BIOCLIMA: Assessing Land use, Climate and Biodiversity impacts of land-based climate mitigation and biodiversity policies in the EU

Technical Report

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1. Executive summary

Project Objectives

The EU Fit for 55 Package and the EU Biodiversity Strategy for 2030, have underscored the role that the agriculture and forestry sectors will have in tackling climate change, protecting the environment and preserving or restoring biodiversity. Exploratory scenario analyses in the 'Clean Planet for All (1)' Communication5 identified important linkages between these objectives that could be synergistic but also antagonistic, depending on the land-use policies applied and their geographic location. Such challenges call for significant advances in integrated land-use planning and policy design. With the call for tender ENV/2020/OP/0014 the European Commission's Directorate General for the Environment has identified the need to explore the potential synergies between the climate change and biodiversity agenda with scenarios and models

The BIOCLIMA consortium has responded to this call with a proposal whose overarching goal is to ***provide a robust ex-ante assessment of the possible impacts and synergies of current EU policies on biodiversity and climate.***

To achieve this goal, the consortium, in collaboration with the Project Steering Committee has designed specific land-use scenarios, indicators and analyses addressing the following questions:

1. What are the impacts on biodiversity of expected land-use under the Reference scenario, (that is, in absence of the Fit for 55 and EU Biodiversity Strategy) and how would measures aimed to achieve climate targets for the LULUCF sectors affect biodiversity compared to the Reference scenario?
2. What would be the contribution to climate mitigation of alternative potential implementations of habitat restoration and conservation targets under the EU Biodiversity Strategy?
3. What is the combined impact of climate and biodiversity policies on land-use change and associated emissions? Which combinations of climate mitigation and biodiversity conservation measures yield positive additive effects and which combinations have contrasting effects on land-use and GHG emissions?
4. What is the combined impact of climate and biodiversity policies on biodiversity indicators? Which combinations of climate mitigation and

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(1) Brussels, 28.11.2018 COM(2018) 773 final

biodiversity conservation measures yield positive additive effects and which combinations have contrasting effects on biodiversity?

5. What are the most important data and modeling gaps that need to be addressed to improve the assessment of carbon stocks and biodiversity impacts from land-use policies?

Scenarios

To address the project objectives, we designed four different sets of scenarios that broadly reflect land-use policies for climate mitigation and biodiversity conservation.

The **BIOCLIMA Reference scenario** is directly based on the official EU 2020 Reference scenario (also used for the modelling of EU energy and climate policies). This Reference scenario is used to test the improved model suite and the linkages between land-use and biodiversity models from task 3 (2) and sets a benchmark against which we compare the other scenarios in terms of land-use (change) and associated LULUCF emissions and biodiversity for the EU until 2050. The scenario is designed as a business-as-usual scenario. Behavioural, demographic, macro-economic and technological assumptions are extrapolation of present trends and are described in chapter 2 of the EU Reference Scenario Report. No additional protection nor restoration is assumed compared to what existed in 2020. No policy is applied to incentivize additional climate mitigation beyond the current trend. In addition to the Reference scenario, we consider five **Climate policy scenarios** that cover the spectrum of land-based mitigation options that would contribute to ambitious climate change mitigation efforts. These includes two levels of ambition with regards to LULUCF mitigation efforts, and three assumptions about Biomass for energy demand, which yields five Climate policy scenarios plus the Reference scenario (the combination of no additional LULUCF mitigation efforts and reference level biomass demand. We then evaluate their impact on LULUCF emissions and sinks and on biodiversity indicators.

In the **Biodiversity policy scenarios,** we simulate different potential implementations of the Nature Restoration Law (NRL) in addition to protecting all old-growth and primary forests, which is a common feature of all scenarios. In total we simulated nine combinations of three assumptions about burden-sharing of restoration efforts and three assumptions on the relative emphasis given to prioritizing restoration efforts (for biodiversity mostly, for carbon sequestration mostly, or equally weighting biodiversity and carbon when setting spatial priorities for restoration). We produce a selection of **Integrated scenarios** that combined the Climate policy scenarios with the three assumptions about NRL implementation burden sharing and adopt the assumption of balanced priorities between biodiversity

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(2) Available upon request to the lead author

and carbon for NLR implementation. This resulted in a total of 18 different integrated scenarios, a subset of which are analyzed in-depth in this report.

Land-use change impacts of Reference scenario and Climate policy scenarios.

Overall, the Reference scenario (REF hereafter) is projected at the EU27 level to lead, by 2050, to a moderate increase in the extent of forest, a small decrease in the extent of agroecosystems and non-forest semi-natural vegetation (transitional woodland and shrubs, heathland and shrubs, unmanaged grassland), and a small extensification of the management of agroecosystems and forests. Other semi-natural ecosystems - urban, sparse vegetation, wetlands, marine and coastal waters - are stable by assumption. Limited and temporary increases in cropland extent and management intensity are however projected by 2030, due to a limited and temporary increase in domestic demand for cereals and sugar beet products.

Overall, at the EU27 level the alternative enhanced Climate policy scenarios could have contrasted land-use change impacts. On the one hand, assuming high lignocellulosic crop biomass demand for energy (as simulated by the PRIMES model) is projected to reverse the decline in cropland, exacerbate the decline in the extent of non-forest semi-natural land covers and to slightly reduce re/afforestation. On the other hand, the application of a 10 EUR/tCO2 carbon price to simulate all policies and local actions that would increase the LULUCF carbon sink slightly enhances re/afforestation trends and generates a mix of significant forest management extensification (through conversion of production-oriented forest to high-intensity multipurpose forests) and intensification (through a conversion from low-intensity multipurpose forests to production-oriented forests) over 2030-2040, partly reverted by 2050 and leading to decreases in deadwood carbon stocks. This carbon price stimulates land-cover and land-use changes that reduce emissions and increase atmospheric carbon removal. This includes extending the forest rotation time. However, the time gap between wood demand and reduced wood harvest, due to extended rotation times, leads to an increase in local wood price and a redistribution of harvest to neighbouring forests. As a result, in scenarios with LULUCF sink enhancement policies, some low-intensity multipurpose forests are converted to production-oriented forests.

Land-use change impacts of Biodiversity policy scenarios.

Overall, at the EU27 level all three increased biodiversity restoration and protection scenarios under the Reference scenario (no land-based Climate policies included) lead to successful extensification of restored managed forest and agricultural land without changing much the projected changes to the extent of various ecosystems. Restoration of managed grassland and cropland however lead to a slight decrease in the consumption of ruminant products through increased prices induced by the assumed lower productivity of cropland and managed grassland, while restoration of forests in some regions has leakage effects (intensification) in other forested regions of the EU. Variations in burden sharing assumptions have limited effect, but assuming that restoration targets by ecosystems are strictly met at the EU-MS level could lead to a slightly higher contribution of forest (relative to grassland) ecosystems to restoration efforts than if more flexibility is allowed.

Land-use change impacts of scenarios combining climate mitigation and biodiversity conservation measures.

Overall, there is limited interaction across the climate change mitigation and increased protection and restoration scenario dimensions as the effects are mostly additive – i.e., the effects on land use of a scenario combining assumptions on both dimensions are broadly equivalent to the sum of effects from scenarios based on related assumptions on each dimension alone – except for the management of forest ecosystems and that of managed grasslands. As compared to applying land-based climate change mitigation policies alone, adding increased protection and restoration does not moderate cropland expansion from climate mitigation efforts relying on high biomass demand, in other words, because restoration and protection do not affect demand for biomass, these area-based conservation measures displace, rather than reduce cropland expansion in scenarios that simulate increased reliance on energy crops. Climate change mitigation policies are not incompatible with extensification of pasture and cropland from increased conservation and restoration. The trade-offs between mitigation and restoration objectives become stronger in the forestry sector, where the impact of climate policies dominates and limits net restoration benefits, but increased protection and restoration allow to buffer related changes in management, and deadwood losses on the long run which will still be high unless future biomass demand is lowered.

Carbon emissions associated with the Reference scenario and climate mitigation policy scenarios.

In the REF scenario, the level of LULUCF net removals stabilizes at approximately 270 million tons of CO2 per year (MtCO2eq/yr) over 2030-2050, despite a decrease in forest management sink (from ~270 in 2020 to ~260 in 2030 and ~230 in 2050), and the EU LULUCF target of a 310 (MtCO2eq/yr) per year by 2030 sink is thus not met in the Reference scenario.

Climate mitigation policies scenarios that include incentives to enhance the LULUCF sink reach the 2030 net removal target for LULUCF emissions. This is due to an increase in the forest land sink and a faster decrease in deforestation emissions. Increased demand of biomass for energy production in absence of incentives for emission reductions, would however lead to a reduction in the carbon sink.

Carbon emissions associated with Biodiversity policy scenarios.

The increased protection and restoration scenarios are projected to lead to climate change mitigation benefits compared to the Reference scenario, through increases in forest set-aside for forests with high carbon sequestration and storage potential, modest and uncertain by 2030, but potentially larger by 2050 (as compared to REF scenario, up to 17 MtCO2/yr less reduction in forest management sink from 2020 to 2050) which represents almost half of the required increase in the LULUCF sink needed to achieve climate mitigation targets for the LUCUF sector.

Carbon emissions associated with scenarios combining climate mitigation and biodiversity conservation measures.

In the integrated policy scenarios, projections of LULUCF emissions by 2050 are dominated by assumptions about climate change mitigation efforts in the forest sector, with protection and restoration leading to a negligible additional impact by 2030 but a moderate increase in forest management sink by 2050 for scenarios without carbon price, showing some additivity. Restoration and protection show no additivity in terms of LULUCF emissions reductions and removals when implemented together with a carbon price.

Biodiversity impacts of expected land-use under the Reference scenario and climate mitigation policy scenarios.

Our results suggest that in the Reference scenario, in absence of any climate change mitigation policies or biodiversity policies, macro-economic, demographic and technological drivers of change may continue to exert pressure on species habitats which may result in declines by mid of the century although there is a degree of uncertainty about projected impacts of the Reference scenario for mean relative local abundance and biodiversity intactness and there might be small (<1%) increases in local species richness and similarity of species composition with respect to local reference (pristine) conditions.

The application of an implicit carbon price causes a modest average increase in biodiversity as measured through species suitable habitat as well as community-based biodiversity metrics. The direct causes of this increase are an increase in forest rotation time, larger forest area because of reduced deforestation and an increased afforestation, as well as a lower conversion of semi-natural non-forest habitats compared to scenarios without LULUCF sink enhancement policies. Scenarios simulating an increase in production of energy crops to replace fossil fuels, result in the expansion of cropland and timber harvest with generally negative impacts on biodiversity, both at species level and community level.

We observe that the systemic projected decreases in intensively managed annual cropland observable in all scenarios, including the Reference scenario, could yield some benefits for open-habitat species, if partially replaced with cropland or grassland managed at low intensity, rather than being afforested as explored here with scenarios where an increased biomass demand is assumed.

The combination of a carbon price and increased biomass demand produces antagonistic effects on species suitable habitat, local abundance, compositional similarity and Biodiversity Intactness Index. Specifically, increasing demand for biomass from forest products and annual and permanent cropland results in a larger increase in intensively managed forest and energy crops, and this reduces the positive effects of the carbon price in terms of rotation time and forest cover.

Biodiversity impacts of scenarios combining climate mitigation and biodiversity conservation measures.

We find that a carbon price can create a financial incentive for reducing deforestation and for de-intensification of cropland and grassland management to reduce net emissions from LULUCF, which in our analyses of integrated policy scenarios was strategically directed to restore areas with the highest biodiversity benefits using maps of restoration priorities; thus creating potential synergies between climate policies and biodiversity policies, especially when assessing benefits through species habitat gains.

Restoration benefits deriving from modelled impacts of the Nature Restoration Law are also observed when considering compositional similarity, local abundance and biodiversity intactness, but not when estimating local species richness. The latter could be driven by increase in generalist species, colonizing managed ecosystems.

Caveats and priorities for model development.

The carbon removal potential of restoration actions in forest ecosystems is certainly an underestimate because soil organic carbon accumulation is not considered in our analyses, and this is especially important when considering restoration of drained peatlands, which is also expected to bring about gains in habitat for several species of EU conservation concern.

Furthermore, emissions and removals associated with restoration’s impacts on the management of cropland and grasslands were not considered and this may lead to an additional underestimation of the climate change mitigation potential of restoration actions. Additional data and model improvements are required to better simulate changes in land management and associated emissions in cropland, managed grasslands and wetlands, and these should be considered for further research and policy support.

Furthermore, models and indicators of ecosystem resilience to natural and anthropogenic disturbances and stressors, such as fires and drought conditions is a key area of development for monitoring the implications of alternative management choices that should be priorities for scenario evaluation of land-use policies.

2. Introduction

The EU Farm to Fork (F2F) Strategy and the EU Biodiversity Strategy for 2030, adopted in the first half of 2020, have underscored the role that the agriculture and forestry sectors should play in tackling climate change, protecting the environment and preserving or restoring biodiversity. Exploratory scenario analyses in the 'Clean Planet for All' Communications5 identified important linkages between these objectives that may either work together or in some cases be antagonistic. Such challenges call for significant advances in integrated land-use planning and policy design. With the call for tender ENV/2020/OP/0014 the European Commission's Directorate General for the Environment has identified the need to explore the potential synergies between the climate change and biodiversity agenda with scenarios and models projecting the expected biodiversity and climate change outcomes of alternative policies, and to identify policy bundles that maximize positive outcomes for both.

The BIOCLIMA consortium has responded to this call with a proposal whose overarching goal is to *provide a robust ex-ante assessment of the possible impacts and synergies of current EU policies on biodiversity and climate.*

The project work was divided into 5 tasks:

- Task 0: Inception phase.
- Task 1: Review of the models available to forecast land-use change, LULUCF emissions and removals and biodiversity responses. (3)
- Task 2: Review of national policies and their implementation.(3)
- Task 3: Model data update and development.(3) A short description of the biodiversity models and scenarios is also in chapter 2 of this document.
- Task 4: LULUCF and biodiversity scenarios generation and evaluation.

This document constitutes the report of Task 4, that concludes the work of the BIOCLIMA project.

Task 4 of the BIOCLIMA project aims to answer the following questions:

1. What are the impacts on biodiversity of expected land-use under the Reference scenario, (that is, in absence of the Fit for 55 and EU Biodiversity Strategy) and how would measures aimed to achieve climate targets for the LULUCF sectors affect biodiversity compared to the Reference scenario?

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(3) Available upon request to the lead author.

2. What would be the contribution to climate mitigation of alternative potential implementations of habitat restoration and conservation targets under the EU Biodiversity Strategy?
3. What is the combined impact of climate and biodiversity policies on land-use change and associated emissions? Which combinations of climate mitigation and biodiversity conservation measures yield positive additive effects and which combinations have contrasting effects on land-use and GHG emissions?
4. What is the combined impact of climate and biodiversity policies on biodiversity indicators? Which combinations of climate mitigation and biodiversity conservation measures yield positive additive effects and which combinations have contrasting effects on biodiversity?
5. What are the most important data and modeling gaps that need to be addressed to improve the assessment of carbon stocks and biodiversity impacts from land-use policies?

In chapter 3 of this document, we describe the scenarios developed to answer these questions. In chapter 4 we analyse the land-cover and land-use impacts to 2030, 2040, and 2050 of the scenarios. In chapter 5 we explore the CO_2 emissions associated with these scenarios and in chapter 6 the biodiversity impacts. In chapter 7 we discuss our results to provide answers to questions 1-4 above, and in chapter 8 we attempt to provide some answers to question 5 based on the experience of BIOCLIMA.

3. Scenarios description

3.1. Scenario characteristics

The scenarios are designed to capture the most important modellable regulatory instruments (e.g., restrictions on use of land, for example extractive activities in old growth forest, or provisions of the Nature Restoration Law), GHG emission targets in the land use sector (e.g. the LULUCF Regulation EU-level net removal target of 310Mt CO_2e by 2030) and other quantitative or qualitative sectorial projections (e.g. about energy mixes to achieve climate targets in the energy sector) for the policy packages and strategies of relevance for BIOCLIMA.

Together with the BIOCLIMA Steering Committee, we identified key scenarios to span the space of relevant alternatives while allowing to stay focused. These scenarios differ from each other on a small number of dimensions that are at the same time policy relevant and modellable at the European scale.

For what concerns climate policies we varied two dimensions:

Biomass demand: Biomass demand from the energy sector as quantified by the PRIMES energy model. We contrasted 3 different Biomass demand scenarios (detailed in the next sections).

LULUCF carbon removals: We considered a carbon price of 10 euros/t C02e applied to the LULUCF sectors, consistent with the target of 310 MT of CO2 of net annual sink by 2030 with a progression beyond 2030 to achieve climate targets for 2040 and 2050 (Figure 1). The carbon price in GLOBIOM-G4M is used as a proxy for all incentive measures that could stimulate landowners and managers to sequester more carbon in biomass and soil.

For what concerns biodiversity policies, we varied the following dimensions:

Burden sharing. The EU Nature Restoration Law proposal does not prescribe a specific maximum burden share to be shouldered by each country, therefore a plausible simulation of the NRL is that of an ‘Unconstrained scenario’ in which conservation and restoration areas can be placed without limits to the amount of restoration shouldered by any country, which means that countries with large proportion of land in poor ecological conditions may theoretically need to restore more than 20% of their land (the EU-level headline target of the Nature Restoration Law); given uneven biodiversity distribution, optimizing restoration effort without limits to burden sharing may result in larger biodiversity gains, but very uneven restoration effort across countries. To explore the expected biodiversity and carbon gains of different burden sharing scenarios we tested 3 options, detailed in the next sections.

Relative importance given to restoration priorities: carbon stocks *versus* species habitats. The geographic distribution of restoration and conservation priorities will change depending on the emphasis given to either of them, we therefore explored a continuum of options by varying the weight given to achieving quantitative targets for carbon stock gains and species habitat gains. For practical purposes we further analyzed the effect of 3 scenarios within this continuum, one with more emphasis given to carbon storage and sequestration, one with higher emphasis on biodiversity gains, and one with equal priority given to both (details below).

3.2. Reference scenario (REF)

The BIOCLIMA Reference scenario is directly based on the official EU 2020 Reference scenario (also used for the modelling of EU energy and climate policies). This Reference scenario is used to test the improved model suite and the linkages between land-use and biodiversity models from task 3 (4) and will set a benchmark for the climate and Biodiversity policy scenarios developed in task 4.2 in terms of land-use (change) and associated LULUCF emissions and biodiversity for the EU until 2050.

The scenario is designed as a business-as-usual scenario. Behavioural, demographic, macro-economic and technological assumptions are extrapolation of present trends and are described in chapter 2 of the EU Reference Scenario Report, and in more detail in Annex II and III of the same report.

The EU is assumed to be an open economy in the reference scenario. For the implementation of climate or biodiversity policies, the trade is capped at the Reference scenario levels, thus the climate and biodiversity scenarios cannot exceed the trade levels (I.e., less or equal imports, higher or equal exports) to avoid leakage effects to the rest of the world.

In this scenario neither additional protection nor restoration is assumed compared to what existed in 2020, and no policy is applied to incentivize additional climate mitigation beyond the trend.

Biomass demand from the energy sector is quantified by the PRIMES energy sector model for the EU Reference scenario (Table 1) (5). In the EU Reference scenario biomass is increasing over time from all major sources (crops, forestry,

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(4) Available upon request to the lead author.

(5) The following biomass types are considered from the GLOBIOM/G4M side: Forest logging residues, forest industry residues, stem wood, perennial lignocellulosic crops (e.g., miscanthus and switchgrass), food crops (wheat, sugar beet, sunflower, rapeseed. Million tons of Oil Equivalent of BIOMASS productions are in Table 1.

waste). Crops production for 1st generation biofuels is reduced after 2030 while lignocellulosic crops production increases.

Af/Re-forestation is limited to areas suitable for forest ecosystems. Wetlands and priority areas for conservation of open-habitat biodiversity are not afforested in accordance with the guidelines on biodiversity friendly afforestation and tree planting (6).

All areas in the upper 10% probability of being old-growth or primary forest among all forest pixels are protected by 2020, i.e., included in the set-aside management zone to restore natural dynamics and old-growth elements, in terms of structural complexity and disturbance levels. This means that in our analyses we protect an area of ~15 Mha, which includes, approximately 3% of all EU forest area that is currently classified as primary or old growth (European Commission. Joint Research Centre. 2021) and an additional 7% of forest area that is closer to be considered old growth if management was suspended. Hence, the selection performed is compatible with the protected area targets and associated guidelines of the EU Biodiversity Strategy.

Table 1 – Biomass production in the EU27 MS under the EU Reference Scenario.

Source of biomass	2000	2005	2010	2020	2030	2040	2050
Crops	807	3758	12966	21378	26785	22078	29240
- Wheat	57	829	3212	4653	8628	8045	3107
- Sugar beet	48	100	702	2321	3266	1406	444
- Sunflower/Rapeseed	702	2829	9051	14332	11277	4221	1643
- Lignocellulosic Crops	0	0	0	72	3614	8407	24046
Forestry	18871	28245	29987	41957	51151	59233	56410
-Harvestable Stemwood	11272	18853	20239	27388	29533	31308	27311
- Residues	7599	9392	9747	14569	21618	27925	29099
Waste	27719	36330	52485	67362	75572	74666	72221
- Solid	25398	31366	40213	50649	57651	52895	45640
- Gas	2261	4321	10060	13699	14215	17328	21517
- Oil Fats	60	643	2212	3014	3706	4442	5064
Black Liquor	13920	15207	14199	13377	13693	14029	14067

Source: EC (2021a): EU reference scenario 2020, Luxemburg, doi:10.2833/35750. Data available here.

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(6) European Commission (2023). Commission Staff Working Document Guidelines on Biodiversity-Friendly Afforestation, Reforestation and Tree Planting. SWD(2023) 61 final

3.3. Climate policy scenarios

All other scenarios have the same macro-economic, demographic, behavioral (e.g., discount rate in adoption of more sustainable technologies) assumptions as in the Reference scenario. The approach to tree-planting and the protection of old growth and primary forest are accounted for in the CClimate policy scenarios in the same way as in REF.

Below we describe the main differences in the CClimate policy scenarios compared to the Reference scenarios.

3.3.1. Low biomass demand scenario (LOW)

This scenario is identical to the REF, except for the projected biomass demand from forest: it stabilizes at the 2030 levels of about 20 Mtoe for forest residues, and about 30 Mtoe for roundwood.

3.3.2. High biomass demand scenario (BIOM)

In this scenario, additional climate mitigation efforts are translated by 2050 in a five-fold increase in production of lignocellulosic crops (from 24 to 133 Mtoe) as compared to the Reference scenario, and a moderate increase in biomass from forestry activities (from 56 Mtoe to 65).

Table 2 – Biomass production (ktoe) in the EU27 MS under the Fit for 55 scenario

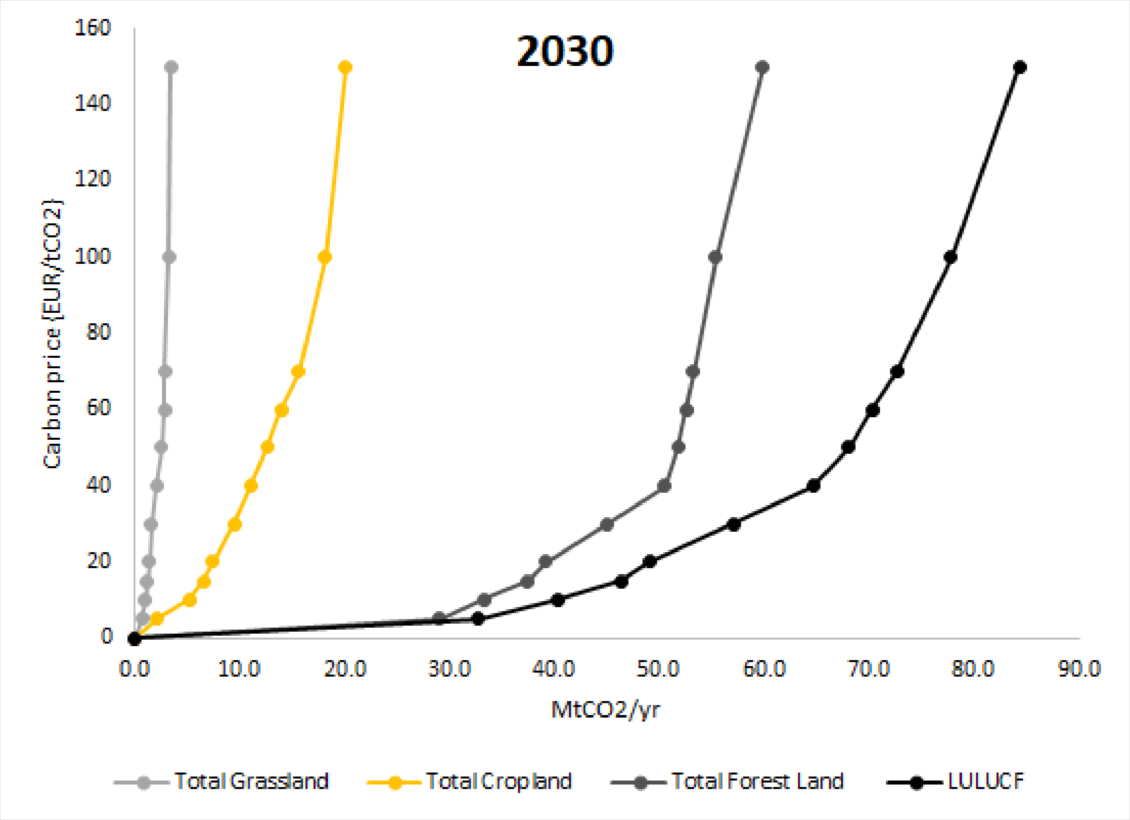
Source of biomass	2000	2005	2010	2020	2030	2040	2050
Crops	807	3758	12966	21643	24954	104411	139368
- Wheat	57	829	3212	5014	8905	11746	5930
- Sugar beet	48	100	702	2277	3646	727	35
- Sunflower/Rapeseed	702	2829	9051	14281	11965	2627	306
- Lignocellulosic Crops	0	0	0	72	438	89310	133097
Forestry	18871	28245	29987	42031	48593	70051	65532
-Harvestable Stemwood	11272	18853	20239	27405	28476	37967	33235
- Residues	7599	9392	9747	14627	20117	32084	32297
Waste	27719	36330	52485	68099	74024	73811	76212
- Solid	25398	31366	40213	49964	54945	41470	41999
- Gas	2261	4321	10060	15120	15373	27899	29149
- Oil Fats	60	643	2212	3014	3706	4442	5064
Black Liquor	13920	15207	14199	13377	13693	14029	14067

Source: EC (2021a): EU reference scenario 2020, Luxemburg, doi:10.2833/35750. Data available here.

3.3.3. Low biomass scenario with LULUCF policies (LOW_LULUCF)

This scenario combines the LOW scenario for what concerns biomass demand with a carbon price of 10 euros/ton applied on the emissions and sinks from the LULUCF sectors, consistent with the target of 310 Mto of CO_2 per year of net annual sink by 2030, leading to an increase of ~40 Mto removals in the LULUCF sector compared to the baseline.

Figure 1 – Marginal Abatement Cost Curves for the LULUCF sector in 2030



Note: Mitigation potentials from rewetting of histosols are not included in the current modelling framework but are assumed to contribute ~30 MtCO2equ/year to the target of the LULUCF Regulation of -310 MtCO2equ/year.

3.3.4. Fit for 55 scenario (FF55)

This scenario combines the BIOM scenario for what concerns biomass demand with a carbon price of 10 euros/ton applied on the LULUCF sectors.

3.3.5. Biodiversity policies scenarios

In addition to protecting all old-growth and primary forests, a common feature of all scenarios, these scenarios include simulations of different approaches to implementing the Nature Restoration Law.

We explored three options for allocation of restoration efforts across countries:

- **Unconstrained burden-sharing (*BC_CF scenarios)**: there is no minimum no upper bound in the fraction of land area that a country can restore; the only target is that 15% of EU land area that is currently under extractive or productive activities is under some form of restoration by 2030 as estimated in the impact assessment of the Nature Restoration Law. (7)
- **Even burden sharing (*BC_CT scenarios)**: each country must restore 15% of their land area.
- **Flexible burden sharing (*BC_CX scenarios)**: there is no minimum bound on restoration, but there is an upper bound of 25% of a country land-area that can be restored. This scenario allows for some flexibility without imposing a very large burden on any country. This variant is also applied to the Integrated Policy Scenarios.

We also explored three options to explore the implications of focusing restoration efforts for climate mitigation or biodiversity conservation purposes:

- **Carbon optimized:** NRL focussed on areas with high carbon value, specifically a 1% gain in carbon stock is valued twice as much as a 1% in total gain in suitable habitat across species. For details see section 2.7.4 in BIOCLIMA data and model descriptions (8) or Chapman et al. preprint.
- **Biodiversity optimized:** NRL focussed towards high biodiversity areas (9), a 1% gain in suitable habitat across species is valued twice as

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(7) The Impact Assessment of the Nature Restoration Law provides some estimates of the plausible allocation of restoration efforts across ecosystems. The estimates in the NRL IA for improvement in condition of managed ecosystems according to Article 9 and 10 of the EC proposal (while maintaining them under management) (under Article 9 and 10 of the EC proposal) are that these would comprise approximately ~15% of the EU. Because BIOCLIMA land-use accounting does not get to the level of Annex I habitats, we limit restoration to agriculture and managed forests, and this is the basis underpinning the 15% of EU land area restored for those analyses.

(8) Available upon request to the lead author.

(9) In BIOCLIMA the following areas that are included in the LULUCF Regulation Revisions Annex II are always avoided for habitat conversion or intensifications LULUCF: existing national Sites of Community Importance according to Council Directive 92/43/EEC

much as a 1% gain in carbon stock (see section 2.7 in BIOCLIMA data and model descriptions (Task 3 document) (8) or Chapman et al. in review.

- **Balanced priorities:** Equal importance is given to meet targets for conserving species of community concern and conserving or restoring carbon stocks in soil or living biomass. This variant of restoration priorities is also applied to the Integrated Policy Scenarios.

In total we simulated 9 combinations of the 3 assumptions about burden-sharing of restoration efforts and 3 assumptions about emphasis given to prioritizing restoration efforts (for biodiversity mostly, for carbon sequestration mostly, or balanced) in this report we show the results only of those with equal priority given to restoring carbon stocks or habitat for species of conservation concern, and focus on the effects of the 3 burden-sharing scenarios, labeled BC05CF (EU priorities without burden-sharing safeguards), BC05CT (each country has the same burden share), BC05CX (there is cap to 25% of country land area to the maximum amount of restoration).

3.4. Integrated policy scenarios

We combined the REF, LOW, BIOM, LULUCF, LOW_LULUCF and FF55 scenarios with the BC05T, BC05F, BC05T restoration and protection scenarios, resulting in a total of potentially 18 different integrated scenarios, a selection of which is analyzed in-depth in this report.

All scenario assumptions and labels are summarized in the Table 3 below.

(Habitats Directive) and Special Protection Areas, classified according to Directive 2009/147/EC (Birds Directive) and primary forests according to Article 29(3) of Directive (EU) 2018/2001 (on the promotion of the use of energy from renewable sources).

Table 3 – BIOCLIMA policy scenarios and related assumptions

Scenario family	Climate policy		Biodiversity policy			
	Carbon price	Biomass for Bioenergy	Area Based Conservation	Restoration burden-sharing	Biodiversity-optimized cropland and grassland management	Biodiversity-optimized forest management
Reference Scenario (REF)	No	Business-as-usual Bioenergy demand	Existing Natura 2000 sites + Old-growth and primary forests conserved.			
Climate scenarios	No carbon price **(LOW, BIOM)** ~10-euros/ton **(LULUCF, LOW_LULUCF, FF55)**	Increase in Bioenergy from crops and forests **(BIOM, FF55)** Stabilization in Bioenergy **(LOW_LULUCF)**	Existing Natura 2000 sites + Old-growth and primary forests conserved.			
Biodiversity scenarios (REF_BC*)	No	Business-as-usual Bioenergy demand	Existing Natura 2000 sites + Old-growth and primary forests conserved. ~15% EU land under restoration	Each MS restores 15% of their land **(*CT)** 15% of EU restored, no limits on national efforts **(*CF)** 15% of EU restored, max 25% of each MS restored **(*CX)**	Priority areas for restoration subject to: reduction in N input, higher share of minimal tillage. Reduction in biomass harvested in managed grassland.	Higher shares of set-aside+multi-functional forests compared to production forest.
Integrated scenarios	No carbon price **(BIOM_BC*, LOW_BC*)** ~10-euros/ton **(LOW_LULUCF_BC*, FF55_BC*)**	Increase in Bioenergy from crops and forests **(FF55_BC*, BIOM_BC*)** Stabilization in Bioenergy **(LOW_LULUCF_BC*, LOW_BC*)**	Existing Natura 2000 sites + Old-growth and primary forests conserved. ~15% EU land under restoration	Each MS restores 15% of their land **(*CT)** 15% of EU restored, no limits on national efforts **(*CF)** 15% of EU restored, max 25% of each MS restored **(*CX)**	Priority areas for restoration subject to: reduction in N input, higher share of minimal tillage. Reduction in biomass harvested in managed grassland.	Higher shares of set-aside+multi-functional forests compared to production forest.

4. Land cover and land use projections

This section summarises projected trends at the EU27 level in land use and land management between 2020 and 2050, including net change to the extent of ecosystems (Figure 4) and management intensity classes for cropland (Figure 5), managed grassland (Figure 6) and forest (Figure 7), as well as changes to the average rotation time of production-oriented forest (Figure 8) and the total deadwood carbon stocks (Figure 9). Trends across various groups of scenarios are summarised in section: first for the Reference scenario (REF scenario; section 4.1), then for alternative Climate policy scenarios (BIOM, LULUCF, FF55, LOW and LOW_LULUCF scenarios; section 4.2), alternative increased protection and restoration scenarios (REF_BC05X, REF_BC05F and REF_BC05T scenarios; section 4.3), and finally a selection of scenarios combining both (LULUCF_BC05X, BIOM_BC05X, FF55_BC05X, LOW_BC05X and LOW_LULUCF_BC05X scenarios; section 4.4).

4.1. Reference scenario

The following trends are projected for the REF scenario over the 2020-2050 time-period.

Forest extent gradually increases until 2050 (Figure 4, +28 thousand km2 or +1.9% in the period 2020-2030 and +72 thousand km2 or +4.8% in the period 2020-2050), due to stabilization of afforestation and reforestation trends and decrease in deforestation. The total forest biomass harvested also increase by 3.6% in 2030, 6.2% in 2040 and 5.6% in 2050, compared to 2020.

Forest management undergoes a small extensification until 2050 (i.e. the ratio of harvested wood relative to annual biomass increments decreases), and a 30% increase in deadwood carbon stocks. As illustrated in Figure 7, the forest management extensification occurs through an increase in the extent of low-intensity multipurpose forest (forests where wood production is only a byproduct from thinning and/or disturbance-induced mortality, increase in the extent of low intensity multipurpose forest by an area representing about 6.3% of total forest in 2020) and high-intensity multipurpose forests (production-oriented forests dedicated to wood production but for which the rotation time is more than 20 years larger than that of forest maximizing biomass production, and equating about 3.2% of total forest in 2020), and through a reduction in the extent of production-oriented forests (by 2050, an area equivalent to 4.2% of total forest area in 2020). This relates to re/afforestation trends (established as multipurpose forestry), as well as a small increase in forest productivity through the evolution of its age structure. As illustrated in Figure 8 the average rotation time of production-oriented forest increases over time, by a little more than 10 years by 2050. As illustrated in Figure 9, total forest deadwood carbon stocks are increasing and then stabilizing in 2050 to levels 30% higher than that of 2020, as result of continued deadwood accumulation in forests already under multipurpose low intensity forest management in 2020 (and to a lower extent, to new deadwood accumulation in forests which management was extensified after 2020 forest management extensification).

The extent of cropland and managed grassland (pasture in Figure 4) slightly decreases by 2050 (Figure 4; -32 thousand km2 or -2.8%, and -10 thousand km2 or -3.0% respectively), even though cropland extent increases slightly by 2030 (Figure 4; +14 thousand km2 or +1.2%). These trends stem from the time-horizon specific balance in land pressure between slowly reducing demand other than lignocellulosic crops (including for ruminant products), increasing demand for ligno-cellulosic crop biomass and re/afforestation efforts.

Cropland management undergoes a small extensification by 2050 and moderate conversion to energy lignocellulosic perennial crops. As demands for land shift, an area representing 4.3% of total 2020 cropland is converted from high intensity annual cropland to perennial lignocellulosic crops. An additional area of high intensity cropland is converted to lower intensity (1.3% of 2020 cropland area) and representing 2.8% of 2020 cropland area represents abandoned high intensity cropland (Figure 5). Yet, by 2030, the net balance is of a small increase in high intensity cropland (about 1.6% of 2020 cropland, Figure 5).

Managed grassland is projected to undergo a small intensification by 2050, as the extent of area decrease is higher for low-intensity (equivalent to 2.5% of 2020 managed grassland extent) than high-intensity managed grassland (equivalent to 0.5% of 2020 managed grassland extent (Figure 6).

Non-forest semi-natural land covers (transitional woodland and shrubland, heathland and shrubs, unmanaged grassland) decrease by 2050, with a peak decline by 2030 (-37 thousand km2 or -5.6% in the period 2020-2030, and -30 thousand km2 or -4.6% in the period 2020-2050; Figure 4). These trends result from the continuous re/afforestation trends, cropland expansion by 2030, as well as and decline in agricultural land after 2030.

The extent of sparse vegetation, wetlands and urban land covers, as well as the freshwater and marine ecosystems remains stable (not shown in Figure 4). These land covers remain identical to 2020 in their extent for all scenarios because they are not explicitly modeled and will therefore not be further reported below.

4.2. Impact of alternative Climate policy scenarios

The following trends are projected for the BIOM, FF55, LULUCF, LOW and LOW_LULUCF scenarios over the 2020-2050 time period.

Applying LULUCF sink enhancement policies causes an extension of the rotation time to increase carbon sequestration. The duration of the extension is such that it maximizes the total profit resulting from selling slightly less wood and incurring a lower costs or higher revenue from net emissions. However, the model requires that wood harvest meets wood demand at the EU level. The gap between wood demand and reduced wood harvest due to extended rotation times leads to increasing production area, and thus in scenarios with a carbon price some low-intensity multipurpose forest is converted to production-oriented forests.

In general, assuming a carbon price (e.g., scenario differences LULUCF vs REF, FF55 vs BIOM, LOW_LULUCF vs LOW) incentivizes slightly higher levels of re/afforestation. Forest cover increases between 2020 and 2050 reach +4.8% in the REF scenario, but +5.5% in the LOW_LULUCF scenario and +4.3% in the FF55 scenario. At the same time, the application of the carbon price is projected to lead by 2040 to a conversion from multipurpose low intensity to production-oriented forests for an area equivalent to 24-27% of 2020 forest area (Figure 7), but also a conversion of production-oriented forests to high-intensity multipurpose forests for an area equivalent to 37-38% of 2020 forest area altogether leading to a net decrease in production-oriented forest of an area equivalent to 4-8% of 2020 forest area (Figure 7). These trends are mostly reversed in the decade 2040-2050, for example we observe a 3-5% decline in low-intensity multipurpose forests in scenarios applying LULUCF mitigations (LULUCF, FF55, LOW_LULUCF) and 2-7% gains in such forests in scenarios that do not (LOW and BIOM). The main change observable in the period 2040-2050 is the transition from multipurpose high-intensity to production forest. The rotation time in remaining production-oriented forests is projected to increase (Figure 8; up to +13 years or +17%). As a result of the conversion of low-intensity multipurpose forests (where deadwood density is a lot higher), the total deadwood carbon stock decreases by 2030 and 2040 (Figure 9).

Assuming an increased biomass demand (e.g., BIOM vs REF, FF55 vs LULUCF scenarios) reduces the space available for re/afforestation (Figure 4; through increased cropland and slightly less ample reduction in managed grassland, see next point), slightly moderates the projected increases in the share of multipurpose low intensity management (Figure 7) and in the rotation time of production-oriented forest (Figure 8), and total deadwood carbon stocks (Figure 9). On the contrary, assuming a stable or declining biomass demand slightly increases re/afforestation trends only when a carbon price is considered (e.g., LOW_LULUCF vs REF), but could lead to highly increased deadwood carbon stocks in the absence of LULUCF policies (e.g., LOW vs REF).

While the application of a carbon price marginally enhances cropland declines and does not affect much cropland management, in the most ambitious scenario increases in energy biomass demand are projected to reverse cropland declines, and lead to a small increase in cropland extent and a significant increase in the share of cropland dedicated to lignocellulosic crops. The projected trends in cropland extent over the 2020-2050 period are positive in scenarios assuming a high level of lignocellulosic crop demand in support of the energy sector decarbonization (up to +60 thousand km2 or +5.2% by 2050 in BIOM and FF55 scenarios; Figure 4), instead of negative in the REF scenario (-2.8%). At the same time an area of about 15% of 2020 cropland extent is converted from high- (and to some extent, medium-) intensity cropland to perennial cropland (Figure 5).

In the context of low energy biomass demand, the application of LULUCF policies (i.e., scenario differences LOW_LULUCF vs LOW, or LULUCF vs REF) leads to a small increase in cropland decline by 2050 (up to -41 thousand km2 or -3.6% in the LOW_LULUCF scenario; Figure 4).

Climate mitigation interventions slightly limit the small declines in managed grassland, without altering the expected slight intensification of managed grassland management. Both high energy biomass demand (e.g., BIOM scenario) and carbon price (e.g., LULUCF scenario) are projected to slightly buffer the projected small decrease in managed grassland over 2020-2050 in the REF scenario (i.e., -1.9% in the BIOM scenario, instead of -3.0%; Figure 4), without changing much the pre-dominance of low intensity managed grassland in the decline (Figure 6).

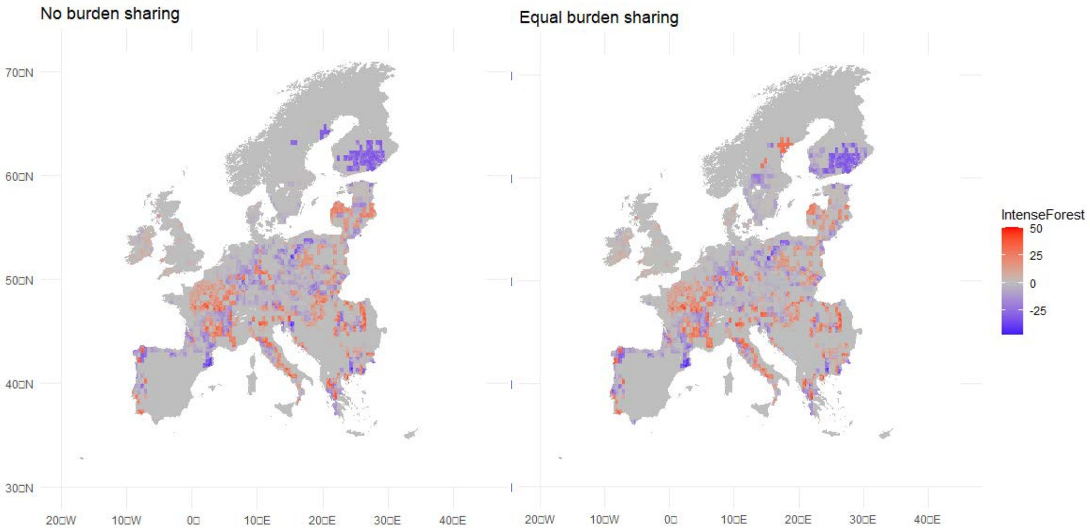
The decline in non-forest semi-natural land covers is projected to be enhanced by climate mitigation interventions, in particular increases in energy biomass demand. As illustrated in Figure 4, while the decline in the extent of non-forest semi-natural land covers (transitional woodland and shrubland, heathland and shrubs, unmanaged grassland) over the 2020-2050 period is about -4.6% by 2050 in the REF scenario, it is projected to be more than three times higher when assuming high biomass demand levels (e.g., -16.3% in BIOM scenario), and to be slightly higher when assuming a carbon price (e.g., -5.8% in LULUCF scenario, and -17.8% in FF55 scenario).

4.3. Impact of alternative increased protection and restoration scenarios

The following trends are projected for the REF_BC05CX, REF_BC05CT and REF_BC05CF scenarios over the 2020-2050 time period.

The policy assumptions of protection of 10% of all forest, combined with restoration efforts in compliance with Article 10 of the NRL alone would result in an overall reduction in timber supply, but the requirement of keeping harvest at a level that matches demand forces intensification of harvesting through shortening the rotation time and conversion from multi-purpose to production forest outside forests that are protected or restored (Figure 2). The spatial patterns of these shifts are broadly similar across restoration burden sharing scenarios.

Figure 2 – Changes in intensively managed forest



Changes in intensively managed forest under the scenario with equal restoration effort among all countries (REF_BC05CT) and with no constraints on burden sharing (REF_BC05CX). Values in red indicate increases in share of intensively managed forest, due to the displacement of forest activities from restoration actions such as the reduction in intensively managed forest depicted in shades of blue.

As depicted in Figure 7, these scenarios lead to an increase in forest set-aside of 1.3% of total 2020 forest, as well as a conversion of an area equivalent to 1.2% of total 2020 forest from low-intensity multipurpose forest management, but also to a net decrease in the extent of low-intensity multipurpose forest (about 4-6% of EU27 2020 forest area), and a net increase in the area of production-oriented forest (about 4-5% of EU27 2020 forest area). The net decrease in the extent of low-intensity multipurpose forest results from the restoration of production-oriented forests to low-intensity multipurpose forest (an area equivalent to about 6-7% of total EU27 2020 forest area), that leads to adjustments in other forests to maintain wood supply levels, with a conversion of an area equivalent to 11-12% of EU27 2020 forest area from low-intensity multipurpose forest to production forest. This adjustment outside restored forests is only partially reverted by 2050, as the pressure from wood demand decreases due to reduced energy consumption. (10) As compared to the REF scenario, the projected increase in the average rotation time of production-oriented forests by 2050 is slightly lower (Figure 8), while the projected increase in total forest deadwood carbon stocks is the same by 2050, with however lower increases by 2030 and 2040 (Figure 9). Varying assumptions about burden sharing only slightly changes the picture, with however a higher net decrease in low-intensity multipurpose forests by 2030 when assuming that restoration targets are met strictly at EU-Member State level (e.g., REF_BC05T as compared to REF_BC05X or REF_BC05F).

While restoration and conservation affect forest management, they do not affect the projected increase in total forest area in the EU27 region (e.g., compare forest extent change in Figure 4 in REF_BC05CX, REF_BC05CT or REF_BC05CF with REF).

The increased conservation and restoration scenarios lead to a moderate de-intensification of cropland and managed grassland, with minor impacts on total agricultural land extent but a slight reduction in the consumption of ruminant products. The restoration leads by 2030 to the conversion of an area equivalent to about 4-5% of 2020 total cropland extent from high intensity to low intensity (Figure 5), and to the conversion of an area equivalent to about 2-6% of 2020 total managed grassland extent from high extraction intensity to low extraction intensity (Figure 6). As compared to the REF scenario, projected changes to cropland and managed grassland extent are minor, with a slightly higher decrease in cropland and a slightly lower decrease in managed grassland extent by 2050 (Figure 4). Varying assumptions about burden sharing only impacts changes to grassland management, with however a lower increase in low extraction intensity managed grassland by 2030 when assuming that restoration targets are met strictly at EU-Member State level (e.g., REF_BC05CT as compared to REF_BC05CX or REF_BC05CF).

Non-forest semi-natural land covers (grassland and heatland) see a slightly lower conversion under reference condition supplemented with increased conservation and restoration scenarios, compared to the REF scenario (Figure 4).

4.4. Impact of alternative integrated scenarios

The following trends are projected for the LULUCF_BC05X, FF55_BC05X and LOW_LULUCF_BC05X scenarios over the 2020-2050 period.

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(10) See Figure 5 and accompanying text of the impact assessment SWD(2020) 176 final accompanying the European 2030 Climate Targets: COM/2020/562: Stepping up Europe’s 2030 climate ambition Investing in a climate-neutral future for the benefit of our people

Increased conservation and restoration and increased climate mitigation are not additive to the effect of climate policies (via carbon price) for the management of EU forest ecosystems. The overall effect is primarily dominated by the effects of the carbon price. As compared to climate mitigation only, adding increased protection and restoration (i.e., LULUCF_BC05X as compared to LULUCF, FF55_BC05X as compared to FF55, and LOW_LULUCF_BC05X as compared to LOW_LULUCF) does not alter projected changes to forest extent (Figure 4) but leads to more moderate intensification (through conversion from low-intensity multipurpose forests to production-oriented forests) and extensification (through conversion from production-oriented forest to high-intensity multipurpose forest, and increase in the average rotation time of production-oriented forests), as illustrated in Figure 7. When protection and restoration and carbon sink enhancement policies are applied together, protection and restoration decrease the forest area available for harvesting and where forest management can be adapted to carbon price (limiting the carbon price effect as compared to no protection and restoration). Thus, protection and restoration under unchanged harvest level put additional harvest pressure on the non-protected/non-restored forests leaving less freedom to forest management adaptation to the carbon price and, as a result lowering the carbon price effect.

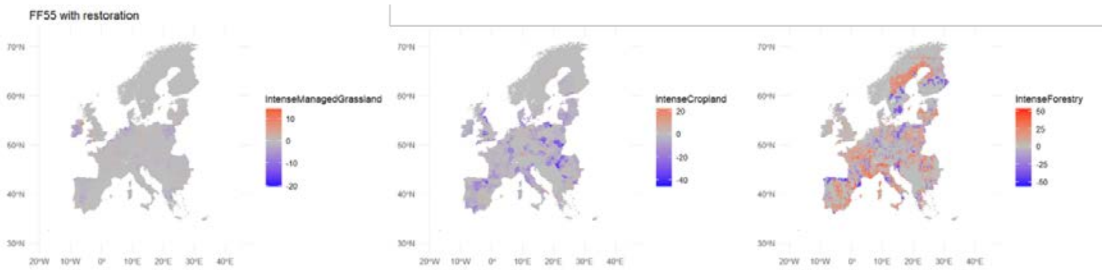
Both scenario dimensions contribute to decreasing deadwood stocks in the short-term (with total effect lower than sum of effects), but increased restoration and protection allows to limit negative impact of climate interventions on deadwood by 2050.

The effect of both scenario dimensions is projected to be additive for cropland management and dominated by increased conservation and restoration for managed grassland. The combination of both scenario dimensions is projected to lead to further adjustment in the consumption of ruminant products. As illustrated in Figure 4, the projected changes to the extent of cropland and managed grassland (pasture in the figure labels) across the different increased Climate policy scenarios is not affected when adding the increased conservation and restoration on the top. Restoration actions further increase the amount of cropland estensification, when combined with LULUCF (Figure 5).

Furthermore, restoration actions bring about extensification of grassland management both when simulated alone (REF_BC05) and in combination with climate policy scenarios, something not seen in scenarios with climate policies alone (Figure 6).

Local extensification due to restoration actions is associated with intensification in other regions; this is particularly remarkable for forestry (similarly to what was observed in variants of REF_BC), due to the exogenous assumptions of increase in demand of forest products. This displacement is far less evident for cropland and managed grasslands (see example for FF55_BC05 scenario in Figure 3).

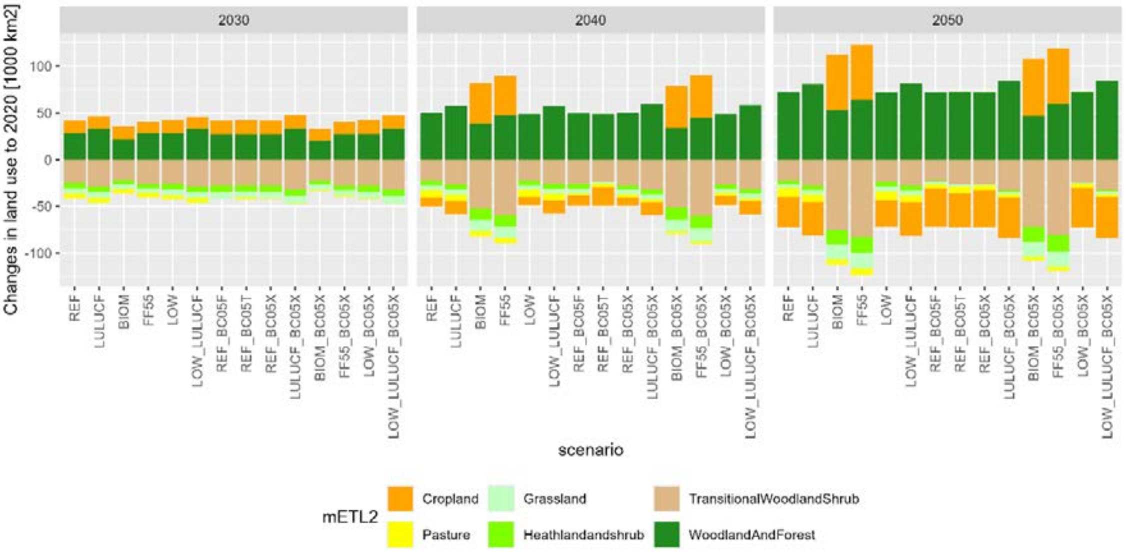
Figure 3 – Changes in intensively managed forest, cropland and managed grasslands



Changes in intensively managed forest, cropland and managed grasslands under the FF55_BC05X scenarios. Values in red indicate increases in share of intensively managed land, values in blue indicate decreasing shares, resulting from replacement of intense management with medium or low-intensity management.

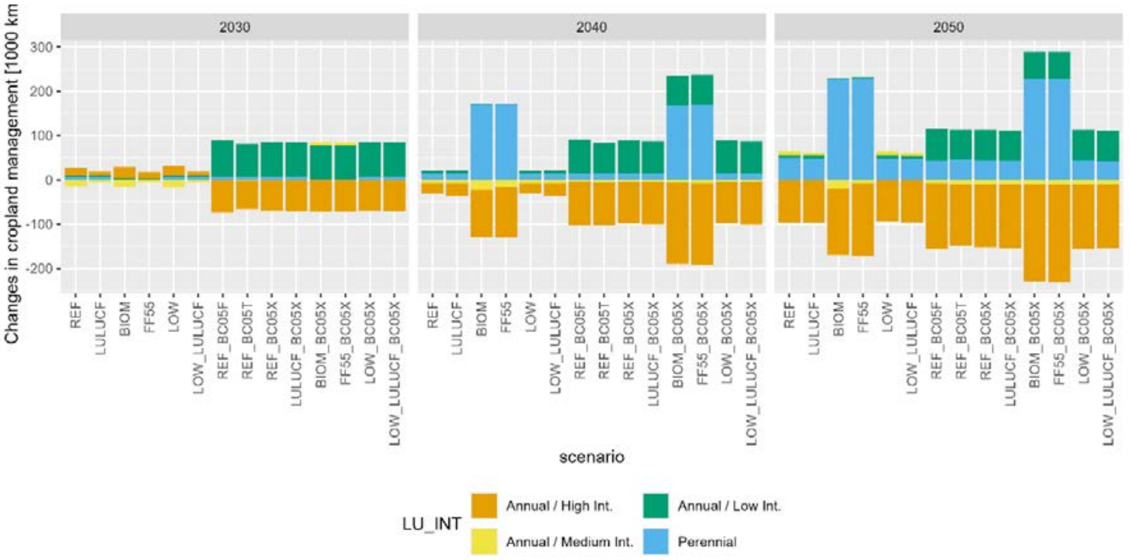
The projected changes to the extent of non-forest semi-natural ecosystems are dominated by climate mitigation assumptions. Specifically in the integrated scenarios the main difference in the fate of transitional habitats, heatlands and natural grasslands is determined by the exogenous demand of biomass for energy production (Figure 4). However, in scenarios with lower biomass demand and with LULUCF enhancement measures, we observe a lower rate of conversion in heatlands and shrubs and unmanaged grasslands in scenarios that include restoration and conservation, compared ith those that do not (e.g. compare LULUCF and LULUCF_BC05X in Figure 4).

Figure 4 – Projected changes to the EU27 extent of ecosystems as compared to 2020



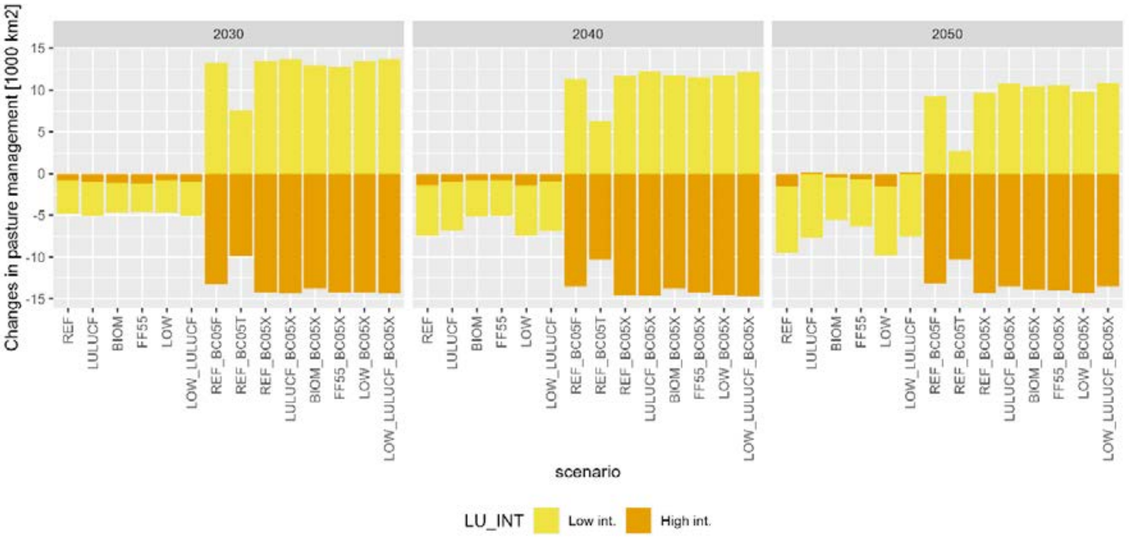
The figure provides for each scenario (x-axis) and selected modified ecosystem type level 2 class (modified ETL2 classes: cropland in orange, managed grassland in yellow, unmanaged grassland in light green, heathland and shrubs in bright green, woodland and forest in dark green and transitional woodland in brown) the absolute net change in extent (in 1000 km2) between 2020 and 2030 (left panel), 2040 (middle panel) and 2050 (right panel).

Figure 5 – Projected changes to the EU27 extent of cropland management classes as compared to 2020



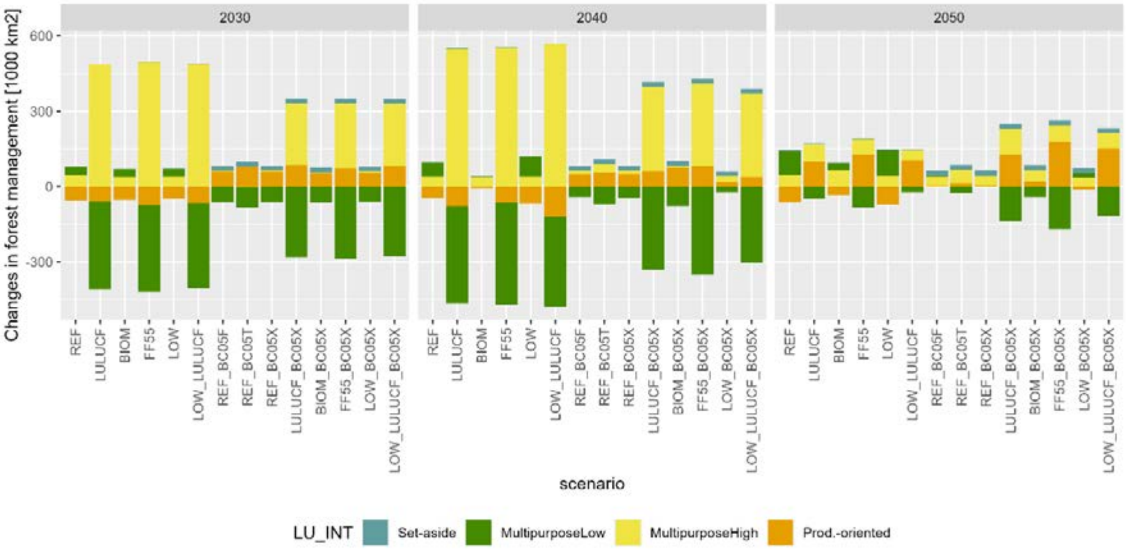
The figure provides for each scenario (x-axis) and cropland management classes (Annual cropland / low intensity in green, Annual cropland / low medium in yellow, Annual cropland / high intensity in orange, Perennial cropland in blue) the absolute net change in extent of each class between 2020 and 2030 (left panel), 2040 (middle panel) and 2050 (right panel), in 1000 km2. The low, medium and high annual cropland intensity classes are combining information on tillage practices (from minimal in low intensity to conventional in high intensity) and average reactive nitrogen input over the crop rotation (from less than 50 kgN/ha/year in low intensity to more than 150 kgN/ha/year in high intensity).

Figure 6 – Projected changes to the EU27 extent of managed grassland management intensities as compared to 2020



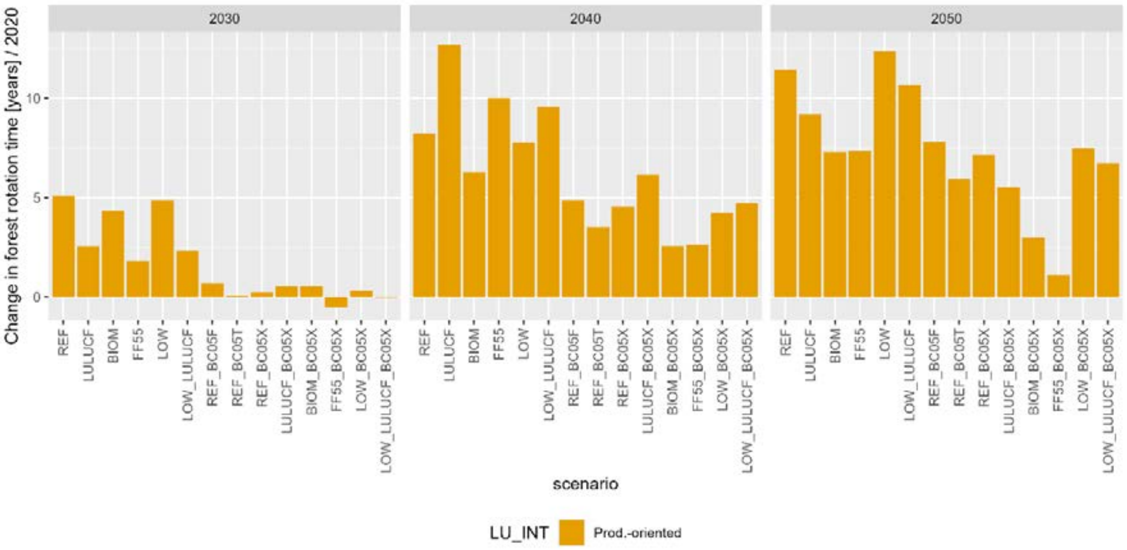
The figure provides for each scenario (x-axis) and managed grassland intensity management classes (low in purple, high in yellow) the absolute net change in extent of each class between 2020 and 2030 (left panel), 2040 (middle panel) and 2050 (right panel), in 1000 km2. The intensity classes are based on the intensity of grassland biomass extraction (50% of biomass in one cut for low, 80% of annual biomass in two cuts for high).

Figure 7 – Projected changes to the EU27 extent of forest management intensity classes as compared to 2020



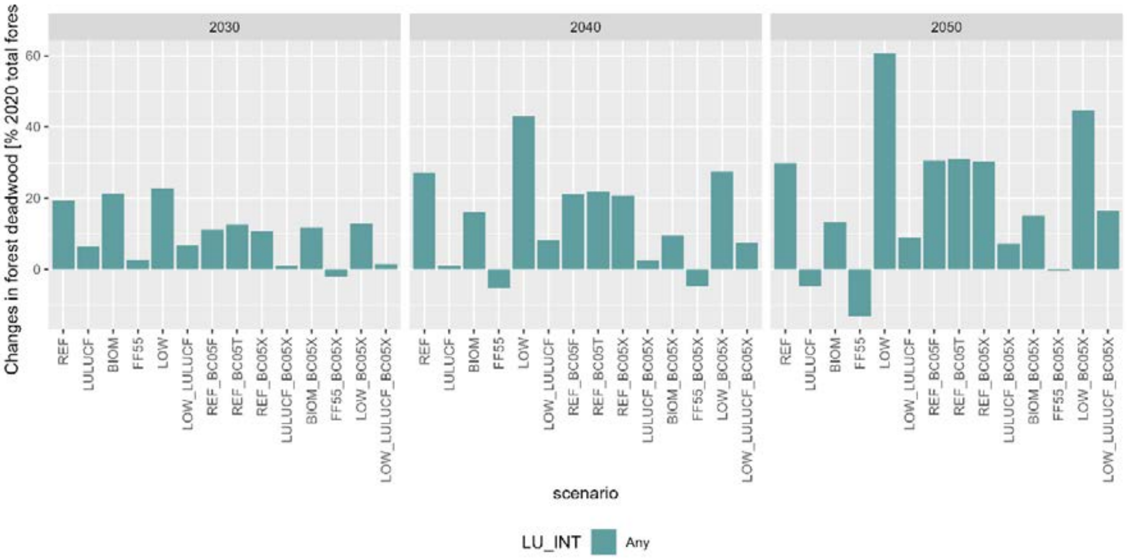
The figure provides for each scenario (x-axis) and forest management intensity classes (set-aside in cyan, low-intensity multipurpose in green, high-intensity multipurpose in yellow and production-oriented in orange) the absolute net change in extent of each class between 2020 and 2030 (left panel), 2040 (middle panel) and 2050 (right panel), in 1000 km2. The intensity classes are combining information on forms of wood extraction and rotation time (no wood extraction in set-aside forests, wood removal only as a byproduct from thinning and/or disturbance-induced mortality in low-intensity multipurpose forests, wood removal from thinning and harvest with a rotation time at least 20 years larger than the rotation time maximising sustainable harvest in high-intensity multipurpose forests, and wood removal from thinning and harvest with rotation time close to the rotation maximising sustainable harvest in production-oriented forests).

Figure 8 – Projected changes to the EU27-averaged rotation time of production-oriented forests



The figure provides for each scenario (x-axis) and one forest management intensity class (production-oriented in orange) the absolute net change in rotation time between 2020 and 2030 (left panel), 2040 (middle panel) and 2050 (right panel), expressed in years.

Figure 9 – Projected changes to the total EU27 deadwood stock in forests



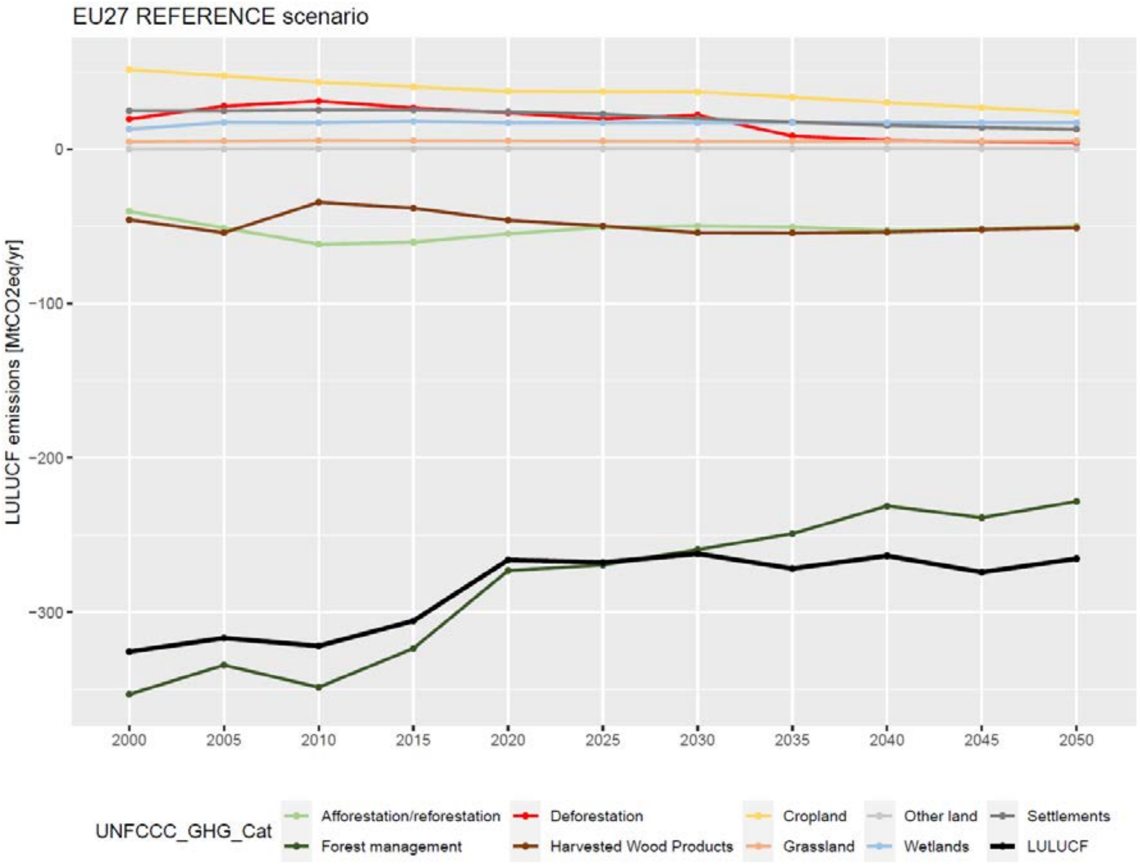
The figure provides for each scenario (x-axis) the relative change in total deadwood stocks (across all management classes) between 2020 and 2030 (left panel), 2040 (middle panel) and 2050 (right panel), in percentage points.

5. Land cover and land use projections

This section summarises projected trends at the EU27 level in LULUCF GHG emissions and removals between 2020 and 2050 for the REF scenario (Figure 11) and changes in emission levels by 2030, 2040 and 2050 as compared to 2020 (Figure 11). The order of presentation is analogous to Section 4, starting with the Reference scenario (REF scenario; section 5.1), then for alternative Climate policy scenarios (section 5.2), alternative increased protection and restoration scenarios (section 5.3), and finally a selection of scenarios combining both (section 5.4).

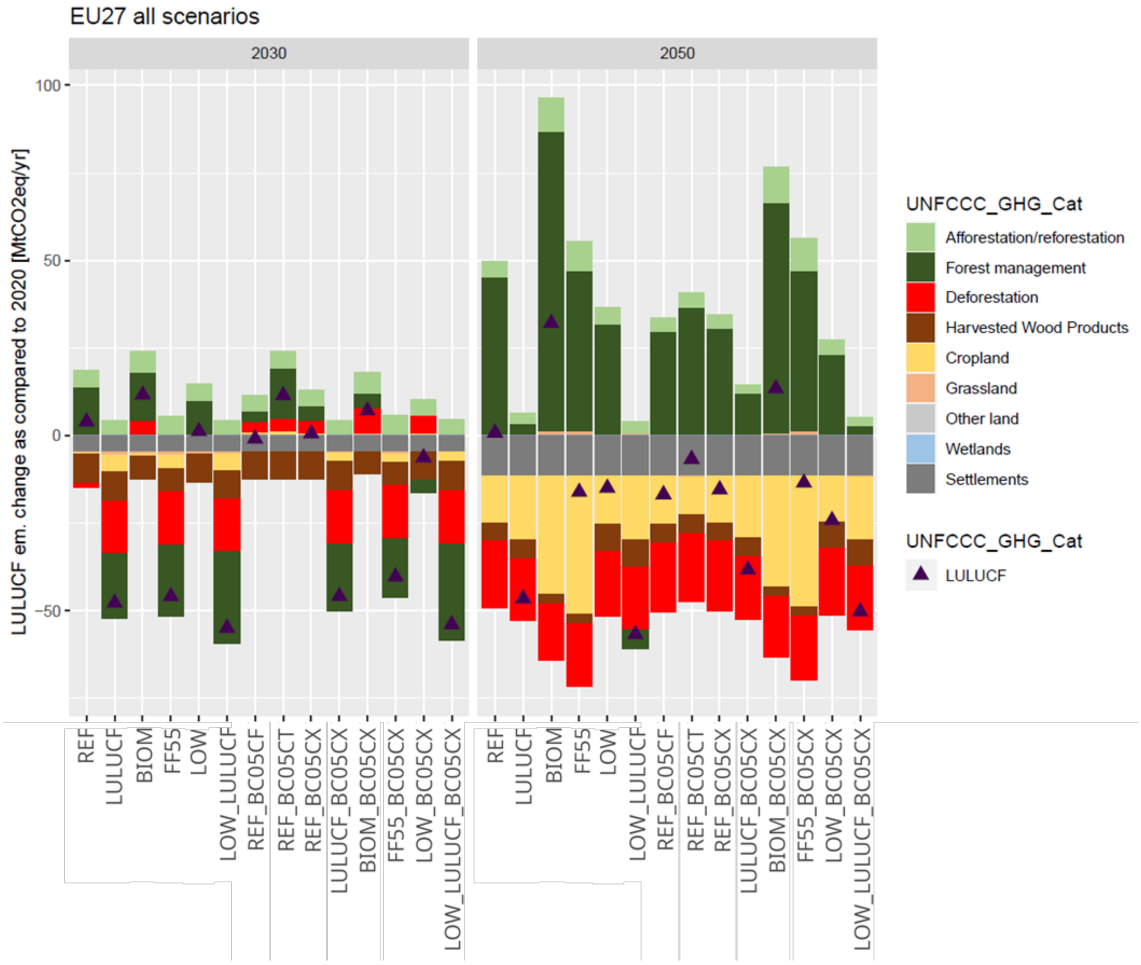
Some trends are common to all scenarios and are described once here. There is a general trend of decreasing of the CO_2 sink in managed forests because of forest aging.

Figure 10 – Projected levels of EU27 LULUCF CO2 emissions over time in the reference scenario



The figure provides for the REF scenario and for each emission category (UNFCCC_GHG_Cat: settlements in dark grey, wetlands in blue, other land in light grey, grassland in light red, cropland in orange, Harvested wood products in brown, deforestation in bright red, forest management in dark green and afforestation/restoration in light green, total in black) the absolute levels of LULUCF emissions (in million ton of CO2 per year, MtCO2/yr) from the year 2000 to the year 2050. Changes in deadwood stock after 2020 due to changes in management are taken into account within the forest management category.

Figure 11 – Projected absolute changes to the EU27 total LULUCF CO2 emissions (in million ton of CO2 per year MtCO2/yr) relative to 2020 for various scenarios and LULUCF sectors



The left panel refers to the period 2020-2030, the right panel refers to the period 2020-2050. Stacked bars with positive values on the y axis indicate increased carbon emissions compared to 2020 (for cropland and other LULUCF categories which in 2020 emit more CO2 than they draw down) or reduced carbon removals (for forest management and other LULUCF categories which in 2020 draw down more CO2 than they emit). Stacked negative bars indicate respectively reduced emissions or increased removals for the same categories. The black triangle indicates the net CO2 balance across all LULUCF categories. Triangles with positive values indicate a reduction in the LULUCF sink (less negative CO2 balance compared to the -273 MtCO2/yr in 2020), negative values indicate further enhancement of the LULUCF sink compared to 2020. Differently from the land use modelling reported in section 4 and used as input to the biodiversity modelling reporting in section 6, for LULUCF emission reporting an increase in the extent of urban settlements is assumed based on historical trends, leading to a decline in related emissions after 2020 due to increased energy efficiencies and a higher share of renewable energy (data from EUCLIMIT6 project).

5.1. Reference scenario

As illustrated by an upward trend in Figure 10 (black line) and a net positive value in Figure 11 (black triangle), net LULUCF removals at EU27 level increase a little further from 2020 to 2040 and stabilizes at around 265 MtCO2/yr, as a result of contrasted trends. The forest management sink decreases until 2040 and then stabilizes at around 230 MtCO2/yr (as compared to -273 MtCO2/yr in 2020), as a result of increasing harvest levels partially compensated by continued afforestation. By assumption, wetland emissions remain constant after 2020. Grassland emissions remain relatively constant and small, while the harvested wood products sink increases slightly until 2030 (about 10 MtCO2/yr), and emissions from both deforestation (in particular, after 2030, down from 22 MtCO2/yr in 2020 to less than 10 MtCO2/yr) and cropland soils (from 37 MtCO2/yr to 27 MtCO2/yr) decrease over time. These emission reductions are not sufficient to compensate the reduced removals from the forest management sink and, as a result, the LULUCF target of a 310 MtCO2/yr sink by 2030 is not met.

5.2. Impact of alternative Climate policy scenarios

As illustrated in Figure 11, when considering high levels of biomass demand (BIOM and FF55 scenarios), the forest management sink decreases further (in particular by 2050, down to 190 MtCO2/yr, i.e., a 85 MtCO2/yr increase in Figure 11) due to increased harvest levels, deforestation emissions increase slightly in the short-term (2030), and cropland emissions are projected to decrease more strongly in 2050, in particular due to accumulated biomass from lignocellulosic crops (11) (from 38 MtCO2/yr in 2020 to 3 MtCO2/yr in 2050, even temporarily turning into a net sink in 2040). The net balance is that total LULUCF emissions are projected to increase further (black triangle in Figure 11, 32 MtCO2/yr sink reduction from 2020 to 2050) instead of stabilizing like in the REF scenario.

On the contrary, when considering low biomass demand scenario (i.e., LOW scenario), total LULUCF emissions remain similar to the REF scenario by 2030, and lead to a slight net decrease in GHG emissions by 2050 (due to the lower decrease in forest and cropland harvest level and associated forest management sink). It should be noted that the changes to LULUCF sink driven

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(11) In the first year when lignocellulosic plantations are established in large scale, large amounts of biomass stocks are built-up. This is accounted for as a sink (mainly in the year 2050). The stocks are harvested then every few years and replaced with newly grown biomass so in the remaining years the balance is neutral, and no sink is generated anymore; the decrease of cropland emissions due to lignocellulosic crop implementation thus is a one-time effect.

by different levels of biomass demand are expected to be at least partially counterbalanced by changes to GHG emissions in other sectors, in particular the energy sector – an energy system model would be needed to reliably estimate this effect.

The carbon price leads to a faster reduction in deforestation and cropland emissions and an increase in forest management sink by 2030 for all scenarios (e.g., LULUCF, FF55, LOW_LULUCF), leading to an increase in LULUCF sink of about 50 MtCO2/yr, sufficient to reach the 2030 LULUCF target (esp. if including additional contributions from fallowing histosoils resulting from drained peatlands, not included here). The extension of the rotation time when a carbon price is applied leads to a large increase in carbon stock, and a moderate increase in CO_2 sink in the forest biomass because the rotation time is extended in younger forests which accumulate biomass relatively fast. These increases in carbon removals are sufficient to more than counterbalance the increased emissions due to the conversion of multipurpose forests to production forests, necessary to keep wood harvest at a level that matches projected demand.

Projected levels of LULUCF emissions by 2050 with carbon price depend on assumptions about biomass demand and their effects on the forest management sink: while the 2030 level of LULUCF sink can be sustained by 2050 under the REF scenario, and even increased in the LOW scenario, it decreases in the FF55 scenario (even when considering the sink from ligno-cellulosic crops accumulated biomass). Staying within the 2030 LULUCF target by 2050 in the FF55 scenario might however still be feasible with additional contributions not modelled here (such as histosoil fallowing).

5.3. Impact of alternative increased protection and restoration scenarios

As illustrated in Figure 11, the various increased protection and restoration scenarios (REF_BC05X, REF_BC05T, REF_BC05F) could lead by 2030 to a lower reduction in forest management sink (up to 11 MtCO2/yr lower reduction from 2020 to 2030 as compared to the REF scenario) as compared to 2020 except for REF_BC05T,which leads to higher net decrease in low-intensity multipurpose forests, (see section 4.3), but also a small, temporary, increase in deforestation emissions because of a higher price of agriculture land. These climate mitigation benefits could be more robust by 2050, with an increase of about 7-17 MtCO2/yr for total LULUCF sink as compared to 2020 (instead of a stabilization in the REF scenario), primarily through a lower 2020-2050 reduction of the forest management sink (30-36 MtCO2eq/yr, instead of 45 MtCO2eq/yr in the REF scenario). Additional climate mitigation benefits (e.g., carbon removal via increased soil organic carbon) through restoration of cropland and managed grassland to lower use intensity may be feasible but are not captured in the analysis as restoration of cropland and managed grassland is currently only modelled as an assumed biomass productivity decrease over restored areas.

5.4. Impact of alternative integrated scenarios

As illustrated in Figure 11, the projected changes in LULUCF emissions from 2020 to 2030 and 2050 are dominated by assumptions about climate mitigation in the forestry sector, with the LULUCF targets only met in scenarios including a carbon price, and lower LULUCF sink for higher levels of biomass demand (see section 5.2). Similarly to what occurs with the REF scenario (see section 5.3), restoration partially mitigates the projected decrease in forest management sink by 2050 when considering alternative levels of biomass demand in absence of LULUCF policies. (e.g., LOW_BC05X vs LOW with slightly lower sink reduction buffering as compared to REF, BIOM_BC05X vs BIOM with slightly higher sink reduction buffering as compared to REF). However, this is not the case when considering a carbon price (i.e., LULUCF_BC05X vs LULUCF, FF55_BC05X vs FF55, LOW_LULUCF_BC05X vs LOW_LULUCF).

6. Land cover and land use projections

Changes in land use and management will have consequences for biodiversity, both at the species and the population level (Newbold et al. 2015; Visconti et al. 2016). For example, displacing one type of land use with can be beneficial for some species and detrimental for others. Since biodiversity impacts are expected to vary among species (Newbold et al. 2018; Daskalova et al. 2020), indicators (Leclère et al. 2020), geographic regions (Fritz et al. 2009; Phillips et al. 2017) and scenarios (Visconti et al. 2016; Leclère et al. 2020; Kok et al. 2023), it is imperative to comprehensively evaluate the consequences of different scenario pathways on biodiversity. We primarily make use of two different biodiversity modelling approaches that are complementary in strength and scope:

a) The ibis.iSDM model (Jung 2023) makes use of species distribution models to produce an indicator reflective of changes in habitat suitability (or "habitat quality") which considers changes in land-use and management intensity, but presently excludes climate variables and spatial configuration of habitat. This indicator is species specific, thus allowing to separate out effects on different species groups, such as those listed in specific annexes such as the Habitat directive, and comprehensively investigate which species benefit from scenarios reflecting increased climate mitigation or integrated restoration efforts.
b) Changes to biodiversity at the species community level were estimated using data from the PREDICTS database (Hudson *et al.*, 2017), a large and taxonomically diverse dataset, with comprehensive geographic representation. Here we present results for the Biodiversity Intactness Index (an aggregation of abundance and compositional results), compositional similarity, total abundance and species richness.

In chapter 6, we first describe the biodiversity data and indicators used (section 6.1), then describe the land-use variable effects on these indicators (section 6.2) and finally we summarize both species-level and community-level indicators for different groups of scenarios: Reference scenario, Climate policy scenarios in section 6.3 and the Biodiversity policy scenarios, and integrated scenarios in section 6.4.

6.1. Summary of applied biodiversity data and indicators

We measured relative changes in projected suitable habitat for 1031 species of European conservation concern (Table 4). These species were selected based on policy relevance as well as available observational biodiversity records. For each scenario and year, we projected the suitable habitat of each species using an ensemble of statistical and machine learning models (see Task 3 report section 2.11 (12)) to produce an ensemble mean suitability, taking values from 0 to 1. The maximum modelling extent was the present range (plus a small buffer to allow for limited dispersal) of the species estimated through a combination of spatial information from the IUCN Red List database, EEA Article 12 and 17 reporting and other sources such as atlas records where available.

The indicator is constructed by fitting one projection per model, biodiversity data type (presence-only or presence-absence) and scenario separately, normalizing (relative to the maximum, a windsorization (‘clamping’) up to upper 1% is applied to cap extreme positive outliers) and averaging them (arithmetic mean) across species and scenarios. This windsorization helps to account for very extreme possible outliers in species-scenario specific indicator values (e.g. for a few small ranged species experiencing large increases), but without discarding indicator values as such. For each species and each decade we then calculated the average relative change plus standard error of the mean in total suitability (sum of the suitability values across the entire range) relative to the initial conditions in year 2020. For example, a value of 2% for the Skylark, *Alauda arvensis*, in 2030 means that the total habitat suitability of the Skylark is projected to increase by 2% in the period 2020-2030 over its present range. We broke down this indicator in groups reflecting distinctions of overall, policy directives, habitat specialism and critical conservation responsibility (threatened species and European endemics). Further details on the model itself, the preparation of input data and the temporal projections of biodiversity impacts see Task 3 report section 2.11.

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(12) Available upon request to the lead author.

Table 4 – Final list of species included in the analyses

Taxon	Unique	BD A12	HD A17	Eu RL endemics	Eu RL threatened	Pollinator Directive	NRL farmland birds
Birds	408	408	0	9	29	0	94
Mammals	72	0	72	0	0	0	0
Reptiles	61	0	61	18	6	0	0
Amphib.	47	0	47	21	7	0	0
Bees	72	0	0	4	7	72	0
Butterflies	97	0	21	30	10	97	0
Other arthropods	75	0	75	8	14	21	0
Molluscs	14	0	14	0	4	0	0
Vascular plants	164	0	164	84	33	0	0
Non-Vascular plants	23	0	23	0	0	0	0
Total	**1033**	**408**	**477**	**174**	**110**	**190**	**94**

Models of local biodiversity measures were constructed using data on biodiversity and land use from the PREDICTS database (Hudson *et al.*, 2017). Mixed effects models were fitted with land use, land use intensity, human population density [ref] and accessibility [ref] as fixed effects and study nested within source as random effects. Model coefficients were projected on to gridded scenario outputs to form spatial layers. The Biodiversity Intactness Index (BII) (Newbold *et al.*, 2016) measures the naturalness of the make-up of species communities through assessing changes in the relative abundance of species within a community. It takes two models, one of total community abundance and another of compositional similarity, which when multiplied form the BII. As well as BII, total abundance, and compositional similarity we also modelled local species richness using mixed effects models as above.

Table 5 – Number of studies, sites and species extracted from the PREDICTS database to construct local biodiversity models

Taxon	Unique	BD A12	HD A17
Species richness	216	12,141	7,870
Abundance	194	11,333	7,321
Compositional similarity	119	394	398

6.2. Land-use variable effects on species habitat suitability

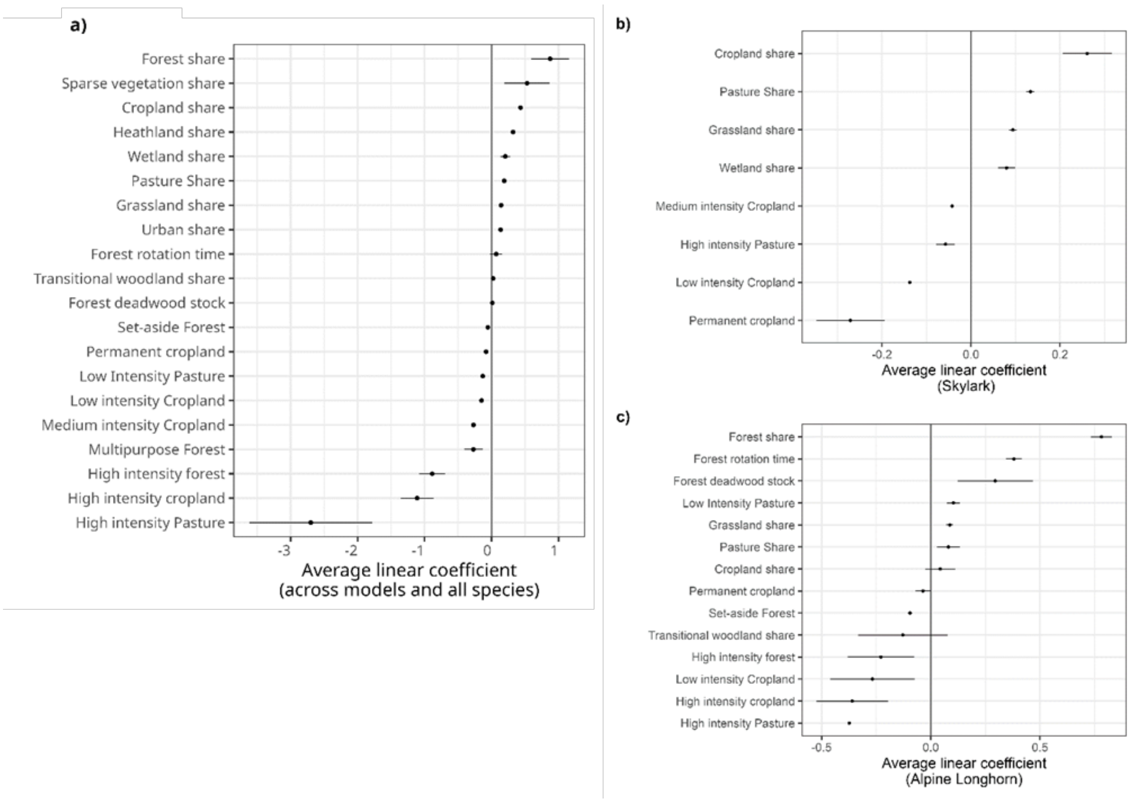
The indicators used for projecting biodiversity impacts originate from ‘dose-response’ biodiversity models, where the ‘average’ response of biodiversity (species occurrences or local communities) is parametrized from observed biodiversity data and/or land-use categorizations.

For the ibis.iSDM model we report the average standardized linear coefficients of the model, average across all species (+/- standard error of the mean) (Figure 12c) and two example species (Figure 12 b-c). It should be noted for interpretability and computational feasibility these coefficients only come from a single linear model, while for the scenario projections an ensemble for different linear and non-linear models was used.

Grand averages across species mask individual variations, for example while the mean relationship between forest rotation time and habitat suitability across all species is close to zero (Figure 12a) the Alpine longhorn beetle strongly benefits from longer forest rotation time (Figure 12c). This is why it is important to disaggregate indices by group of species associated with a given ecosystem.

We find that variables associated with land-cover shares are on average positively correlated and informed by the respective priors for the species, while variables associated with management intensity are overwhelmingly negative, especially for higher intensity levels (e.g. intensive cropland has a worse impact than lower cropland management intensities, Figure 12).

Figure 12 – Average standardized linear coefficients across all species



Average standardized linear coefficients across all species (a) and two selected species representative of croplands (b) and forests (c). The coefficients can be interpreted as the slope of the linear relationship between one unit increase in the model covariate (listed one per row) and one unit increase in the habitat suitability for a given species. Positive values mean that an increase in the covariate results in an increase in the suitability of the species. Coefficients are based on a single fitted model (glmnet) and groups of variables where only included if the species had some affinity towards them (for example from known habitat preferences).

6.3. Biodiversity impacts for the Reference scenario and Climate policy scenarios

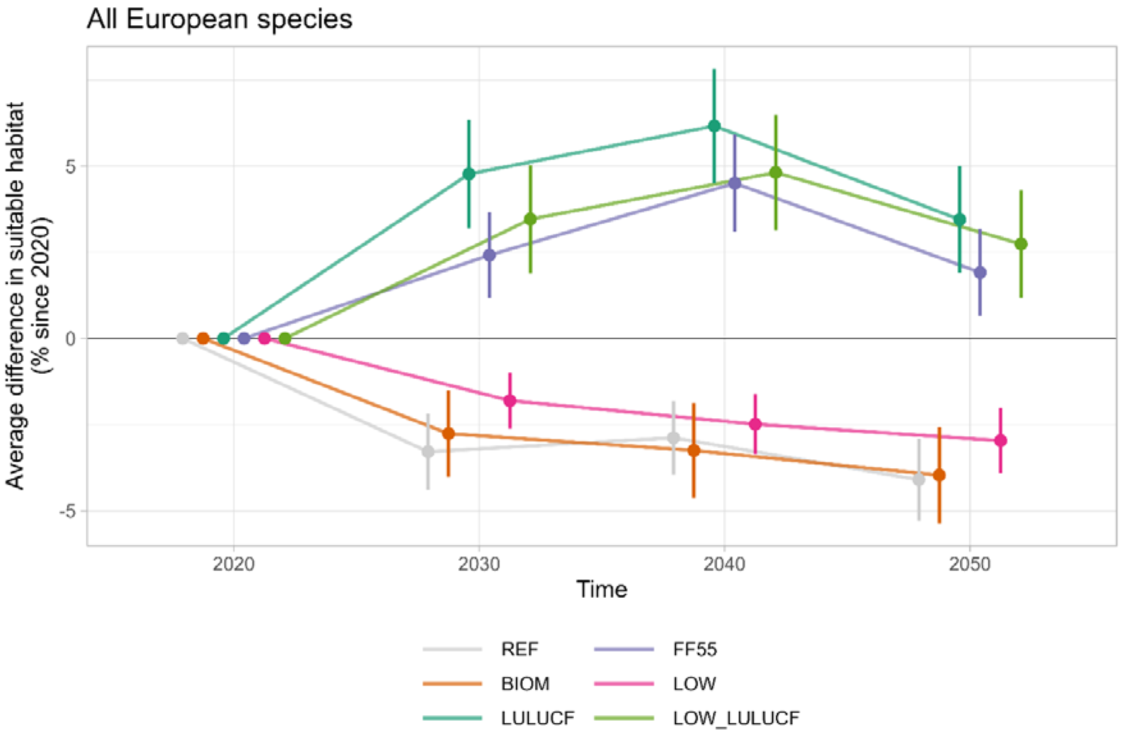
6.3.1. Species-level indicators

Under the Reference scenario, in absence of additional climate and biodiversity policies, we observe a small decline in mean habitat for species of ~4% by 2050. The main driver of this is the loss of natural land-cover types due to afforestation as well as overall decline in agricultural areas (across all management intensities). We find that the application of a 10 EUR/tCO2 implicit carbon price (FF55, LULUCF, LOW_LULUCF) has positive effects on biodiversity, with a peak observed by 2040, followed by a decline in the period 2040-2050 (Figure 13). The main driver of this increase in suitability with a LULUCF policies, is the higher share of forests due afforestation (see Figure 4 for land-use trends and Figure 12 for the mean positive standardized coefficients for forest area share), an increase in multi-functional forest with high harvest rate, and a lower overall reduction in transitional woodlands and shrubs than scenarios with higher increase in bioenergy production, and comparable with the Reference scenario (Figure 4).

This decline between 2040 and 2050 in scenarios where a carbon price is introduced is driven by the switch in trends in shares of production forest (net decline in 2020-2040 and small increase afterwards) as well as a shortening of the rotation time, which are two of the main changes in management occurring in this period (Figure 7 and Figure 8) and are respectively negatively and positively correlated with trends in species habitat of most forest-related species (mean regression coefficient of Figure 12) .

We observe slight declining trends with all scenarios without a carbon price. The common features of these scenarios that we can attribute these trends to are smaller increases in forest cover compared to those with LULUCF policies, and similar losses in cropland (Figure 13). Scenarios with high increase in lignocellulosic crops (BIOM) here perform slightly worse than those with low biomass demand (LOW) by 2050. This is driven by lower losses in natural vegetation (heatland, shrublands, unmanaged grasslands) in LOW and REF compared to BIOM (see Figure 4 for what concerns land-use projected trends).

Figure 13 – Trends in species suitable habitat (mean and standard error of the mean) for REF (black) and 5 Climate policy scenarios for the period 2020 to 2050

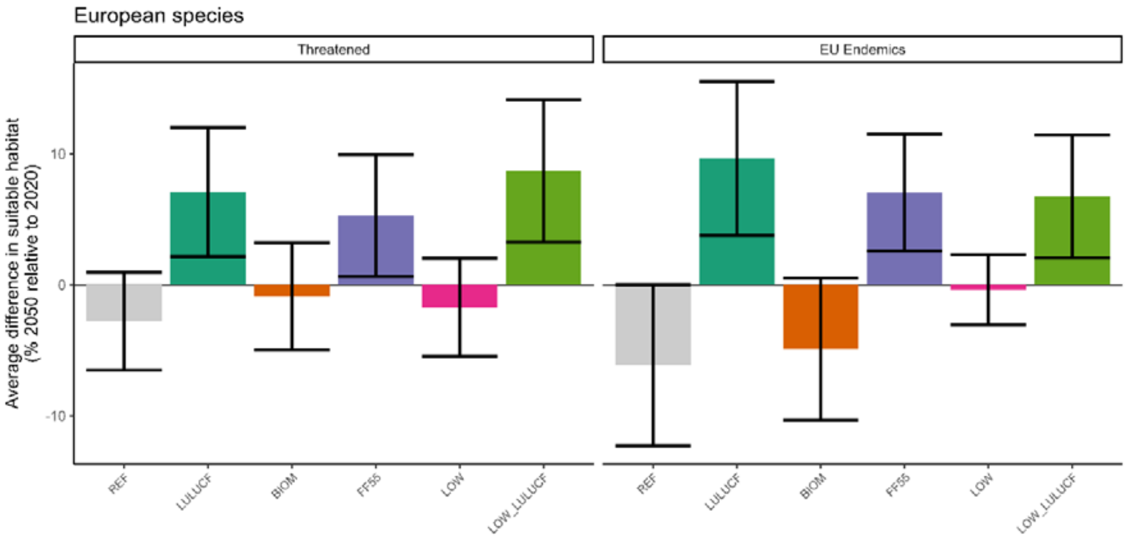


All indices are standardized relative to the initial conditions in year 2020. The uncertainty bars are the Confidence Interval calculated as ±1.96 Standard Error of the Mean.

We also investigated whether species of conservation concern, such as those listed as critically endangered (CR), endangered (EN) or vulnerable (VU) in European Redlists, or species which are known to be EU endemics are differentially affected by the various climate mitigation actions.

We find that the direction of changes and the relative performance of scenarios is the same when considering only threatened and endemic species compared to considering all species modeled in BIOCLIMA. However, the magnitude of changes is larger for threatened species and EU endemics compared to all species (compare Figure 13 and Figure 14). The reason for the larger magnitude of average gains compared to the indicator including all species, is that both threatened and endemic species have relatively smaller ranges and therefore any positive change (e.g. increase in forest cover, especially multipurpose forests) will proportionally have larger benefits. However, we also find a much larger spread around the mean value in suitability trends, suggesting that there the prognosis to 2050 among threatened and endemic species is quite variable and dependent on local projected trends within the relatively smaller distribution ranges of these species.

Figure 14 – Percentage difference in species suitable habitat between 2020 and 2050 (mean and standard error) for REF and 5 Climate policy scenarios disaggregated by threatened (CR, EN, VU) or European endemic species.

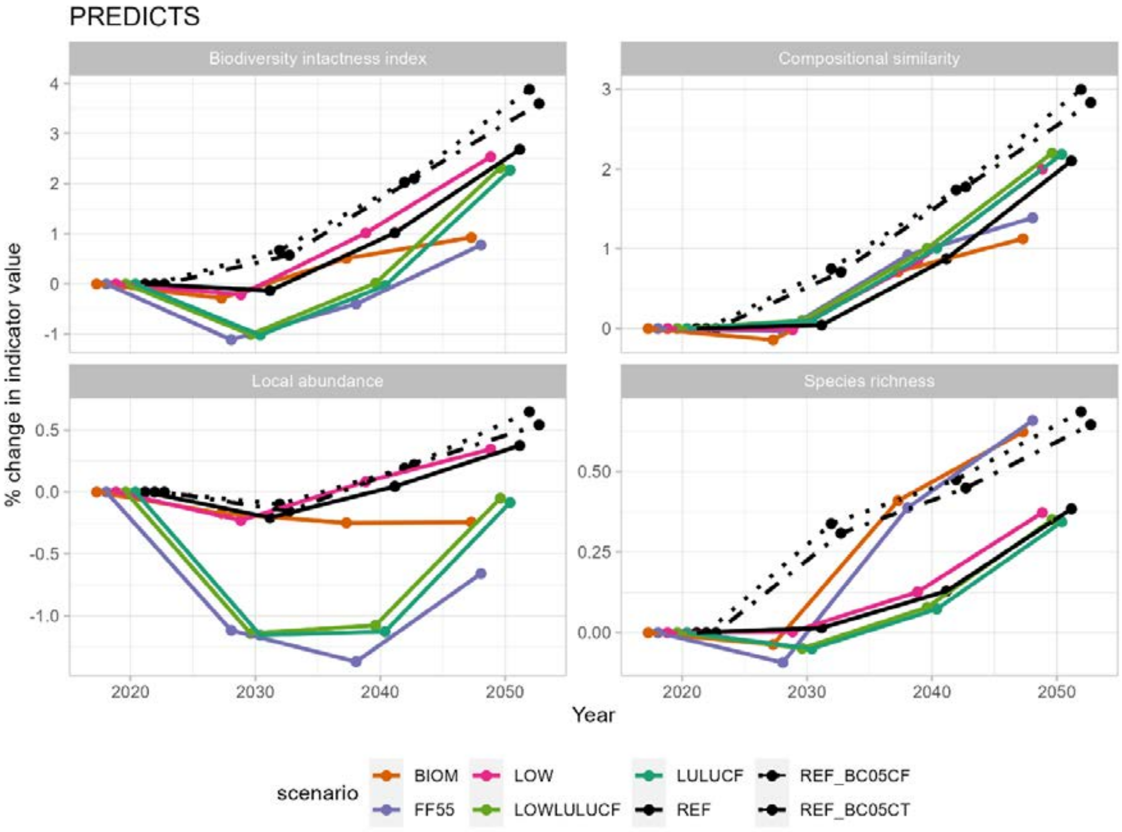


All indices are standardized relative to the initial conditions in year 2020. The uncertainty bars are the Confidence Interval calculated as ±1.96 Standard Error of the Mean.

6.3.2. Community-level indicators

All Climate policy scenarios show improvements in mean values of local biodiversity across Europe by 2050 (Figure 15). A pattern consistently predicted across scenarios is the time lag in biodiversity response for BII, species richness and compositional similarity. Trends accelerate between 2030 and 2040 and the greatest gains are observed by 2050. This could be attributed to the maturing of young secondary vegetation over the three decades, with a corresponding improvement in biodiversity in the later stages of maturity.

Figure 15 – Trends in percentage change of mean local biodiversity metrics across Europe from 2020 to 2050 for the Reference scenario and Climate policy scenarios



Points indicate the percentage change in mean values across all model iterations for the Biodiversity Intactness Index, compositional similarity, local total abundance and species richness.

6.3.2.1. BII

Across Europe, there is improvement in mean BII for all scenarios, although the magnitude of this change is small, with mean BII only improving by between 0.7% and 3.9% by 2050 (Figure 15). Of the climate change mitigation scenarios, BIOM and FF55 appear to have the smallest impact for biodiversity, increasing BII by less than 1% by 2050 (Figure 15). Other climate change scenarios show similar trends to that of the reference scenario, increasing BII by between 2.0 and 2.6% by 2050.

Although the differences are minimal when looking at the average change in BII across Europe, there are patterns that emerge when considering changes at the biome level (Table 6). The most degraded biome in 2020, the 'temperate grasslands, savannas and shrublands' continues to degrade in all but the LULUCF and LOW_LULUCF scenarios. In contrast, the 'temperate coniferous forests biome' and 'temperate broadleaf and mixed forests' increases in all scenarios. BII is predicted to increase in 'Mediterranean forests, woodlands and scrub' in all scenarios but BIOM and FF55. It is likely that the decline in this biome for these scenarios, as well as comparable decreases for 'temperate grasslands, savannas and shrublands', is driving the smaller increase in BII in the Europe-wide trends (Figure 15). 'Boreal forests/taiga' show improved BII in the reference scenario and two climate mitigation scenarios: BIOM and LOW. Tundra is predicted to decrease in BII in all scenarios, but these declines are of a low magnitude.

Table 6 – Average values of mean % change (±SD) in BII between 2020 and 2050 per biome for each scenario

Scenario	Boreal Forests/Taiga	Mediterranean Forests, Woodlands & Scrub	Temperate Broadleaf & Mixed Forests	Temperate Conifer Forests	Temperate Grasslands, Savannas & Shrublands	Tundra
REF	1.18 (±3.7)	0.56 (±6.77)	4.06 (±14.53)	0.32 (±2.89)	-1.15 (±0.84)	-0.22 (±0.68)
BIOM	0.92 (±3.43)	-1.2 (±8.61)	1.63 (±9.31)	0.65 (±3.36)	-1.23 (±0.96)	-0.23 (±0.68)
LULUCF	-0.8 (±4.88)	0.23 (±7.37)	4.07 (±14.06)	0.44 (±3.52)	0.27 (±1.17)	-0.63 (±1.15)
FF55	-0.89 (±4.73)	-1.5 (±8.6)	2.05 (±9.69)	0.68 (±3.63)	-1.3 (±1.01)	-0.63 (±1.15)
LOW	1.25 (±3.84)	0.64 (±6.91)	3.75 (±14.05)	0.47 (±2.88)	-1.18 (±0.83)	-0.22 (±0.68)
LOW_LULUCF	-0.6 (±4.89)	0.34 (±7.49)	4.07 (±14.03)	0.42 (±3.47)	0.04 (±1.03)	-0.63 (±1.15)

6.3.2.2. Compositional similarity

The trends in mean compositional similarity are comparable with those of BII, with BIOM and FF55 showing the smallest gains in compositional similarity by 2050 (Figure 15, compositional similarity plot). The other climate change scenarios follow a similar trajectory to the reference scenario with comparable increases in compositional similarity by 2050. As with BII, mean compositional similarity is predicted to increase across Europe between 2020 and 2050 (Figure 15).

6.3.2.3. Abundance

When considering mean local abundance across Europe, there is no significant increase observed for any of the climate change scenarios, with some (e.g. FF55) resulting in a decrease by 2050 (Figure 15). This suggests that the actions required to mitigate climate change in these scenarios have little benefit for local abundance, and in some cases may be detrimental (FF55: -0.7 mean local abundance in 2050, Figure 15).

6.3.2.4. Species richness

By 2050, species richness is predicted to improve for all climate change mitigation and reference scenarios, but this increase is marginal. Compared to the reference scenario (REF), we see different emerging trends for BIOM and FF55, which show a slightly greater increase in species richness by 2050. This increase is small, around 0.62 for the climate scenarios, compared to an increase of 0.37 in the reference scenario (Figure 15).

6.3.3. Differences between species-level and community-level indicators

Both species-level and community-level indicators generally predict the Reference scenario to be among the worst performing, with either stable or declining biodiversity trends. There are, however, some differences. Broadly speaking, community-based indicators are stable or positive across all scenarios while species-level indicators decline under both the REF, LOW and BIOM scenarios, for reasons explained in section 6.3.1.

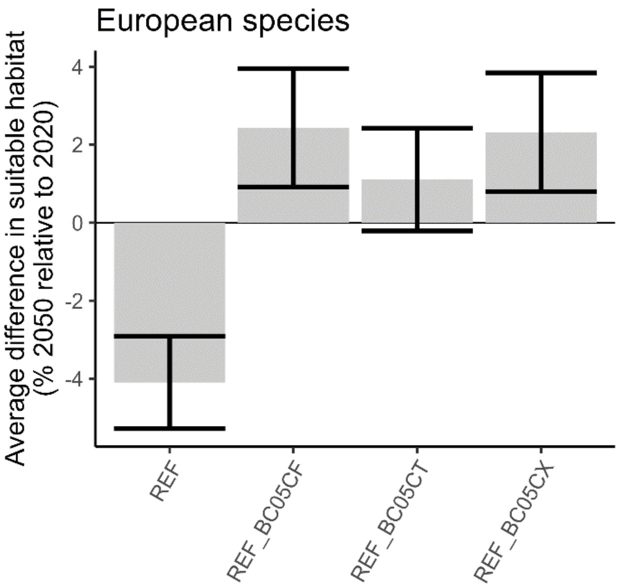
Another fundamental difference is the trend in the period 2030-2050, where we see a general reversal (from increases to slight decreases) in the single species biodiversity indicators, and accelerated increases in the community indicators. This is likely to be a result of different modelling assumptions, rather than genuine differences in how whole parameters of entire community (total richness, total abundance, community composition) respond as opposed to trends in suitable habitat averaged across species. The PREDICTS indicators include forest age as a covariate and predicts an increases in abundance, BII and compositional similarity (relative to pristine habitat) towards the end of the simulation period thanks to delayed forest cuts. The species distribution models use management (rotation time) as opposed to forest age, as a covariate, therefore anticipate these changes.

6.4. Biodiversity impacts for increased protection and restoration scenarios

6.4.1. Species-level indicators

The application of restoration measures to the baseline scenarios switches the long-term trends for species habitat from negative to positive. However, at the European level we did not find notable differences in restoration benefits between different burden-sharing assumptions except for the fact that implementing priority areas for restoration in absence of burden-sharing limitations or with flexible-sharing restoration are marginally better than setting an equal restoration burden across countries (Figure 16). This is to be expected, as these two scenarios give more flexibility for restoration actions to happen where they have the highest benefit for biodiversity.

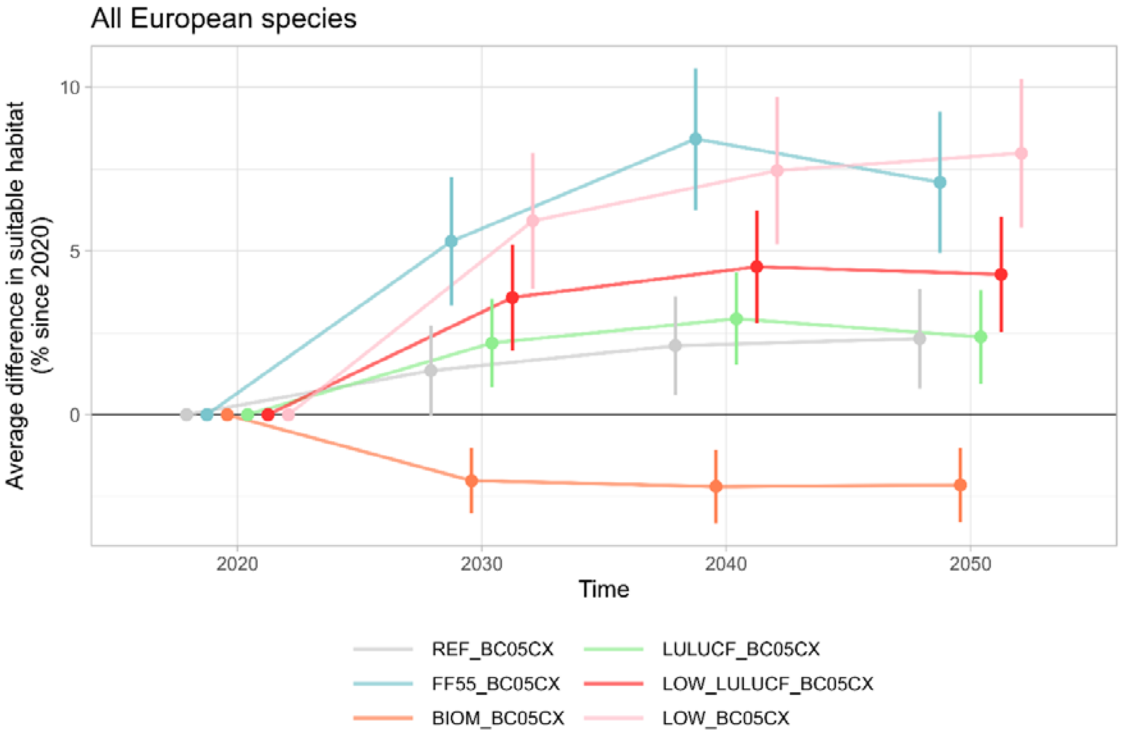
Figure 16 – Percentage difference in species suitable habitat between 2020 and 2050 (mean and standard error) for REF, and RED plus application of biodiversity conservation measures



BC05CF indicates EU-wide restoration priorities, without provisions to balance burden sharing between countries, BC05T indicates that each country has a fixed restorable area set at maximum 15% of their land surface, BC05X indicates that there is restorable area is capped at maximum 25% of the country surface area. This burden-sharing assumption has been applied to all integrated scenarios. The uncertainty bars are the Confidence Interval calculated as ±1.96 Standard Error of the Mean.

We find that all land-use scenarios that integrate both climate mitigation measures and biodiversity conservation measures increase the amount of suitable habitat for species by 2050 with the exception of the scenario with high biomass demand for energy production in absence of LULUCF enhancement mechanisms (Figure 17).

Figure 17 – Trends in species suitable habitat (mean and standard error of the mean) for integrated climate and biodiversity scenarios for the period 2020 to 2050

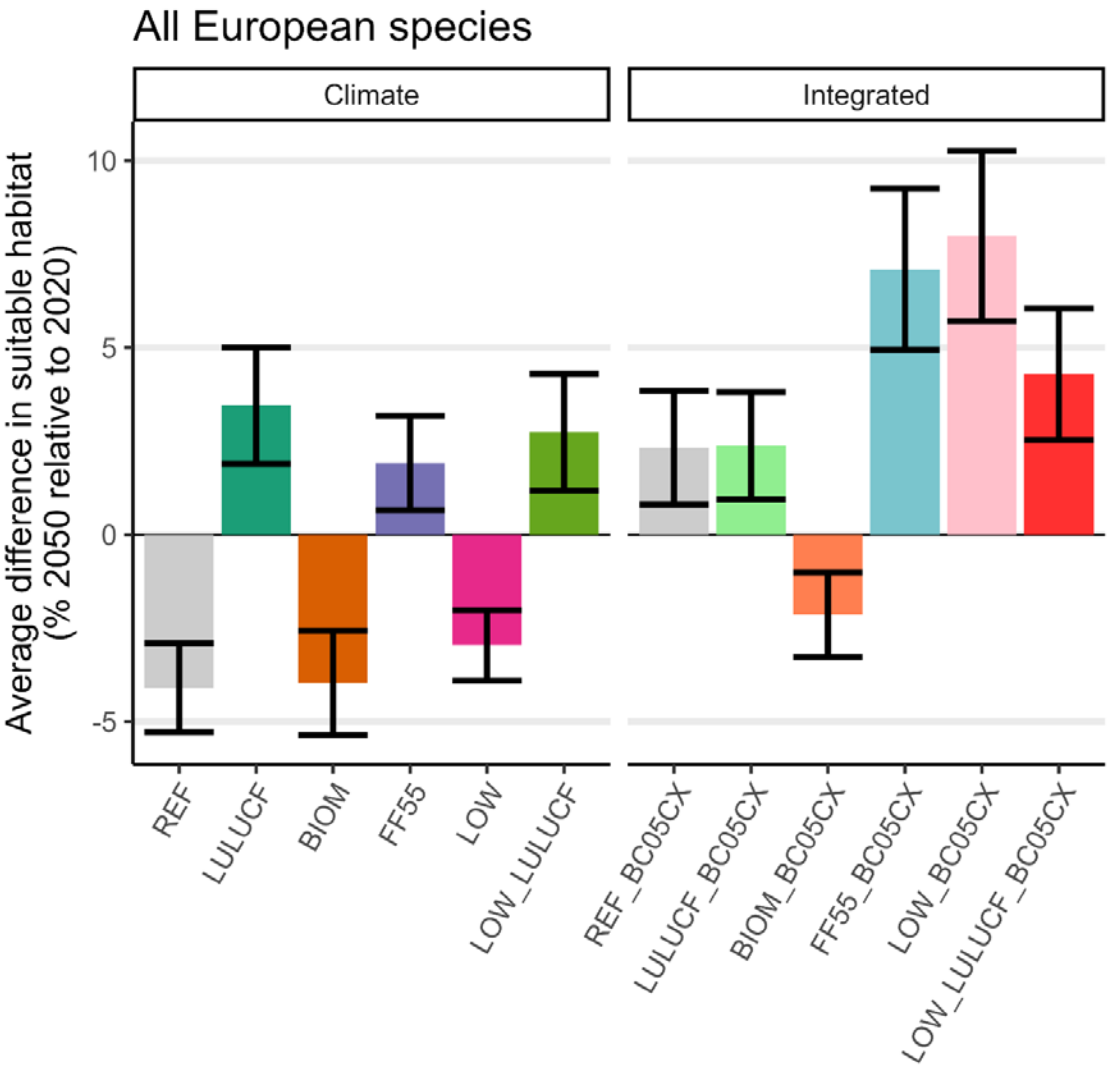


All indices are standardized relative to the initial conditions in year 2020. The uncertainty bars are the Confidence Interval calculated as ±1.96 Standard Error of the Mean.

The biodiversity trends are comparably similar or better than equivalent scenarios without biodiversity conservation measures (Figure 17).

The slight decline in suitable habitat for species between 2040 and 2050 which was observable with all scenarios including LULUCF-enhancing is greatly diminished or entirely disappears when restoration measures are included. This is because the main drivers of biodiversity trends in restoration scenarios are the extensification of management in cropland and grassland (switch from high-intensity to low intensity, Figures 5 and 6) that is common to all scenarios that integrate climate policies with restoration actions and that appears in 2030 and remains almost constant throughout the simulation period and is assumed to have immediate benefits in terms of gains in habitat suitability in the species distribution model used to derive these indicators.

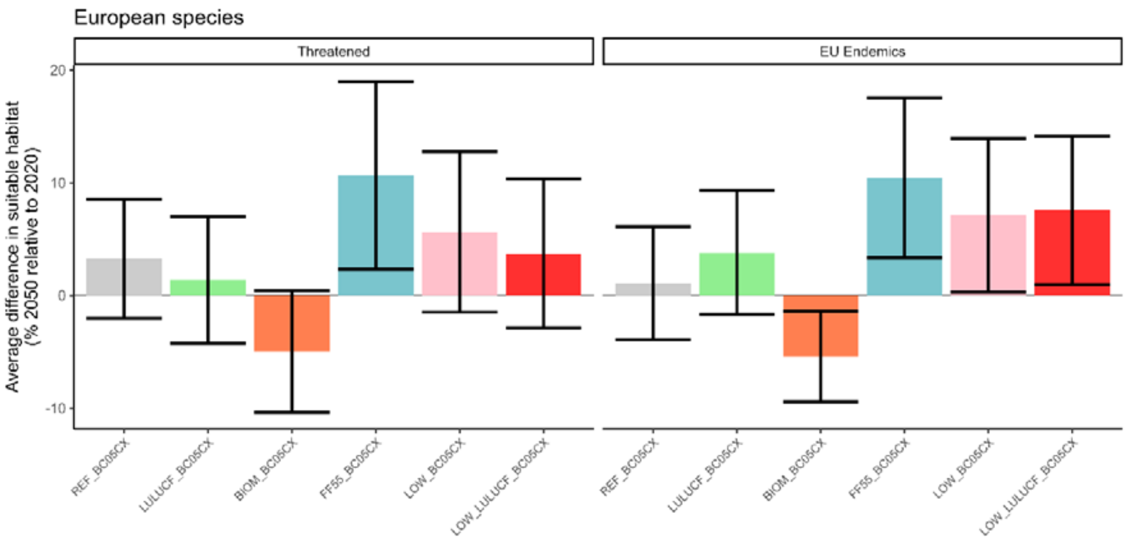
Figure 18 – Percentage difference in species suitable habitat between 2020 and 2050 (mean and standard error) for REF, 5 Climate policy scenarios and integrated scenarios



The uncertainty bars are the Confidence Interval calculated as ±1.96 Standard Error of the Mean. The value for each histogram for climate policies are the same as those for the year 2050 of Figure 13 while those for Integrated policy scenarios are the same as those for the year 2050 of Figure 16.

When disaggregating trends by Threatened and Endemic species, we find an amplification of the combined positive effects of climate and biodiversity conservation policies, similarly to what was observed with climate policies alone (Figure 19). The spread of trend values around the mean is for integrated scenarios even wider than for climate only scenarios, indicating that local restoration benefits can bring large local benefits but also losses, e.g. resulting from indirect effects via intensification of forestry and agriculture elsewhere (e.g. see Figure 2).

Figure 19 – Trends in species suitable habitat (mean and standard error) for climate scenarios and integrated scenarios of climate policies and conservation and restoration actions disaggregated by threatened (CR, EN, VU) or European endemic species

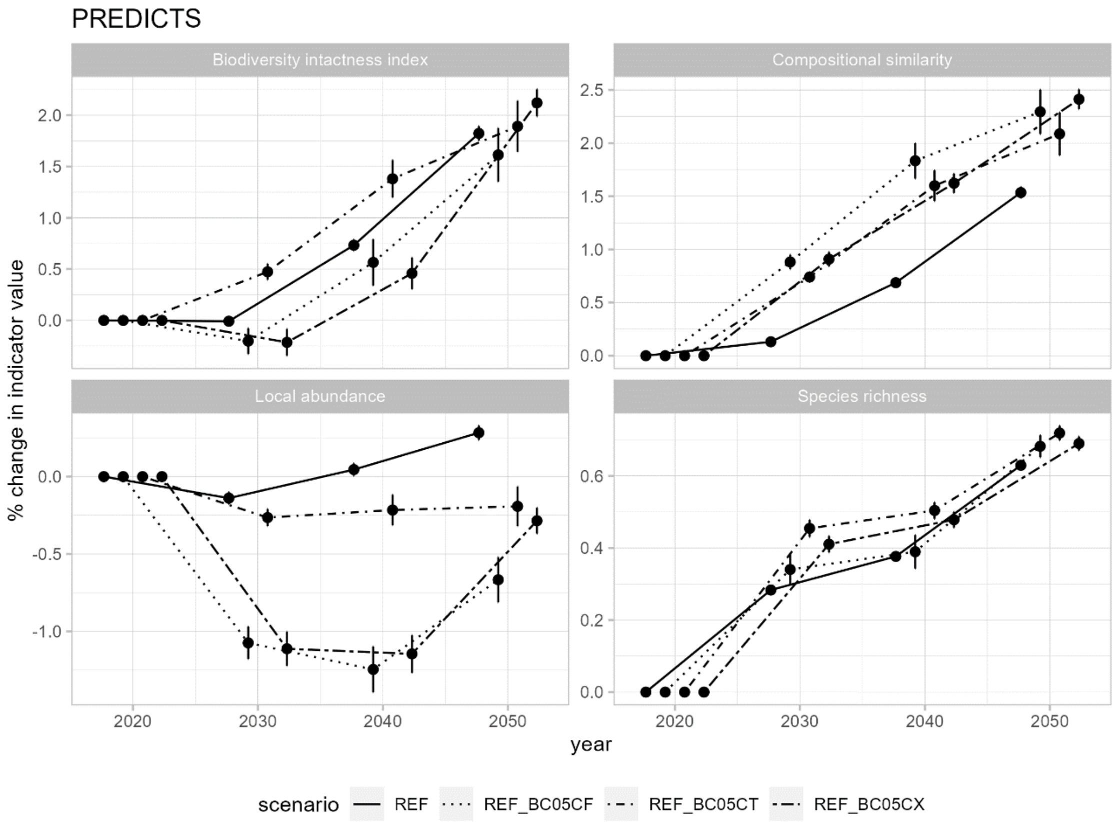


All indices are standardized relative to the initial conditions in year 2020. The uncertainty bars are the Confidence Interval calculated as ±1.96 Standard Error of the Mean.

6.4.2. Community-level indicators

We find marginal differences between the baseline reference scenario and conservation and restoration scenarios when considering average responses across Europe for compositional similarity but not for biodiversity intactness and species richness, while we find some overall negative effects for mean population abundance (Figure 20). When examining mean values across Europe, there appears to be little difference between the trajectories for the local biodiversity metrics for the three restoration scenarios towards 2050. This is compatible with our findings for species-level indicators and mitigates the need for some countries to take on a greater burden of restoration.

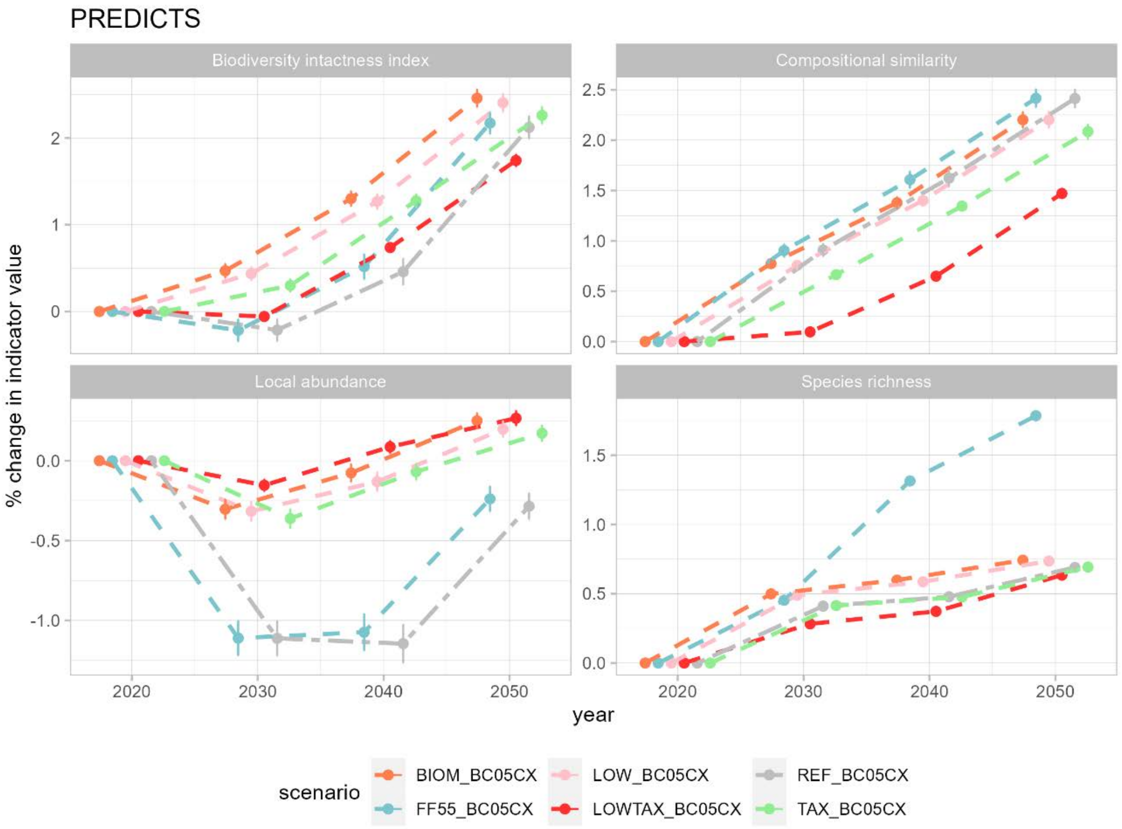
Figure 20 – Trends in percentage change in mean values of local biodiversity metrics across Europe from 2020 to 2050 for the increased protection and restoration scenarios



Points indicate percentage change in mean values across all model iterations with SE indicated by bars for the trends in the Biodiversity Intactness Index, in compositional similarity, in local total abundance and in species richness.

A similar pattern can be seen when considering integrated scenarios of climate policies and conservation and restoration actions (Figure 21). No significant differences in mean values across Europe are estimated between all scenarios for BII, compositional similarity and total local abundance (Figure 21 A-C). However, when considering species richness, it is estimated that the FF55 scenario integrated with conservation and restoration actions significantly outperforms all other integrated scenarios. This difference emerges after 2030 and may be caused by the removal of high intensity cropland combined with the removal of high intensity production forest that is forecast in this scenario.

Figure 21 – Trends in percentage change in mean values of local biodiversity indicators across Europe from 2020 to 2050 for climate scenarios and integrated scenarios of climate policies and conservation and restoration actions



Points indicate mean values across all model iterations with SE indicated by bars for the trends in the Biodiversity Intactness Index, in compositional similarity, in local total abundance and in species richness.

6.4.3. Differences between species level and community-level indicators

Qualitatively speaking integrated scenarios tend to outperform climate policies only scenarios both when assessed with species level and community level indicators and in this sense the overall assessment of the importance of restoration measures does not change depending on the type of indicator used. The main difference among biodiversity indicators is that while species-level indicators greatly benefited from lower biomass demand both with and without restoration (e.g. compare REF_BC and LOW_BC with BIOM_BC in Figure 18 or BIOM with LOW in Figure 13), the community-based metrics did not benefit from lower biomass demand with the integrated scenarios Figure 21). A possible explanation is that increases in intensively managed and permanent croplands under the FF55 and BIOM scenarios with restoration could have occurred in more densely populated areas. The PREDICTS framework accounts for population density and, everything else equal, all community-based indicators would have lower values in densely populated regions. This means that the displacement of intensive forestry and agriculture due to local restoration actions, particularly acute in some regions under high biomass demand scenarios (see Figure 2) is likely to be associated with higher losses of suitable habitat by the species distribution models due to their not accounting for population density, than by the PREDICTS family of indicators. In the future accounting for population density, alone and in interactions with land-use shares, will be useful to further investigate this possibility.

7. Discussion

We structure the discussion of our findings around the key policy questions of this project.

7.1. What are the impacts on biodiversity of expected land-use under the Reference scenario and Climate policy scenarios?

Under the Reference and Low biomass scenarios we found an average reduction in habitat for all species modeled of 3-4% by 2050, attributable to losses in farmland habitats (overall reduction in agricultural areas) and lower gains in forest cover compared to other climate scenarios (Table 4). Under the same scenarios, local community-based indices are stable or increasing, with stronger increases projected by 2050 in local species richness for the Low biomass scenario.

Our results therefore suggest that in the absence of any climate policies or biodiversity policies, macro-economic, demographic and technological drivers of change may continue to exert pressure on habitat for species which may result in declines by the middle of the century (Figure 13). However, there is a large degree of uncertainty about projected impacts of the Reference scenarios, e.g. for Biodiversity Intactness (Table 6) and to some extent also for species-level indicators, especially when investigating Endemics and Threatened species, with some projected to be gaining habitat even under this scenario Figure 14).

The results for the LOW and REF scenarios for species distribution indices are comparable with the biodiversity trends for the indices with similar modeling approaches found in the SSP3 Rural Revival and the SSP2 Eco-Centre scenarios described in Veerkamp et al. (2020). The authors also report on Mean Species Abundances, using the GLOBIOM modeling approach, broadly comparable with the PREDICTS model applied here, but found small but consistent negative trends across all scenarios simulated, compared to the stable or increasing trends observed in this study. This is most likely due to the fact that Veerkamp et al. accounted for climate impacts in both of their indicators analyses, while we investigated exclusively the effect of land-use change, to be able to compare scenarios exclusively based on land-use trajectories.

Under the BIOM scenario we found declines in species habitat trends when averaging across all species. This is due to the increase in perennial lignocellulosic crop extent of >100,000 km^2 by 2050 which is generally correlated with loss of habitat for the species modelled here.

Scenarios where LULUCF enhancement measures are applied result in larger increases in forest extent than REF and BIOM, and both rate of conversion of semi-natural non-forest habitats and rotation time increase comparable to REF but lower than BIOM (section 4.2). These three factors combined cause a modest average increase in biodiversity as measured through species suitable habitat as well as community-based biodiversity metrics. This result is not surprising, given that richness of forest-related animal and plant species in the EU is higher than for other habitat specialist and this is true also among species modelled in this study (e.g., 35% are associated to forest ecosystems versus 12.5% associated to cropland).

The combination of a carbon price and biomass demand as applied in the FF55 scenario results in slightly antagonistic effects the biodiversity metrics investigated. Increasing demand for biomass from forest products and annual and permanent cropland reduces the positive effects of the carbon price in terms of rotation time and forest cover.

Our results suggest protecting all existing old growth and primary forests, plus those that are closer to being considered old-growth, up to 10% of all forest area, combined with the management of natural forests with extended rotation time (for example from 60 to 80 years in Mediterranean and Temperate forests or Birch, and from 90 to 110 in Boreal forests), offers a good compromise between maintaining production forests, restoring carbon through the mid-21st century, and maintaining sufficient habitat for forest species.

7.2. What is the potential contribution to climate mitigation of different potential implementations of habitat restoration and conservation targets under the EU Biodiversity Strategy?

Our results indicate a moderate net positive long-term (e.g., 2050) climate mitigation benefit from increased protection and restoration efforts via reduced forest management GHG emissions. In particular, as detailed in section 5.3, we project increased protection and restoration efforts to sustain the forest management carbon sink, which is instead expected to reduce by 2050 in the REF scenario due to increased harvest levels. This climate mitigation benefit can reach up to 15MtCO2/yr, which represents one third of the projected 2020-2050 forest management sink reduction in the REF scenario. The carbon removal potential of restoration actions in forest ecosystems is certainly an underestimate because soil organic carbon accumulation is not considered in our analyses.

The carbon removal benefits of restoration actions are not projected to occur when considering incentives to increase forest carbon removal (see section

5.4), that is projected to more profoundly impact the management of EU forests and reverse the decline in the forest management sink projected for the reference scenario. And even when projected (i.e., in scenario without carbon price), the projected long-term and short-term forest management sink effects depend on relatively complex, time-varying and uncertain knock-on effects on the management of the rest of EU forests, and the implications of these multiple forest management changes on forest carbon dynamics. For example:

- As detailed in section 4.3, our scenarios include the restoration of both a share of forest under low-intensity multipurpose management to more restrictive set-aside management (as a contribution towards protection targets, for an area equivalent to 1% of total EU27 2020 forest extent) and a share of the forest under production-oriented management to low-intensity multipurpose management (as a contribution towards protection and restoration targets, for an area equivalent to 6-7% of total EU27 2020 forest extent). In order to maintain the supply of wood biomass, we project a subsequent intensification leading to a conversion of other multipurpose forests to production-oriented forest (an area equivalent to 11-12% of total EU27 2020 forest extent), leading to a net gain in production-oriented forest and a net loss in multipurpose forest.
- These changes in forest management practices are expected to affect the carbon cycle of forests in various ways, depending on their initial management change trajectory and local climate and soil conditions. The forest restored from low-intensity multipurpose management to more restrictive set-aside management increases the amount of deadwood by a factor of three. The forest restored from the production-oriented management to low-intensity multipurpose management increases live biomass by 28% and the amount of deadwood by a factor of 2. At the same time, in the forests which were converted from low-intensity multipurpose management to production-oriented management for supporting wood supply, live biomass and deadwood decrease to respective levels of production-oriented forests.

These results are consistent with literature pointing to potential trade-offs between biomass provision, carbon sequestration in forests and increased protection and restoration objectives, with a significant but uncertain potential to reduce such trade-offs through widespread and context-specific adjustments to forest management practices (Gusti et al. 2020; European Environment Agency. 2023; Rosa et al. 2023; Korosuo et al. 2023). Additional and likely long-term monitoring and modelling efforts are required to understand and harness the potential of alternative EU forest management trajectories to meet multiple objectives. This should also include the impacts of expected increased natural disturbances from future climate change and potential increased resilience to those from protection and restoration measures, not considered in this analysis.

Carbon fluxes from changes in extent and management of cropland and managed grasslands are projected to be smaller in magnitude than for forest management, but similarly expected to depend on uncertain indirect land use change, ecological and biophysical dynamics. These dynamics are mediated in the short-term through markets, and in the longer run through changes in the demand for agricultural products as well as changes in ecosystem service provision such as pest control, pollination and drought resilience (e.g. Barreiro-Hurle et al. 2021; European Commission. Joint Research Centre. 2022). Our projections do not account for changes in ecosystem services provision, assuming by design that the EU trade balance in agricultural products remains unaffected by alternative scenarios as compared to the Reference scenario. The projections do however account for changes in EU demand for agricultural products in response to prices changes triggered by changes in land availability and productivity, with a projected decrease the demand of land intensive products such as beef for increased protection and restoration scenarios. This contrasts with the forestry sector, for which the consumption of wood is assumed to be met at Member State level in all scenarios. The importance of indirect land use change responses is not restricted to increased protection and restoration efforts and can for example play a significant role in determining the net climate mitigation impacts of climate mitigation efforts in the EU agricultural sector (e.g. Frank et al. 2021).

Our result only partially covers potential climate mitigation impacts associated with the increased protection and restoration actions. We already discussed the lack of accounting of SOC in forests; in addition to this, it is important to highlight the value of soil carbon accumulation associated with the re-wetting drained peatlands formerly converted to agricultural areas or subject to afforestation. These land-use changes and associated carbon flows could not be included in the modelling and are expected to generate particularly large climate mitigation co-benefit through reduced GHG emissions, for relatively limited cost (e.g. Fellmann et al. 2021).

Further to this, our results are affected by the empirical data used to estimate yield reductions associated with transitioning from production-oriented forest management to multi-functional forest management, and with yield reductions associated with extensification of grassland and cropland management. Lower yield reductions are likely to materialize in the future (Barreiro Hurle et al. 2021) and this would reduce the indirect negative effects of reduced management intensity where restoration occurs, through management intensification or habitat conversion elsewhere. Considering all of these factors suggests that our analyses underestimate, potentially by a significant amount, the climate mitigation and adaptation benefits of habitat conservation and conservation, something we come back to in section 8 with regards to recommendations for model and scenario improvements.

7.3. What is the combined impact of climate and biodiversity policies on land-use change and associated emissions? Which combinations of climate mitigation and biodiversity conservation measures yield positive additive effects and which combinations have contrasting effects on land-use and GHG emissions?

Overall, in terms of land use and LULUCF emission trajectories, our results depict a limited interaction across climate mitigation and increased protection and restoration scenario dimensions for the agricultural ecosystems, but a more significant interaction for forest ecosystems.

In the agricultural sector, as compared to climate mitigation alone (e.g., BIOM, LULUCF, FF55, LOW_LULUCF), additionally considering the extensification of agricultural ecosystems (e.g., adding BC05X scenario-related assumptions) is not projected to lead to increased agricultural land extent and does not prevent the expansion of cropland required to meet perennial crop biomass demand in most ambitious scenarios (e.g., BIOM scenario), with resulting pressures on semi-natural ecosystems projected to be only slightly modulated. Similarly, assuming increased climate mitigation on top of increased protection and restoration efforts is not projected to prevent the extensification of agroecosystems. As a result, there is limited interaction across these scenario dimensions for LULUCF emissions related to cropland and grassland management, with the largest signal (a temporary decrease in cropland management emissions through perennial crops biomass accumulation) being primarily affected by related biomass demand assumptions. As mentioned in the previous section, some measures not accounted for here (e.g., fallowing/rewetting of drained organic soils) could be synergistic towards both climate mitigation and biodiversity objectives, and expected to be promoted in scenarios targeting those objectives.

In the forestry sector, in terms of changes to forest ecosystem extent and management, as well as related LULUCF emissions, the impacts of the Climate policy scenario assumption dominate but do not fully override that of increased protection and restoration assumptions, with non-additive effects. While the projected restoration to set-aside forest management from increased protection and restoration scenarios is not affected by additional consideration of climate mitigation interventions (by design), projected changes to the extent of other forest management classes is affected by both climate mitigation and increased protection and restoration assumptions. While impacts from climate mitigation assumptions (and in particular, the carbon price) seem to dominate, considering additional protection and restoration efforts lead to more moderate intensification (through conversion from low-intensity multipurpose forests to production-oriented forests) and extensification (through conversion from production-oriented forest to high-intensity multipurpose forest, and increase in the average rotation time of production-oriented forests). When it comes to LULUCF emissions, outcomes are strongly dominated by climate mitigation assumptions, with a reversed decline in forest management carbon sink projected to occur when considering a carbon price, which is compensatory, rather than additive to potential climate benefits from increased protection and restoration. Assuming a reduced future level of demand for forest biomass by 2050 (in particular for bioenergy) may lead to additional gains in forest management sink. This however would be obtained at the cost of reduced climate mitigation in other sectors that may vary considerably depending on several factors (e.g. Myllyviita et al. 2021), and cannot be quantified by the employed modeling framework.

Several of the above-mentioned features relate to explicit modelling framework and scenario assumptions that needs to be considered when interpreting the results. For example, the difference between the agricultural and forestry sector in the extent to which interactions between the various policy dimensions can be diagnosed in projected land use and LULUCF emission outcomes can be directly related to how demand is modelled. While the demand for harvested wood biomass is inelastic by design in the model, and can hardly decrease, this is not the case for agricultural products: as a result, interaction between policy dimensions that have potentially conflicting impacts on biomass use are by default stronger in terms of land use for the agricultural sector, and a complete assessment of interactions needs to consider both land use and demand outcomes. From this perspective, based on our results and in agreement with available literature, biomass use-related conflicts between biodiversity and climate objectives can be expected in both sectors. The latter depends on both contextual elements that will affect future demand (e.g., dietary choices and lifestyle changes, waste reduction efforts, increased circularity, alternative energy sector decarbonization strategies, etc.) and estimated potential for land management adjustments (including integrated pest and nutrient management and conservation agriculture practices, as well as closer to nature forestry) to defuse trade-offs between multiple goals, that could not be comprehensively assessed in this study. Finally, the main results also depend on specific scenario assumptions: recent policy developments include some safeguards (e.g., REDIII provisions to limit the provision of energy biomass from old-growth forests and heathlands) are not fully accounted for. Accounting for these may lead to different impacts of various scenario dimensions on land use and LULUCF emission outcomes.

7.4. What is the combined impact of climate and biodiversity policies on biodiversity indicators? Which combinations of climate mitigation and biodiversity conservation measures yield positive additive effects and which combinations have contrasting effects on biodiversity?

In the BIOCLIMA analyses restoration was simulated as a decrease in management intensity of forest, cropland and managed grassland over approximately 15% of EU land surface. This was implemented in GLOBIOM as average yield reductions of 20% in crop and managed grasslands when switching from high to low-intensity cropland and grassland management, and ~75% yield reductions when transitioning from production-oriented to multi-purpose forestry (~80% of annual increments are harvested in production forests in average and ~20% are harvested in multi-purpose forest as exogenous assumptions). These yield losses were compensated through intensification or extensification of cropland, managed grassland and forestry outside restoration areas, to satisfy projected demands for timber products, crops and livestock, thus dampening the total net benefits of restoration.

Some of de-intensification is achieved already with the application of a carbon price, and therefore there is limited additionality in terms of total extent of land-use change (see section 4.3) but there is some additionality in terms of suitable habitat for species, as these restoration actions are more targeted spatially towards species that would benefit the most from habitat restoration (Chapman et al. 2023). This effect is clearly noticeable when assessing the impact of restoration using trends in species habitats as an indicator (Figure 18) where some additional benefits of restoration are visible even when coupled with the FF55 and the LOW_LULUCF scenarios.

Restoration benefits are also observed when considering compositional similarity but not when using species richness, local abundance or biodiversity intactness (Figure 20). Local abundance, also a component of biodiversity intactness, considers total abundance of all species, including those invading a local community from other ecosystems, due to habitat conversion or intensification. Additionally, the local community biodiversity metrics, averaged at the European level, are more sensitive to the total amount of land-use change and its interaction with other covariates such as human population density, as opposed to biogeographic patterns of species distribution and they are therefore complimentary in this sense.

Restoration actions also improve on the negative impacts for species habitat of a high biomass scenario (compare BIOM and BIOM_BC and FF55 and FF55_BC in Figure 18).

In summary a carbon price can create a financial incentive for reducing deforestation and for de-intensification of cropland and grassland management to reduce emission from LULUCF, which in our analyses of integrated scenarios was strategically directed to areas with the highest biodiversity benefits using maps of restoration priorities; thus creating potential synergies between climate policies and biodiversity policies, especially when assessing benefits through species habitat gains. At the same time, we observe that the systemic projected decreases in intensively managed annual cropland observable in all scenarios, including the Reference scenarios, could yield some benefits if that was associated with decrease in cropland management intensity, e.g. due to restoration efforts, (Figure 13, Figure 18, Figure 21).

8. Data and modelling gaps and recommendations for future integrated assessment of climate and biodiversity policies

The BIOCLIMA project is among the first in doing a comprehensive integrated assessment of land-use policies for climate mitigation and biodiversity conservation using spatially-explicit scenarios and models. Doing so has required several modifications to existing models to allow for soft-links (I/O) and feedbacks, as well as to better align the models inputs, outputs and assumptions with the policies we intended to simulate.

Several lessons and open questions emerged from this work, which we illustrate below, with the intent of guiding future data collection and model improvements.

To our knowledge, this project is the first ever in training species distribution models that are sensitive to land-use management intensity for a large number of species, and at the continental scale. In order to achieve this, we used the best gridded land-use intensity data we could obtain for the present day (Dou et al. 2021), however these land-use data are themselves modelled and come with potential inaccuracies and uncertainties, for example annual cropland management intensity is separated in three arbitrary classes, the same we applied in our projections to the future, but using several continuous measures of management intensity (e.g. pesticide and fertilizer application), together with information on small landscape features, using for instance JRC data (Fraucqueur et al. 2019). Improving the baseline data of cropland management intensity, will help improve the robustness of the statistical relationships between species occurrence rate and cropland management intensity. With regards to species distribution modelling, separating the different types of annual and permanent croplands is also likely to be important, at the moment olive groves, fruit orchards, vineyards, Miscanthus, switchgrass, giant reed and other permanent energy crops are all lumped into one land-use class in our analyses, and the same is true for all annual crops. While it is theoretically possible to map them spatially using Copernicus land-cover data, separating too many types of crops would result in an unfeasibly large number of predictors which would make it impractical to automatically fit model coefficients for a large number of species. It would also be impractical to project the spatial distribution of these crop types at fine resolution as it would require having repeated observations over time, to train our statistical downscaling model of land-use transitions.

Continuous measures of grassland management intensity, e.g. number of mowing events per year, or fraction of plant material grazed or mowed (Figure 8 in BIOCLIMA task 3 report), would also improve the accuracy of our accounting of grazing extent and intensity in the EU. For what concerns the impact of grazing, in BIOCLIMA we only considered grassy fields in both semi-natural and artificial grasslands; consideration of grazing in shrublands and wood-pastures will improve the accounting of livestock (artificially concentrated into grassland habitats in our analyses) as well as its biodiversity and GHG impacts.

An area of improvement for BIOCLIMA is the alignment in definition and expected harvestable wood yields of closer to nature forestry from the BIOCLIMA Steering Committee, and the application in GLOBIOM-G4M of multi-purpose forestry. A refinement and associated sensitivity analysis could be conducted in the continuation of this project in 2024.

One of the main areas of advancement in BIOCLIMA has been the statistical downscaling (spatial and thematic) of GLOBIOM-G4M to 5 arc-minutes resolution and 9 land-cover categories and several management intensity classes. While the downscaling routine employed here is actively and constantly being enhanced in its main functionality of empirically informed LU change downscaling, certain features required in BIOCLIMA revealed the need for specific developments and the lack of available data for parameterization. For the current BIOCLIMA setup mostly involves agnostic downscaling of LU management intensity projections from preceding models, i.e. GLOBIOM-G4M, by intersecting their finest resolution outputs (NUTS2 for cropland and pasture, and half degree for forestry), essentially assuming homogeneity across, onto the higher 5 arc-minutes spatial scale. However, and as already mentioned, limited options on high resolution management intensity data are further amplified when considering its temporal dynamics, i.e. how observed LU management changes over time. This renders an empirically based estimation of their determinants and driving factors as well as the potential of downscaling LU management projections over space and time an ambitious endeavour.

Moreover, thematically navigating between different LU classifications and their implied transitions in effective covered area, e.g. CLC, UNFCCC, and ecosystems type level 2 (as encountered in BIOCLIMA), constitutes an issue that emerges at the interface of LUC and biodiversity modelling and has not received exhaustive attention in the literature. Despite appearing as a niche question, the treatment of these thematic transitions affects biodiversity relevant land area coverage and, thus, introduces potential bias to biodiversity outcomes that can only be resolved when spatially explicit dataset in changes of land management intensity become publicly available to use. The main data gaps and uncertainties in land-use modelling uncovered in this project could be disseminated to the Destination Earth user exchange forum to start a conversation with relevant earth-observation stakeholders about improving data for model calibration and validation.

Moreover, cropland, grassland and forest management simulations in BIOCLIMA have ignored future impacts of climate change on plant growth and disturbances (fires, pests, wind throw). For example, plant growth is affected by CO_2 atmospheric concentration, temperature and precipitation patterns, with forest standing stock expected to increase in boreal forest due to climate change and decrease in Mediterranean forest. A re-analysis of the scenarios produced in this report, by accounting for climate change on cropland and grass productivity and forest dynamics will be a priority for the continuation of this project.

The estimates of carbon stocks and growth in old-growth forests are likely underestimated (Luyssaert et al. 2008) and future integrated scenarios should invest efforts on revising carbon accumulation curves of old-growth forest both in tree biomass, as well as the understory, the epiphytes and the soil organic carbon accumulating in old-growth forests. It is possible that an upward revision of the carbon accumulation in old-growth forest may favour a larger share of forest set-aside than what found in our analyses when measures are taken to reduce emissions from forest management.

In BIOCLIMA 1 we assumed wetlands to be static in the analyses, re-wetting of formerly drained peatlands is a key target of the Nature Restoration Law which is expected to have substantial positive effects on GHG fluxes and on biodiversity. A critical advancement will be to specifically simulate re-wetting by first identifying priority areas based on their potential contribution to achieving climate and biodiversity targets (e.g. using data from Chapman et al. 2023) and then assess the realized contributions once direct and indirect impacts on land-use via land market feedbacks have been taken into account using GLOBIOM/G4M.

Improvement of the land-use data will need to be matched by improvement in biodiversity observations used to train the ecological models used here. For the species-based biodiversity indicator (ibis.iSDM model) there are number of uncertainties regarding the biodiversity observation data. Although we considered an exhaustive sample of European species (Table 4), impacts could not be reliably estimated for all species listed, often because of a lack of public data of precisely georeferenced observations and bias in these observations towards highly populated and accessible areas, which results in under-sampling in more intact habitats compared to more impacted ones. We attempted to mitigate this through filtering of observational data and using information on species-associated habitat preferences or threats in the form of priors; but these were not available for all species. Future work to be done in the continuation of BIOCLIMA, should aim to reduce the number of species and focus on improving the quality of the input data, both in terms of biodiversity observations used to train the models, as well as land-use and other environmental covariates, and dedicate more efforts in independent validation of these models. The production of statistics about the combination of species and geographies with the least coverage or the largest bias during 2024 may help opening a discussion with the EU Biodiversity Platform, the EUROPABON and BIODT project consortia and the Knowledge Centre on Biodiversity about mobilizing data with restricted access.

As the BIOCLIMA models and scenarios are intended to be used to understand the impact of land-use policies, it is important that the mechanism by which policy measures impact land-use change, and how these changes impact biodiversity; the climate community has developed detection-attribution frameworks that allow to assign quantitatively the relative responsibility of different natural and anthropogenic sources to the net GHG fluxes. We attempted to have a transparent detection attribution framework for at least one biodiversity indicator here (section 6.2) but the complex, often non-linear and spatially-dependent relationship between land-cover, land-use, management intensity and other variables (e.g. topograhy, soil, human population density), makes it very difficult to derive straightforward and conclusive interpretations of the causal relationships between land-use changes and biodiversity trends. Nevertheless, the development of diagnostic tools and easy-to-interpret visualizations of causal relationship between scenario assumptions/land-use change and biodiversity status and trends is an important and necessary advancement for the reminder of this project and for any other integrated assessment that includes biodiversity indicators. We expect, during the continuation of BIOCLIMA, to further develop our detection-attribution framework and use this not only ex-post, to interpret and discuss scenario results, but also to formulate proposals for alternative policy scenarios, based on the causal relationships identified.

For what concerns the biodiversity indicators, climate change impacts (both in terms of extreme events such as wildfires or range shifts of species) are currently not considered in the biodiversity models, which implies that that observed biodiversity impacts are certainly an underestimate. For some of the biodiversity models (ibis.iSDM) climate change impacts and fire regimes will be integrated in the continuation of this project with results presented in the 2nd half of 2024.

Wildfires and other natural disturbances dynamics are strongly dependent on forest management with the scientific literature offering sometimes contrasting evidence about the optimal management strategy for maintaining forest resilience under climate change (Donato et al. 2006; Keenan et al. 2021; Zylstra et al. 2022) but with increasing evidence that allowing natural forests to regenerate, and reducing the intensity of logging activities reduces the risk of intense wildfires (Lindenmayer et al. 2020). The inclusion of specific modeling of fire dynamic under alternative management scenarios, including closer to nature forestry and forest restoration actions, will be important to fully account for the costs and benefits of alternative forest management, including on climate adaptation.

A limitation of BIOCLIMA has been the omission of restoration measures to improve the ecological condition of non-managed habitats in Annex I of the Habitat Directive, to meet the restoration targets highlighted in the Article IV of the Nature Restoration Law. This is a necessary improvement that will need to be considered in the continuation of this project that will require spatially-explicit data on ecosystem condition, available already for forest ecosystems in Europe (Maes et al. 2023).

During the course of the BIOCLIMA project, CAP strategic plans have been developed and can now be considered to develop new scenarios that integrate the CAP and the objectives of the Farm 2 Fork strategy. This will be a priority task jointly developed by the CAPRI and GLOBIOM modeling teams for BIOCLIMA 2 and that will include a participatory phase of scenario design.

A key data gaps in this context is lack of information on the yield impacts of reducing fertilizers and pesticides input, and shift from conventional to organic farming. Earlier studies have used pessimistic assumptions about yield losses. For example, Barreiro-Hurle et al. (Barreiro 2021) applied a homogenous 10% yield loss for all crops and all regions when reducing pesticides by 50% in 2030 and a mean 26% yield loss when shifting from conventional to organic farming, and other studies have assumed even higher losses. Barreiro-Hurle et al. suggest that these assumptions may be pessimistic due to constant improvement in integrated pest controls, selections of new plant varieties and general improvements of general farming techniques. Here we implemented a flat 20% loss in production for each step in reduction of crop management intensity from high, to low intensity (<50 kg of Nitrogen per hectare and minimal tillage), the 20% reduction in yield was similarly applied when shifting from high to low intensity in grassland management. Crop-specific and region-specific data from the farm accountancy data network (FADN) may help identifying where reducing cropland management intensity will result in the best trade-offs between agricultural production losses and biodiversity benefits.

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