zagaria:** Conceptualization, Methodology, Data curation, Visualization, Writing – original draft. **Louise O'Connor:** Data curation, Writing – review & editing. **Wilfried Thuiller:** Writing – review & editing, Funding acquisition. **Peter H. Verburg:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

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.

Data availability

All 2050 land use scenarios can be downloaded at: https://doi.org/10.34894/NWGCBY

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2023.102766.

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