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Impact of the EU biodiversity strategy for 2030 on the EU wood-based bioeconomy

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ABSTRACT

The EU Biodiversity Strategy (EUBDS) for 2030 aims to conserve and restore biodiversity by protecting large areas throughout the European Union. A target of the EUBDS is to protect 30 % of the EU's land area by 2030, with 10 % being strictly protected (including all primary and old growth forests) and 20 % being managed 'closer to nature'. Even though this will have a positive impact on biodiversity, it may negatively impact the EU's wood-based bioeconomy. In this study, we analyze how alternative interpretations and distributions of the EU's protection targets may affect future woody biomass harvest levels, exports of wood commodities, and the spatial distribution of managed areas under wood demands aligned with SSP2-RCP1.9. Using the model GLOBIOM-Forest, we simulate scenarios representing a variety of interpretations and geographic distributions of the EUBDS targets. The EUBDS targets would have a limited impact on EU harvest levels since the EU can still increase its wood harvest between 21 % and 24 % by 2100. With strict protection of 30 % of the area, the EU harvest level can still be increased by 10 %. Moreover, the most likely scenario (10 %/20 % protection within each MS) will result in increased net exports in the coming decades, but a slight decline after 2050. However, if protection is intended to also represent site productivity or to re-establish a green infrastructure, then EU net exports will also decline before 2050. With the decreased EU roundwood harvest, increased harvest will occur in other biomes and mostly leaking into boreal regions.

1. Introduction

Forest-based bioeconomy aims to utilize forest resources to replace fossil-based raw materials and products (Wolfslehner et al., 2016). In the EU, forest resources and associated bioeconomy are controlled by several policy instruments, including those recently formulated under the European Green Deal (Aggestam and Giurca, 2021, Lier et al., 2021). As many of these instruments are still in the revision process, it would be difficult and premature to investigate the overall impact of the Green Deal on the EU forest-based bioeconomy. There are, however, some aspects of the Green Deal that are already well documented and could be investigated. One of them is the EU Biodiversity Strategy for 2030

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(EUBDS), which addresses the current trends in biodiversity decline and sets a path to recovery (IPBES, 2019, Leclère et al., 2020). This plan includes a target to protect 30 % of EU land and sea areas by 2030 (EC, 2020a, b), of which one third (10 %) should be strictly protected and include all primary and old-growth forests. The remaining two thirds (20 %) should be under what is labelled as "closer-to-nature" management (Larsen et al., 2022). Currently, 23.3 % of EU forests are protected, including 4.7 % strictly protected and 18.6 % protected in other non-strict ways (WDPA, 2020).

To reach the EUBDS targets, many EU Member States (MS) need to adjust their land management and policies. However, the spatial distribution of protection within the EU has not been specified in the EUBDS. There are indeed ongoing scientific and political discussions concerning the spatial distribution of future protected areas (Hermoso et al., 2020) and the ways in which efforts to increase protection should be coordinated among the EU MS. In the current EU discussions, an equal allocation is considered at the level of countries or biogeographical regions (EC, 2022), but other distributions are also plausible since the EUBDS also includes objectives at the finer landscape scale. This is formulated as "green infrastructure", a "strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity" (EC, 2013). Thus, MS are encouraged to conserve, manage and restore sufficient areas of functional habitat networks to support viable species populations and their migration. This should be achieved by protected areas, including the Natura 2000 network (EC, 2013, 2019a), sustainable forest management, as well as 'closer to nature' management. The latter is currently defined only at EU scale (EC, 2023a) and needs to be translated into MS guidelines and local management practices. Additionally, its implications in terms of providing wood, non-woody ecosystem services and biodiversity require thorough assessment.

Another key role of EU forests described in the EU Green Deal is the contribution to reach climate neutrality by 2050 (EC, 2019b, EC, 2021a), given their ability to absorb and store large amounts of carbon (EEA, 2020a). Combined, climate and conservation policies may create synergies and increase the overall environmental and socioeconomic sustainability. However, forests can be used for climate change mitigation in contrasting ways, namely to sequester carbon on the forest land (Griscom et al., 2017), store carbon in long-lived wood products (Mishra et al., 2022) and replace fossil fuel-based products and energy sources (Hurmekoski et al., 2023). The emphasis placed on the different climate mitigation functions vary across policy domains (Pitzén et al., 2023). Mitigation through woody biomass uses in the bioeconomy may conflict with environmental sustainability and biodiversity conservation (Blattert et al., 2023, Mazziotta et al., 2022), due to potential management intensification (Betts et al., 2021). Forest growth, harvest and management vary widely across the EU as well as the future CO_2 sequestration trajectories of EU member states (Pilli et al., 2017, Pilli et al., 2022).

Achieving the EUBDS protection targets in the EU may have spillover effects in other parts of the world where wood is imported from (Rosa et al., 2023, Cerullo et al., 2023), with an increased risk of failing to achieve the targets of the Kunming-Montreal Global Biodiversity Framework (GBF, 2022). The reason is so-called leakage when decreased harvest in one region results in increased harvest elsewhere to meet the same wood demands. For example, Kallio et al. (2018) identified leakage when constraining EU wood harvest levels. However, they solely studied leakage given different country-level harvest, thus not varying neither management regimes nor areas protected within and among countries, both of which are key components of the EUBDS and further likely affecting leakage.

Protection according the EUBDS targets could have considerable impacts on the EU forest sector. Lotze-Campen et al. (2018) suggested a 13 % reduction in EU roundwood harvest potential when expanding the network of EU protected areas. However, they limited their analyses to year 2040 and simulated scenarios without any link to the EUBDS targets or the EU climate neutrality. Indeed, Schier at al. (2022) disclosed that EU roundwood harvest may be reduced by 9 %-48 % by 2030 and 11 %-58 % by 2050 when considering scenarios aligned with the EUBDS. However, they studied solely Germany and extrapolated the results to the rest of the EU without considering the very large spatial variation in allocation of protected areas and wood production.

Forest sector models provide an appropriate tool to investigate the impacts of polices on global resources use and bioeconomy while studying the complex dynamics of forest sector. Such models include aspects of forest management, forest industries, spatial explicit wood production costing as well as trade patterns, and enable the connection between wood supply and demands (Toppinen and Kuuluvainen, 2010, Latta et al., 2013, Riviere and Caurla, 2020). The forest sector Global Biosphere Management Model GLOBIOM (Havlík et al., 2011, Lauri et al., 2021) simulates management regimes and protection areas spatially explicitly at a 50 km^2 scale in the EU and at a coarser resolution globally. The model accounts for forest growths in each simulation unit and intensity of harvest according to management regimes applied within each unit. Hence, this model structure enables to simulate how changing distribution of management regimes would affect harvest, forest industry production and global trade in a consistently connected way. Further, GLOBIOM allows to capture potential wood harvest leakages in other global regions through wood trade.

The overall aim of this study is to investigate effects of alternative approaches to protect forests under policy targets aligned to the EUBDS on woody biomass harvest, considering also leakage outside the EU on different spatiotemporal scales. We contrast six scenarios of increased protection against a baseline scenario of unchanged protection. We quantify the leakage outside EU resulting from increased protection, including biomes that can be expected to compensate for the consequential decreased harvest within the EU. The spatially explicit scenarios differ in terms of how the protection is distributed among: EU member states, biogeographic regions, forest productivity across the green infrastructure, and combinations thereof. We further conduct a sensitivity analysis assuming a stricter interpretation of the conservation policy where all 30 % of the forest land is strictly protected. We use the state-of-art forest sector model GLOBIOM for simulating forest management and the resulting impacts on wood harvest and trade under each of the seven forest protection scenarios until year 2100.

2. Material and methods

2.1. Modelling approach

The scenario simulations were conducted using the Global Biosphere Management Model (GLOBIOM) (Havlík et al., 2011, 2014),a global spatially-explicit agricultural and forest sector model. The model is solved recursively for each 10-year time step by maximizing the economic welfare, defined as the sum of the producer and consumer economic monetary surplus (S.M4). Here we specifically used GLOBIOM-forest, which includes forestry, forest industry and bioenergy modules, as described in Lauri et al. (2019, 2021, S.M1), but where the agricultural sector is simplified to include just one product, energy crops (S. M5). The wood supply in the EU region is modelled on a 0.5° grid (ca. 50 km^2) while the demand and trade are modelled using 57 economic global regions (including 28 EU Member states as single regions, see Table S.M3.2), where wood supply in regions outside EU is modelled at the resolution of 2.0° (ca. 200 km^2). Land-use and land-management change is modelled according to linear land-use and land-management change costs functions following the approach of Havlík et al. (2011).

Woody biomass supply is based on spatially explicit harvest potentials, harvest costs, transportation costs and forest-/management-regime specific land-use change costs. The harvest costs are based on G4M output and transportation costs on Di Fulvio et al. (2016). The initial forest conditions for starting our simulations (year 2020) and economic optimizations match FRA (2020) country level data on forest area, standing biomass stocks, the World Database of protect areas (WDPA, 2020) grid level data, Global Forest Management Map (Lesiv et al., 2022) grid level data. These constitute the basis for the forest types generation and assignment of forest management regimes (S.M1). Sustainable harvest potentials are based on MAI (Mean Annual Increment) for each grid cell, as simulated with the Global Forest Model G4M (Kindermann et al., 2006, 2008; Gusti and Kindermann, 2011). Moreover, for the historical periods 2000–2020, management areas are scaled to match with FAOSTAT country level harvest volumes (FAO, 2023). Using G4M data and global age-class database (Besnard et al., 2021), the model generates initial grid level biomass growth curves and structures, that are subsequently calibrated to the country level biomass stocks. Within each grid cell, the model can have different management regimes with different age-class dynamics, mortality and harvest intensity. After 2020, the age-class dynamics develops endogenously and the model is not allowed to harvest more than long term biomass growth, represented by the mean annual increment (MAI).

GLOBIOM-forest applies three management regimes (close to nature, multifunctional, high intensity) and three main forest types (primary, managed and secondary forests), each characterized by two species groups (conifer/broadleaf). Primary forests have not been used historically for wood production, managed forests are currently used for production while secondary forests are abandoned managed forests. The management regimes in GLOBIOM forest differ in the proportion of MAI that can be harvested. In high intensity management, the whole MAI can be harvested while in multifunctional and close to nature management, only a part of it can be harvested, up to a maximum threshold set for each management regime (Table 1). Consequently, harvest volume can be changed in each simulation grid cell by changing the managed forest area, the forest management regime or by changing the share of MAI harvested within each management regime.

Table 1
Management regimes calibration and parametrization in the simulated EU protection scenarios (S.M1-2).

Management regime	Area, year 2020 (Mha)	Area calibration method	Maximum allowed roundwood volume harvest (% MAI)	Maximum allowed logging residues harvest volume (% Potential)
Strict protection	7.8	Primary forests allocated according to Lesiv et al. (2022), National level area matching to FRA, 2020. Strict protection forest areas according to IUCN categories Ia, Ib, II, III (WDPA, 2020).	0	0
Closer to nature	30.5	Non-strictly protected forests (IUCN classes IV-V-VI, S.M2) within the Natura2000 network (WDPA, 2020)	50	0
Multifunctional	92.7	Residual after assigning all the other classes.	75	25
High intensity	32.6	Planted forests according to Lesiv et al. (2022)	100	50

In all scenarios simulated, the EU (EU27 and UK, hereafter referred as EU) forest area was fixed at 164 M ha, following FRA (2020) forest cover harmonization. For Norway, the forest area was fixed at 12.8 M ha following FRA (2020). The total area available for management was kept constant over time.

After the initialization of starting year 2000, the allocation of area shares to the four management classes in each grid cell 2000–2100 was controlled endogenously by the model and based on the economic optimization (i.e. maximization of economic surplus), aiming to fulfil demands for wood at national level under each scenario.

GLOBIOM-forest includes 26 wood-based products, five harvested products and deadwood. These includes as an example four paper and paperboard grades, four pulp grades, three mechanical forest industry products, four forest industry by-products and two recycled products (S.M1). Bioenergy includes traditional fuelwood, woodchips and wood pellets. Forest industry and wood pellets production capacities are based on FAOSTAT production data for 2000–2020 (FAO, 2023). Final product demands are based on constant elasticity demand functions, which are parametrized by reference volumes, reference prices and elasticity coefficients. Exceptions are modern bioenergy demand, which is based on the socio-economic and climate pathways (SSP-RCP), sourced from the MESSAGE energy model (IIASA, 2020), and the traditional bioenergy demand, which is assumed to stay constant over time. After 2020, the demand volumes change over time based on gross domestic product (GDP) development and human population growth following the SSP-RCP scenario data (Riahi et al., 2017, IIASA, 2020). Trade is modelled by using bilateral trade flows. Bilateral trade calibration volumes are based on the BACI trade database for 2000–2020 (Gaulier and Zignago, 2010). After 2020, trade volumes evolve following trade dynamics, which depend on constant elasticity trade-cost functions parametrized by historical trade volumes and transport costs.

2.2. Protection scenarios

We simulated six scenarios on how to reach the EUBDS protection targets for 2030, contrasting them against a scenario of no change in protection, termed Current protection (Table 2). All scenarios assumed national timber demands for mitigating climate change aligned with the EU Green Deal policy package and the aim that EU should become climate neutral by 2050 (IIASA, 2020). In GLOBIOM, this is implemented as a bioenergy demand from the MESSAGE model (Riahi et al., 2017) following a 1.5 degrees warming scenario (RCP1.9) and a socio-economic development following a "middle of the road" (SSP2) until the year 2100. This leads to an increased EU woody biomass demand of 31 % during 2020–2100 (IIASA, 2020), see also *Sensitivity analyses*.

The model was first run for a calibration period of 20 years (2000–2020), where it was forced to reproduce the harvest volumes for this period according to FAOSTAT (FAO, 2023). Next, the model was run recursively until year 2100 in 10 years-time steps. The protection scenarios were implemented after year 2020, i.e. in year 2030.

2.3. Sensitivity analyses

We investigated effects of a stricter interpretation of the conservation policy objective compared to the main scenarios (Table 2) by applying '30 % strict protection', i.e. no harvest, on the total 30 % of forests under future protection. We also investigated effects of assuming lower increase in future EU wood demands (8 % increase during 2020–2100 instead of 31 %). This could reflect a broad combination of socioeconomic growth (SSPs) and climate development (RCPs), reducing the expected increasing rate of wood demand in the future, similarly to assuming 'RCP6.5′ instead of RCP1.9 (Lauri et al. 2019). The sensitivity analyses were applied to three main scenarios: EU, Country, Green infrastructure.

Table 2
Assumptions of the six protection scenarios simulated.

Scenario name	Description
Current protection	Maintains current EU protection areas.
EU	An economy-driven scenario. Protection is distributed to land where it has the least impact on economy in terms of wood production and harvested wood products within the EU. Areas that are currently least profitable to harvest are progressively moved to strict protection and 'closer-to-nature' management until the 10 %/20 % target is reached. Forest areas mapped in each grid cell as potential primary forests (7.5 Mha in EU) in Sabatini et al. (2020) were excluded from future management.
Biogeographical region (BioGeo)	As EU, but objectives are achieved for each EU biogeographical region. This scenario aims to reach representativeness of the EU biogeographical regions in the allocation of protection.
Country	As EU, but objectives are achieved for each EU country. This scenario aims for equal distribution of protection areas in each EU country, and it is the intended implementation according to the EU Guidelines (EC 2022).
Country BioGeo	As EU, but objectives are achieved for both each EU country and EU biogeographical region. This scenario aims to reach representativeness of the EU biogeographical regions in the country-level allocation of protection.
Country Productivity	As Country BioGeo, but allocation of protection within countries so that protected and unprotected forests have the same country-level mean productivity (including both new and areas protected already in 2020). This scenario aims to distribute protection to not only the least profitable land, but considers also representativeness concerning productivity (affecting biodiversity) and EU Habitat types.
Green Infrastructure	As EU, but allocation of the 10 %/20 % protection target within each grid cell (0.5°). This scenario aims to distribute protection to rebuild the EU green infrastructure and facilitate dispersal and migration of species.

2.4. Leakage effects of biodiversity protection scenarios

Given the scenarios for protection within the EU, we finally also investigated how changes in future harvest levels within the EU may affect wood harvest in other biomes. Leakage means that a decrease of production or biophysical activity in one region is offset by an increase of production or biophysical activity in other regions (S.M3.3). We quantified leakage by absolute harvest volumes (increased harvest in other biomes) or by rates (overall change in other regions relative to the EU). Specifically, we investigated leakage of roundwood harvest and production of semi-finished wood products.

3. Results

3.1. Protected forest area in Europe

The EU scenario, collectively reaching the policy objectives at EU level, would mean doubling the forest area under strict protection and increase the area under a 'closer-to-nature' management by 1 % compared to Current protection (Table 3). All other scenarios would mean protecting larger proportions of the area than 10 % and 20 % across all the EU (Table 3). The Green Infrastructure scenario means protecting the largest area, with an 8 % increase of the forest area under strict protection, compared to the EU scenario. This is explained by the current protection area of some simulation units already exceeding the unitary protection targets, while at the same time increasing the protection area in other units, summing up to protecting 13 %/25 % at EU scale (Table 3).

Under the Current protection scenario, there will be a 22 % expansion of high intensity forest management, increasing by 22 Mha between 2020 and 2100, with a parallel reduction of multifunctional management (Fig. 1). This intensification trend in unprotected forest areas is driven by the increasing wood demands under the climate neutrality assumed for all simulated scenarios. The six scenarios with expansion of protected areas reduce the areas available for other types of management (multifunctional and high intensity) (S.R2.1). Relative to the Current protection scenario, the increase in protected area of the Green Infrastructure scenario (Fig. 1), firstly reduces the areas under both multifunctional and high intensity management. Later, the development is similar to Current protection with an increase of high intensity management at the cost of decreasing multifunctional management. The other scenarios will fall between these two extremes.

3.2. Distribution of forest protected area

The EU scenario, collectively reaching the policy objectives means increasing strict protection in countries where wood production gives a relatively low profit (Fig. 2). Bulgaria, Ireland, Italy, Netherlands, and Romania would protect more than 15 % of their forest area, while countries like Finland and Sweden instead would contribute minimally (Fig. 2). This contrasts the Country scenario, where strictly protected areas are evenly distributed among all the EU countries. The same holds true under the Green Infrastructure scenario, although leading to a higher overall protection (Fig. 2, Table 3. S.R2). In some countries (e.g. Portugal, Spain), the Country scenario means decreased 'closer to nature' management compared to Current protection. This is due to areas changing into becoming strictly protected within the country and can even lead to a net increase in the total protected area. This results from our assumption that new strictly protected areas are preferably distributed to areas that are currently under close to nature management.

3.3. Harvested volume and wood prices

The EU biomass harvest volume (sum of roundwood and logging residues) projected under the Current protection scenario (and aiming for climate neutrality) is expected to increase by 31 % during 2020–2100, and by 10 % already by 2030 (Fig. 3). Compared to Current protection, the EU scenario will reduce harvest by 1 % in 2030 and 3 % by 2100. A harvest reduction of 5–7 % by 2100 is projected if additional protection is distributed equally among biogeographical regions or countries. However, if the additional protection is distributed equally

Table 3
Strictly protected forest and 'closer to nature' management given EU protection scenarios.

Scenario	Strictly protected (Mha)	Closer to nature management (Mha)	Strictly protected (% of total forest area)	Closer to nature management (% of total forest area)
Current protection	7.8	30.5	5 %	19 %
EU	16.2	32.5	10 %	20 %
BioGeo	16.8	36.1	10 %	22 %
Country	16.6	37.1	10 %	23 %
Country BioGeo	17.5	37.2	11 %	23 %
Country Productivity	16.6	38.5	10 %	23 %
Green Infrastructure	20.7	40.6	13 %	25 %

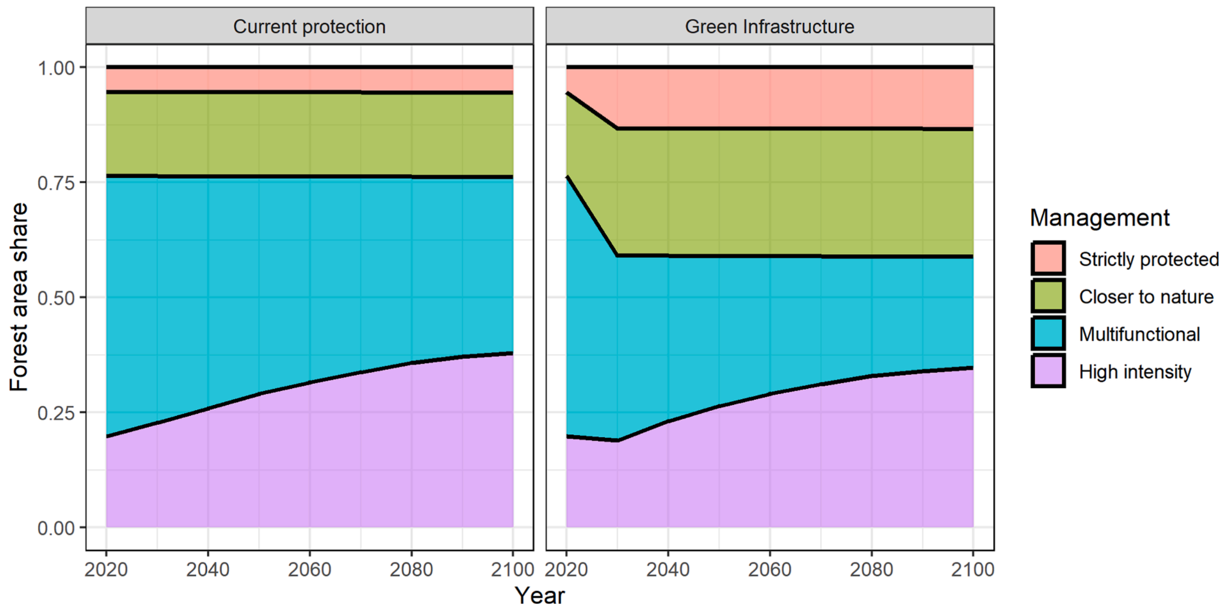

Fig. 1. Development of the proportion of EU forest area (of total forest area) managed by different regimes from year 2020 to 2100 assuming the Current protection and Green Infrastructure scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

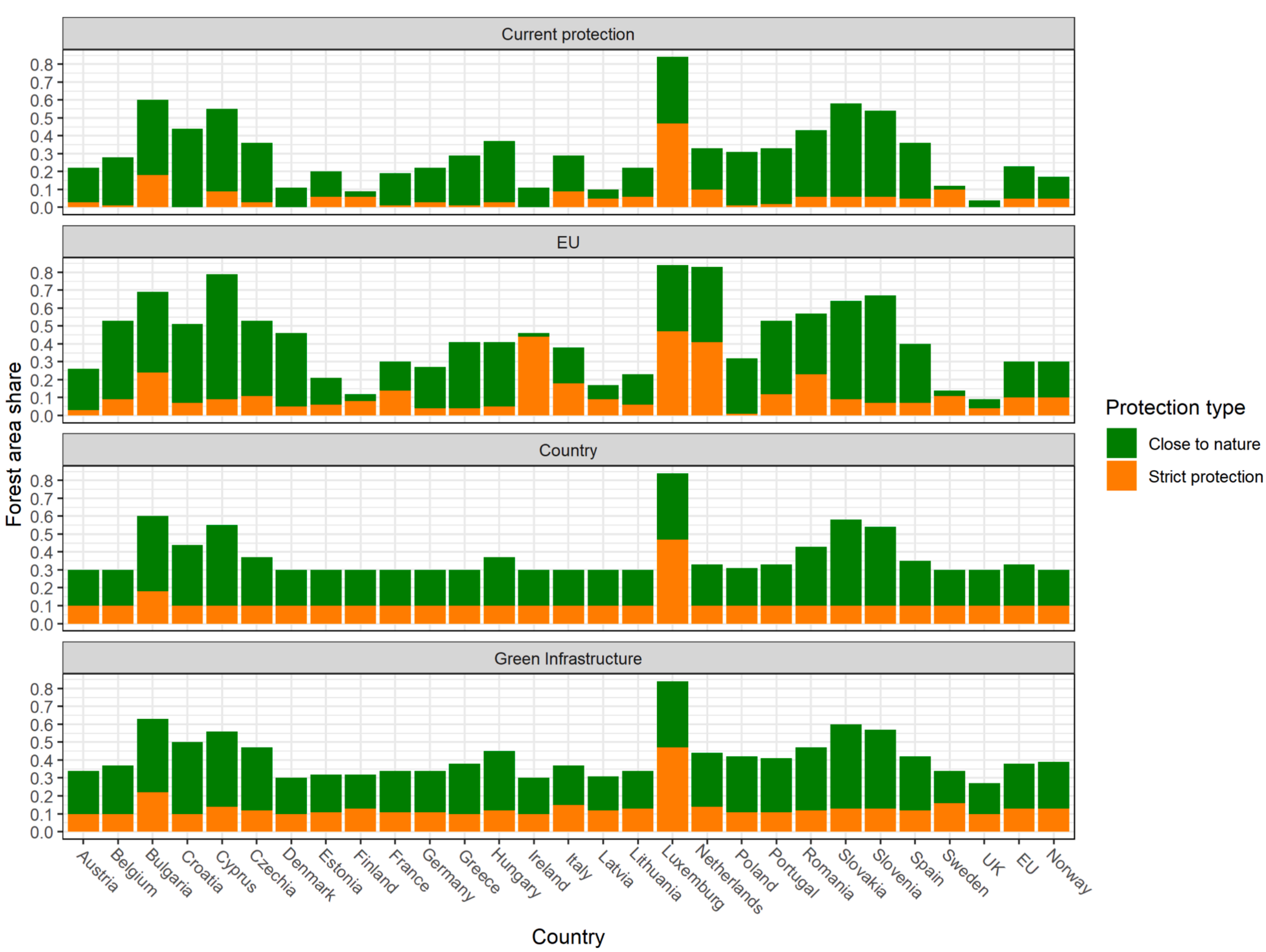

Fig. 2. Share of forest area protected in different EU countries (incl. UK and Norway) from year 2030 onwards assuming different scenarios of strict protection and close to nature management.

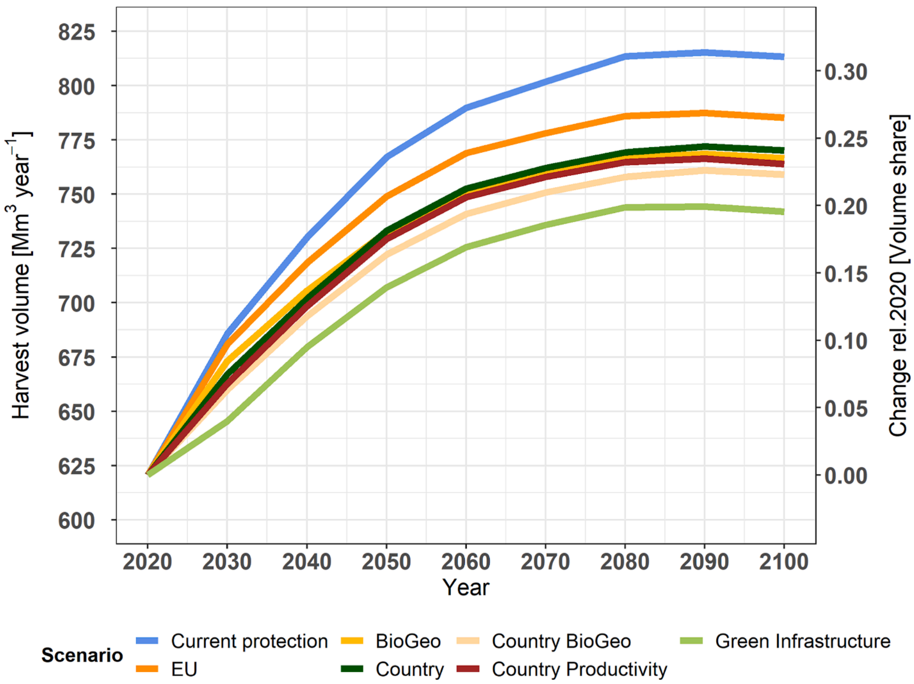

Fig. 3. Development of yearly forest biomass (including roundwood and logging residues) harvest volumes in the EU under SSP2-RCP1.9 and the protection scenarios simulated in absolute volumes (left) and as relative changes compared to the year 2020 (right).

among the 0.5° grid cells, Green Infrastructure, the reduction will be higher (6 % by 2030 and 9 % by 2100), simply because a larger area is protected (Table 3, Fig. 2). Nevertheless, all scenarios that increase protection will allow to increase EU harvest by at least 21 % (increasing from Current protection to Green Infrastructure; Fig. 3).

The impact of protection scenarios on wood assortment prices for the EU follows the same order as the one obseved for harvest volumes (S.R5). Under the EU scenario, we observe increases in prices of 2–4 % until 2030 compared to the Current protection scenario. Under the Country scenario the increases are 6–15 % and under the Green Infrastructure prices increase between 10–30 %. Conifer wood assortments tend to be more impacted than broadleaves and the price increase is transient and declines over time.

3.4. Distribution of harvest volume among countries

Independently of protection scenario, individual countries will generally increase their future harvest by 2100 (4a-b), albeit less than with Current protection (Fig. 4c-d). The changes over time in harvest volumes will range between −28 % (Czech Republic) and + 125 % (Luxembourg).

Five out of the six countries with the largest harvest volumes by 2100 (Germany, Finland, France, Poland and Romania) (Fig. 4, S.R3) will maintain or increase harvest levels in the long term with all protection scenarios, but in short term (2030), Germany and Sweden could experience a 6–12 % harvest reduction compared to the current levels under the Green Infrastructure scenario. The proportional impacts of the protection scenarios on harvests are generally higher on single countries than on the whole EU (cf. Fig. 3 and Fig. 4). For example, the EU level harvest reductions would reach 9 % under the Green Infrastructure scenario, while for individual countries this would range between 0–17 %. However, this conclusion concerns comparison with the Current protection scenario and year 2100 with assuming strong harvest increase overall (Fig. 3). If we would compare year 2100 to current harvest levels (2020) under the Green infrastructure scenario, we find harvest increase by 20 % at EU level, but between −28 % and + 105 % at national level.

Compared to Current protection, the EU scenario means larger reductions (more than 5 Mm^3 in 2100) for only one country (France; 4c-d), while with the Green infrastructure scenario particularly the Northern countries and countries with large wood harvest volumes will be affected (4c-d). However, harvests in the Northern countries will still be similar to current level (4b). In the Country scenario, the country-level relative impact is lower, as more countries are involved in reaching the protection target. In this scenario, impacts over 5 Mm^3 are projected for Germany, Poland, Finland and Sweden. Whereas, with the Green Infrastructure scenario, impacts over 5 Mm^3 are projected for Sweden, Poland, Finland, Germany, France and Norway.

3.5. Net export and wood industry production

In year 2020, the EU was a net importer of roundwood biomass (−18 Mm^3 in 2020), and will remain being importer independently of scenario (Fig. 5a). However, because of increasing harvests under all scenarios (Fig. 3), we project reduced roundwood net import rate towards 2100. Regarding semi-finished wood products, the EU was instead a net exporter (57 Mm^3 in 2020) (Fig. 5b). When summing the historical roundwood and semifinished products net exports (Fig. 5c), the EU was instead a net exporter of 39 Mm^3 in 2020. The trade advantage in semi-finished products is expected to continue to grow until 2040 and thereafter decline, due to increased competitiveness of other regions (South America, Asia). The impact of increased protection on the net export closely reflects the impacts on the EU biomass harvest volumes (Figs. 3-5). Net export of semi-finished products will decline under current levels in most scenarios after year 2040, whereas the EU scenario would allow to maintain current export levels. By 2100, the net export of semi-finished products would decline with 4 Mm^3 under the Country scenario and with 21 Mm^3 under the Green Infrastructure scenario, compared with the current level (Fig. 5b). Nevertheless, under all scenarios EU would remain a net exporter of semi-finished wood products.

Among the major wood production countries (Germany, Finland, France, Sweden), all protection scenarios will reduce the net export, given their expected future decreased economic competitiveness within the EU (S.R3). In parallel, other major wood-producing countries are

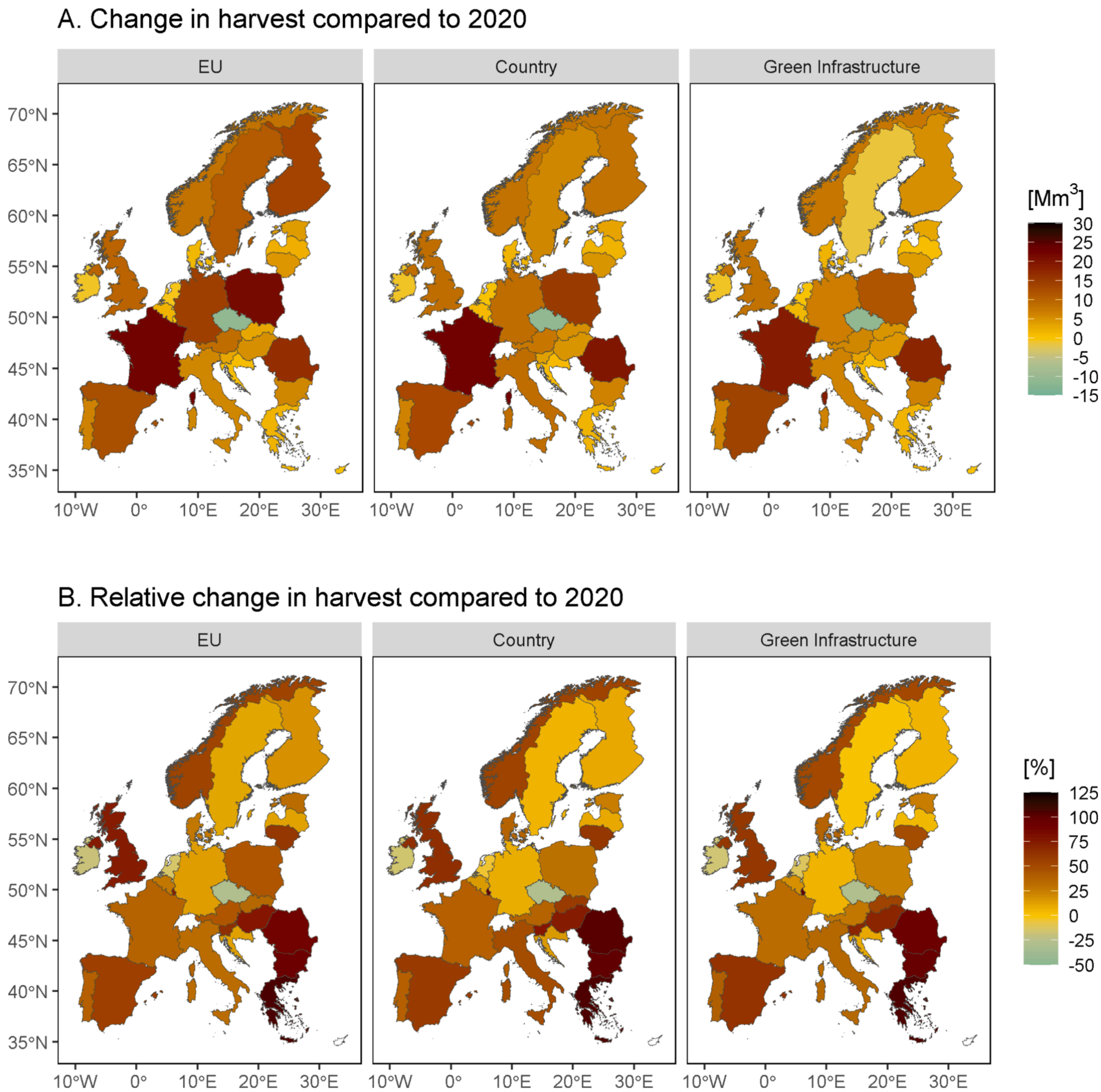

Fig. 4. Change in harvest volumes per country in 2100 for three protection scenarios when comparing to year 2020 in absolute (A) and relative values (B), and when comparing in year 2100 to the Current protection scenario in absolute (C) and relative values (D) under SSP2-RCP1.9.

expected to increase their competitiveness, as a result of their expected economic growth (Poland, Romania).

Net export of semifinished products is closely related to the industrial production levels. The changes in production of the main semifinished products categories (sawnwood and woodpulp) reflect the order of scenario impacts and magnitude for harvest volumes in EU (Fig. S.R3.7). However, among the main producing countries, Sweden is unable to maintain current sawnwood and wood pulp production under the Country and the Green Infrastructure scenarios. Similarly, Germany experiences a reduction of sawnwood production under these scenarios, while the other major wood producers are still able to maintain or increase their levels (Fig. S.R3.8-Fig S.R3.10). French woodpulp production is more strongly affected under the EU scenario compared to the Country scenario (Fig S.R3.10), and oppositely to the other major producers, the Country and Green Infrastructure scenarios are more impactful than the EU scenario.

The EU was historically a net importer of wood pellets (−30 Mm^3 in 2020). The net export of wood pellets is projected to become more negative over time under all scenarios (Fig. 5d), because of the expected bioenergy demand increase under RCP1.9 which cannot be satisfied by increased harvest from EU forests. Hence, there is a larger increase of woodpellets import from other global regions. Compared to the Current protection scenario, the protection scenarios will lead to a 3–6 % decrease in wood pellets net export towards year 2100 (i.e. import increase by 1–2 Mm^3) (Fig. 5d).

3.6. Sensitivity analyses

Assuming strict protection of 30 %, instead of 10 % of the EU forest area, the biomass harvest would decline by 10–15 % compared to the Current protection scenario in year 2100 (Fig. 6a). However, also with this high protection level, the harvest would increase compared to today. Nevertheless, the harvest reduction given by 30 % strict protection combined with the Green Infrastructure scenario is large enough for EU to become a net importer after 2040 (Fig. 6b). With all other scenarios simulated, the EU would remain a net exporter albeit at a lower level than with Current protection.

If instead assuming lower future demand for wood, i.e. following climate change mitigation leading to the RCP6.5, EU harvests may still somewhat increase in the coming decades under all scenarios. Moreover,

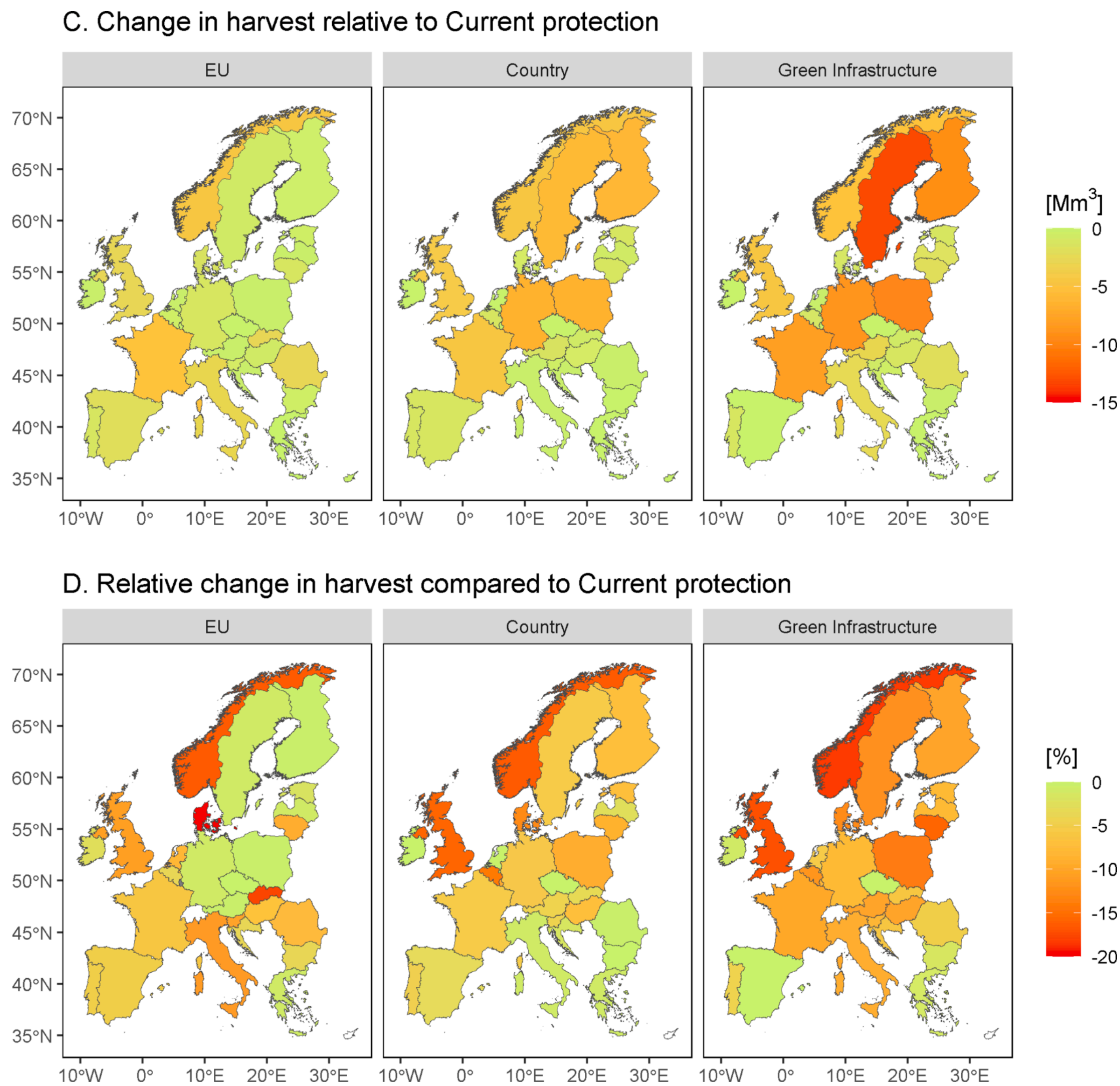

Fig. 4. (*continued*).

harvest could possibly decrease (2–6 %) with protection scenarios compared to the RCP6.5 Current protection scenario (Fig. 6c). Net-export would follow a similar development as for the main scenarios until 2060, and thereafter continue to decrease sharply, though remain positive until 2100 (Fig. 6d).

3.7. Leakage outside EU and in other sectors

Up to 79 % of the decreased roundwood harvest within the EU resulting from the protection scenarios would result in increased harvest in the rest of the world (Table 4, Fig. 7). This relative change is hereafter referred as EU leakage rate. Specifically, the average leakage rate in EU roundwood harvest ranged between 22–79 % (Table 4, Fig. 7). However, this is compared to the Current protection scenario, which assumes a large harvest increase in the future (Fig. 6). The leakage is immediate, but also transient resulting from new equilibria reached after the middle of the century.

During the coming 40–50 years, the leakage only affects harvest in the boreal parts of the world, with negligible impact on the tropics or the temperate region (Fig. 7). After 2060, the contribution of the tropical region starts to increase, going from 10 % to 20 %, in parallel to a decreasing contribution from the boreal region toward the end of the century (Fig. 7, S.R4).

The relatively lower leakages after the middle of the century are caused by a contraction of the global roundwood harvest rate (Fig. 8A). This is driven by the development in bioenergy feedstock in the rest of the world, where a substitution of roundwood by wood pellets from energy crops is projected to take place (Fig. 8B). However, the relative effect of the EUBDS protection on these future leakages is rather low, and the trade dynamics are mainly driven by historical trade developments and GDP growth.

Hence, we note two complementary effects, on one hand a global contraction of roundwood harvest takes places reaching 50 Mm^3 in the most ambitious protection scenario (30 % Green Infrastructure). On the other hand, harvest from energy crops increases and reaches a maximum of 45 Mm^3 under the same scenario (Fig. 8). Another leakage effect is endogenously considered in the model, with an intensification of forest management in unprotected forest areas within the EU.

4. Discussion

We present the impacts of alternative spatial allocations of protected areas according to the EU Biodiversity Strategy (EUBDS) on the EU forest sector, considering specifically wood harvest and wood-based

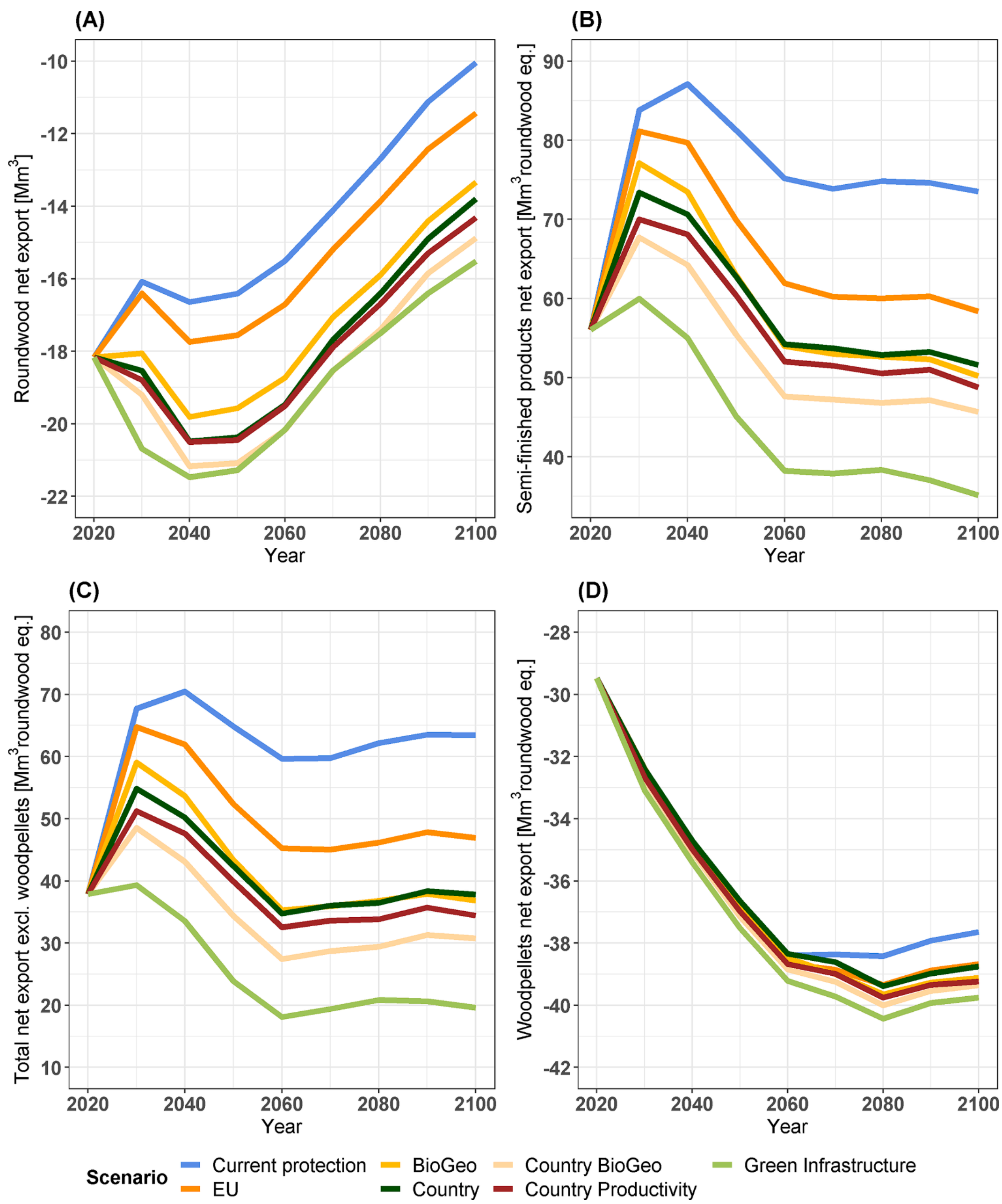

Fig. 5. Development of EU net export of different wood assortments under SSP2-RCP1.9 and different protection scenarios, specified by roundwood(e.g. sawlogs, pulpwood) (A), semi-finished products (eg. sawnwood, woodpulp) (B), total net export (sum of roundwood (A) and semi-finished products (B) (excluding woodpellets), C) and woodpellets net export (D).

industry developments. We provide a seamless understanding of implications of different interpretations of targets, including spatial trade-offs, EU external impacts and a global perspective. We show that the EUBDS will have a larger risk of impact on the forest industries than on harvest levels, and further that these risks concern the last half of the century. Implementation of the EUBDS in fact still allows for an increase of the EU forest harvest level by 21 % to 31 %, depending on the spatial distribution of the EUBDS targets. We expected the EUBDS protection to have larger impact on the EU forest industries net export of roundwood and semifinished products. However, the most likely scenario (10 %/20 % protection within each MS) means increased net exports than current ones in the coming decades, but slightly lower after 2050. With protection also aiming to be representative of site productivities or rebuilding the green infrastructures, net exports decreased also during the coming decades. The study also allowed to show that the leakage resulting from decreased EU roundwood harvest (ca. 80 % of the decrease) will correspond to higher harvest in boreal regions outside the EU, but a minor increase in tropical regions.

In terms of total EU woody biomass harvest levels, we show that an implementation of the EUBDS would have limited impact. At the EU level, we project that harvesting can increase by 24 % between 2020 and 2100 with implementation at the EU level, and by 21 % with the green infrastructure implementation. A very strict interpretation of 'closer-to-nature' management, i.e. strict protection and hence excluding 30 % of the land from harvesting, would restrict harvest more, but still allow for higher future harvests than today (10 % increase). Nevertheless, our scenarios did not account for potential impacts of increased harvests on non-timber ecosystem services and biodiversity outside protected areas. Increasing harvest to strive for climate mitigation targets might cause adverse effects on forest multifunctionality (Blattert et al., 2023), which

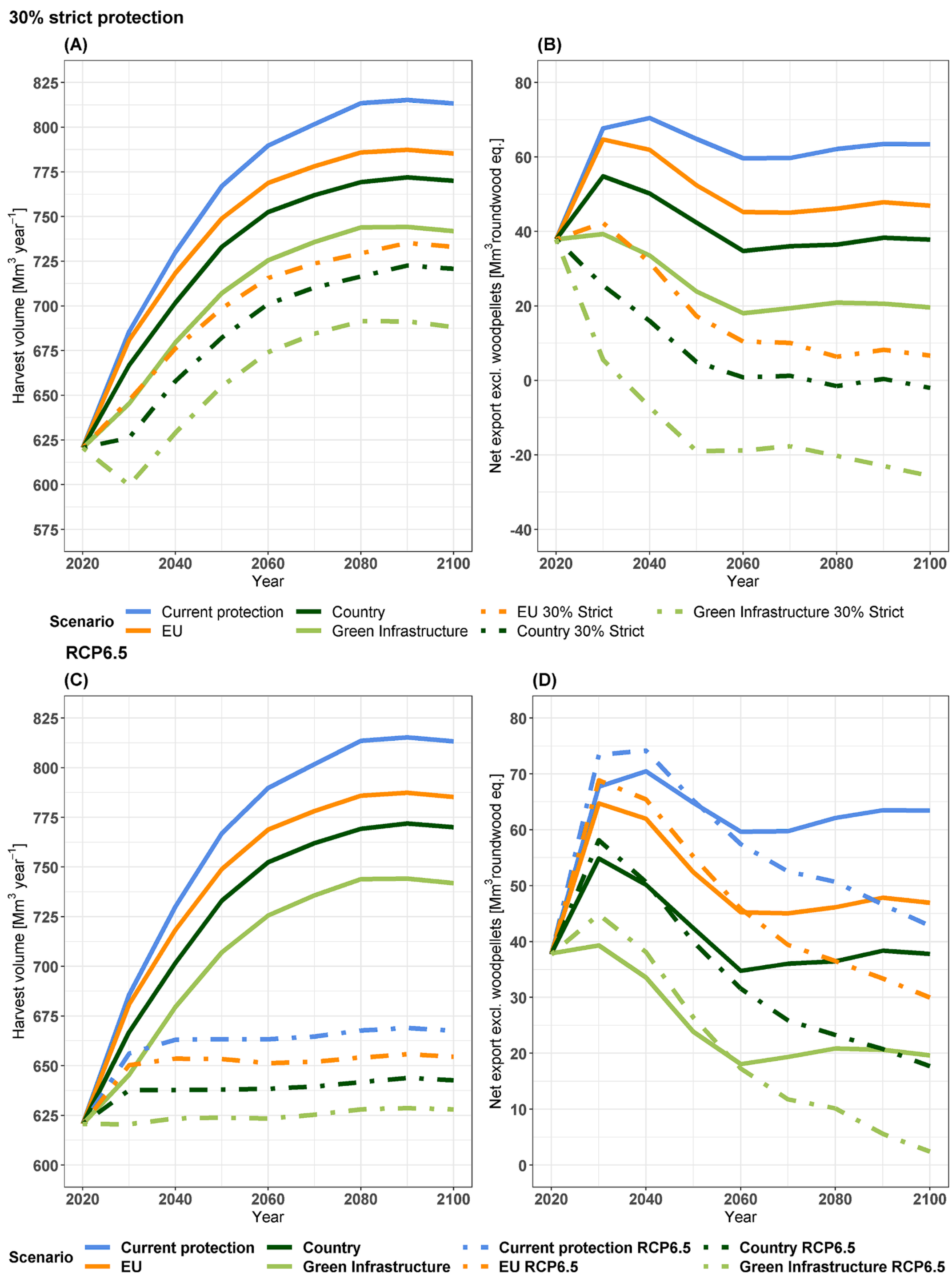

Fig. 6. Harvest (A) and net export (B) projections assuming considerably increased protection, specifically 30% strict protection (dashed line) under SSP2-RCP1.9. C and D show the corresponding trajectories under a considerably lower demand for wood following the SSP2-RCP6.5 scenario (dashed line). For comparison, the trajectories of the four main scenarios from Figs. 3 and 5 are also shown (solid lines).

is a central objective of the EU Forest Strategy (EC, 2021b). Future studies should take this multifunctional view into account while exploring the interplay of protection and mitigation policies.

Our findings of 2 % to 6 % harvest reductions by 2050 contrast the recent study of Schier et al. (2022) who claimed an overall harvest reduction of 11–58 % by 2050 for the EU27 compared to a baseline development that aligns to our RCP6.5. The main reason for the difference is that they applied a stricter definition of "old-growth" forest adopting variable age thresholds (i.e. more than 120 years for Norway spruce and 160 years for oaks) for identifying old growth forests and further excluding them from wood harvesting in the future. Such an age-based identification of "old growth" forests implies that any forests that over time reaches the threshold automatically becomes protected. We believe that this overestimates impact of the EUBDS, as forest age per se cannot be considered sufficient information for identifying "old-growth" forests according to EC (2023b), recommending that a series of complementary structural indicators would be needed.

Our study is the first one to provide long-term developments beyond 2050 and also effects of alternative distributions of increased protection in accordance with the EUBDS. Concerning the near-coming decades,

Table 4
Change in roundwood harvest (Mm^3 over bark) in EU and Rest of the World compared to the Current protection scenario and associated harvest leakage rate* (%) for six scenarios (see also Fig. 7 for scenario EU, Country, Green Infrastructure).

	Scenario	2030	2040	2050	2060	2070	2080	2090	2100
EU Harvest decrease (Mm^3 $year^{-1}$)	EU	−4.3	−11.2	−16.8	−18.8	−19.6	−21.8	−21.7	−21.2
	Country	−17.1	−24.9	−29.0	−30.0	−30.2	−32.5	−31.7	−31.0
	Green Infrastructure	−35.6	−43.3	−49.5	−49.2	−48.0	−49.4	−50.3	−50.1
	EU 30 % Strict	−36.8	−52.5	−65.6	−68.9	−70.3	−74.2	−70.3	−70.2
	Country 30 % Strict	−54.8	−65.7	−75.8	−76.2	−76.2	−79.6	−76.0	−76.8
	Green infrastructure 30 %	−77.4	−90.4	−97.9	−96.0	−95.0	−97.5	−99.3	−100.1
Rest of World Harvest increase (Mm^3 $year^{-1}$)	EU	2.8	6.5	11.6	12.0	4.6	6.0	4.9	6.4
	Country	12.5	18.2	20.9	20.1	11.4	13.8	11.7	13.8
	Green Infrastructure	26.6	33.5	38.4	29.8	20.2	24.9	25.0	29.2
	EU 30 % Strict	24.2	36.3	43.6	32.5	22.5	29.0	30.8	35.3
	Country 30 % Strict	38.8	50.2	55.0	39.0	31.9	39.3	43.2	48.0
	Green infrastructure 30 %	56.9	71.2	76.9	52.4	44.3	53.1	57.5	64.7
Leakage rate (%)*	EU	66	58	69	64	24	28	22	30
	Country	73	73	72	67	38	42	37	44
	Green Infrastructure	75	77	78	60	42	50	50	58
	EU 30 % Strict	66	69	66	47	32	39	44	50
	Country 30 % Strict	71	77	73	51	42	49	57	62
	Green infrastructure 30 %	73	79	79	55	47	55	58	65

*Leakage rate (%) = -100 x (Rest of the Word harvest increase/EU harvest decrease).

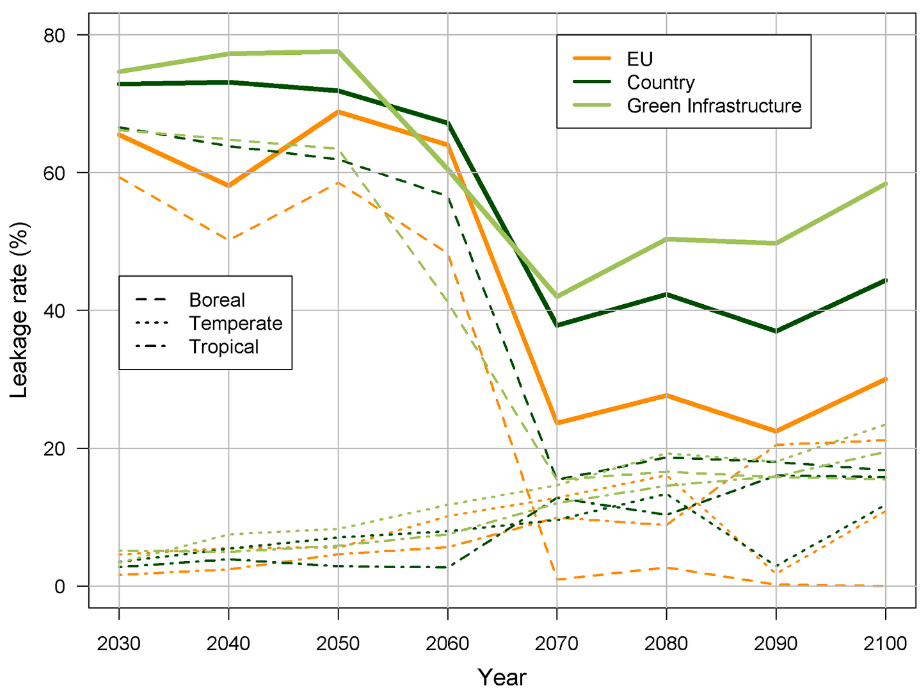

Fig. 7. Roundwood leakage rates from the EU to three forest biomes outside the EU given three protection scenarios compared to the Current protection scenario (Table 4).

our results are generally in line with Lotze-Campen et al. (2018) that estimated a reduction in stemwood harvest of 45–73 Mm^3 by 2040 when expanding protection areas (compared to their baseline), which aligns to the 43 Mm^3 reduction in stemwood harvest estimated with the Green Infrastructure scenario in the present study. The main reason for the higher reductions in Lotze-Campen et al. (2018) is that they assumed a higher 26 % increase in strictly protected area by 2040 instead of our 13 % in the Green Infrastructure scenario.

We find that applying any scenario to protect forests according to the EUBDS will dampen the future increase in EU harvest level and will be compensated by increasing roundwood harvests in other regions. For every cubic meter reduction, the rest of the world will increase its harvest by up to 0.79 cubic meters. The rest of EU harvest reduction will translate into lower global roundwood harvest and consumption, which could potentially be replaced by the consumption of other commodities (including fossil based) not included in our modelling. However, the global roundwood harvest reduction (max. 50 Mm^3 $year^{-1}$) is relatively insignificant compared to the current global roundwood harvest (3.9 Billion m^3 in 2020). This level of leakage is in agreement with estimated the roundwood harvest leakage by Kallio et al. (2018) for the year 2030. However, we further show that the leakage will decrease over time. This decreasing leakage trend occurs due to the structure of GLOBIOM-forest that accounts for the interaction of roundwood from natural forests with other sources of woody material from energy crops within and outside the EU. These additional sources of wood will compensate for the reduced roundwood harvest in the EU and thus decrease the leakage outside the EU in the long run. The boreal region absorbs most of the leakage, as also concluded by Kallio et al. (2018) and Schier et al.

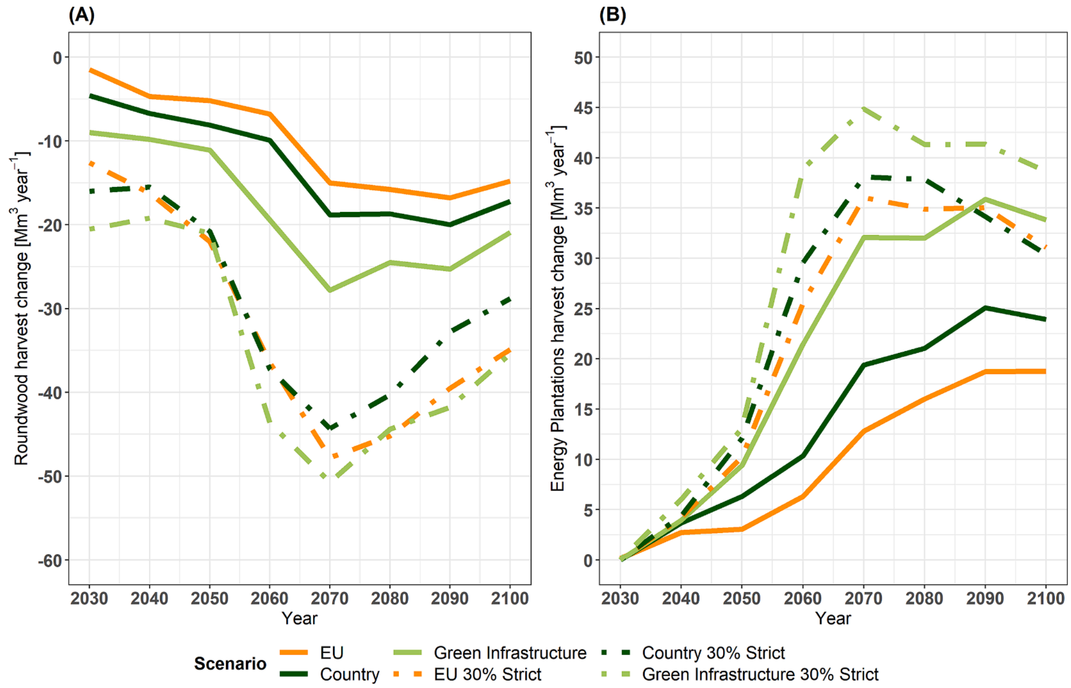

Fig. 8. Development of roundwood harvest (A) and energy crops harvest (B) compared to the Current protection scenario under SSP2-RCP1.9.

(2022). However, although the impact on the tropical region is fairly low in terms of wood volumes, the tropical region has much higher endemic biodiversity that might be under risk (Hill et al., 2019, Jung et al., 2021). Rosa et al. (2023) have accounted for global biodiversity impacts of combined increasing wood harvests and expansion of protection/'closer-to-nature' management of the EU forest. They conclude that increasing strict protection to more than 25 % of the EU currently managed forestland by 2100 increased the global extinction risk compared to continuing current forest management. However, a major limitation of their work is that their biodiversity measure concerned plants, mammals and birds by applying the countryside species-area relationship. A focus on just these species groups will underestimate the biodiversity benefits of protection within the EU, as these are not the main groups negatively affected by forestry in the EU. These are instead species associated with deadwood, old forests (rich in deciduous trees) (EEA, 2020b) and concern species-rich groups of invertebrates, fungi, cryptogams etc. Thus, further work is needed to understand leakage effects of adopting protection according to the EUBDS.

Our study also presents solutions for how decreased harvest due to increased protection can be mitigated for within the EU, by intensified management in non-protected forest. An intensification of harvest in forest area managed for production is identified as a solution to mitigate for the implementation of the EUBDS in Finland (Räty et al., 2023). Intensified harvesting on production land also comes out as a solution when optimizing management to reach also biodiversity targets under increasing wood demands (Blattert et al., 2022, Eggers et al., 2022), and constitutes a strategy under climate smart forestry for facing future European wood demands (Yousefpour et al., 2018).

Additionally, non-strictly protected areas under 'closer to nature' forest management (20 %), can provide up to an extra 6–7 % of EU wood harvest, compared to strictly protecting entirely 30 % of the area. Therefore, wood harvest from non-strictly protected areas could also substantially contribute to mitigate impacts of the protection policy.

Our work can provide quantitative basis for calculating the compensation for economic loss of harvest income through a payment for ecosystem services (Wunder, 2015), assuming the generation of at least biodiversity and climate benefits, alongside wood production as a co-produced provisioning service (Kangas and Ollikainen, 2022). This analysis could also help targeting the marketing of voluntary payments (Forsius et al., 2021). Yet, it is important to keep in mind that the national policies and institutional framework in each MS will vary (Primmer et al., 2021).

Overall, this study provides a negotiation basis for demonstrating that it would be possible to achieve common EU policy conservation targets without disproportionate impacts on the forest sector demands inside and outside EU by applying different approaches to allocate protected areas.

CRediT authorship contribution statement

Fulvio Di Fulvio: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tord Snäll:** Writing – review & editing, Writing – original draft, Conceptualization. **Pekka Lauri:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Nicklas Forsell:** Writing – review & editing, Writing – original draft, Conceptualization. **Mikko Mönkkönen:** Writing – review & editing, Funding acquisition, Conceptualization. **Daniel Burgas:** Writing – review & editing, Conceptualization. **Clemens Blattert:** Writing – review & editing, Conceptualization. **Kyle Eyvindson:** Writing – review & editing, Conceptualization. **Astor Toraño Caicoya:** Writing – review & editing. **Marta Vergarechea:** Writing – review & editing. **Clara Antón-Fernández:** Writing – review & editing. **Julian Klein:** Writing – review & editing. **Rasmus Astrup:** Writing – review & editing. **Jani Lukkarinen:** Writing – review & editing. **Samuli Pitzén:** Writing – review & editing. **Eeva Primmer:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fulvio Di Fulvio reports financial support was provided by ERA-Net Cofund scheme. Fulvio Di Fulvio reports a relationship with International Institute for Applied Systems Analysis that includes: employment. If there are other authors, they declare that they have no known

competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2025.102986.

Data availability

Data will be made available on request.

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