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PRACTICE AND POLICY

Leakage of biodiversity risks under the European Union Biodiversity Strategy 2030

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Article impact statement: Enhanced forest conservation in the EU shifts roundwood production to more vulnerable countries and increases risks to biodiversity globally.

Abstract

The European Union Biodiversity Strategy 2030 (EUBDS) aims to regain biodiversity through enhanced forest conservation and protection, which may lead to increased timber harvest in non-EU countries. We aimed to identify the potential leakage of biodiversity risks as induced by the EUBDS. We created an indicator framework that allows one to quantify vulnerability of forest biodiversity. The framework is based on 26 biodiversity indicators for which indicator values were publicly available. We weighted single indicator values with countrywise modeled data on changed timber production under EUBDS implementation. Nearly 80% of the indicators pointed to higher vulnerability in the affected non-EU countries. Roundwood production was transferred to countries with, on average, lower governance quality ($p = 0.0001$), political awareness ($p = 0.548$), forest coverage ($p = 0.034$), and biomass ($p = 0.272$) and with less sustainable forest management ($p = 0.044$ and $p = 0.028$). These countries had more natural habitats ($p = 0.039$) and intact forest landscapes ($p = 0.0001$) but higher risk of species extinction ($p = 0.006$) and less protected area ($p = 0.0001$) than the EU countries. Only a few indicators pointed to lower vulnerability and biodiversity risks outside the EU. Safeguards are needed to ensure that implementation of EUBDS does not cause harm to ecosystems elsewhere. The EU regulation on deforestation-free supply chains might have limited effects because the sustainable management of existing and even expanding forests is not well considered. Sustained roundwood production in the EU is needed to avoid placing more pressure on more vulnerable ecosystems elsewhere. Decreasing species and habitat indicator values nevertheless call for global conservation and protection schemes. The EUBDS helped pave the way to the Kunming–Montreal Biodiversity Framework. Yet, lower values for the indicators mean governance and biodiversity engagement in non-EU countries suggest that this global framework might not sufficiently prevent leakage of risks to biodiversity. Effective land-use planning is necessary to balance conservation schemes with roundwood production.

KEYWORDS
biodiversity indicators, deforestation, protected areas, risk assessment, roundwood production, sustainable forest management, vulnerability

INTRODUCTION

Alarmed by the continued loss of biodiversity and the threat this poses to nature and human well-being (CBD, 2022a), nature conservation and the designation of more protected areas are high on the political agenda. In December 2022, parties to the Convention on Biological Diversity (CBD) agreed to conserve 30% of the world's land and oceans by 2030. This decision expands the European Union Biodiversity Strategy (EUBDS) 30% target (EU, 2020) to a global level. The EU strategy, in addition, requires the strict protection of at least one third of the EU's protected areas, including all remaining EU primary and old-growth forests. However, there are trade-offs between biodiversity protection and other forest ecosystem services, such as timber production (Blattert et al., 2020; Gutsch et al., 2018; Vergarechea et al., 2023) and carbon sequestration in forests and forest products (EU, 2018; Nabuurs et al., 2018; Werner et al., 2010). In addition, transnational leakage effects (Meyfroidt et al., 2020) of forest conservation need to be considered because conservation can create incentives for third parties to increase timber harvesting elsewhere (Gan & McCarl, 2007; Jonsson et al., 2012; Kallio et al., 2018; Li et al., 2008; Schier et al., 2022; Sohngen et al., 1999). Cerullo et al. (2023) point to a considerable risk that EU harvesting restrictions will further shift harvesting pressures to the tropics. The EUBDS therefore explicitly states the need to ensure that EU actions, including enhanced forest protection, do not result in deforestation in other regions of the world (EU, 2020). Also, the regulation on deforestation-free supply chains (EUDR) (EU, 2023) aims to ensure that no deforestation or degradation occurs through the import of wood products or a number of agricultural commodities to the EU market.

Schier et al. (2022) modeled roundwood production leakage under the EUBDS. They showed that until 2050, roundwood production in the EU will decrease by 58% (339 million m^3) under an intensive protection scenario and by 10% (65 million m^3) under a moderate scenario. Globally, this deficit is compensated for by 50–60%, depending on the scenario, by increased production of roundwood in non-EU countries and possibly by a substitution through nonwood products. Missing is a quantification of leakage effects that considers effects of the increased roundwood production on biodiversity in the affected non-EU countries, including pressures and status and responses of forest ecosystems. Although the need for forest conservation and protection of biodiversity is undoubted, the challenge for the EU remains how to implement forest protection without constraining other essential forest ecosystem services in the EU and without leakage of biodiversity risks to other forests globally.

We aimed to clarify whether the production leakage expected from implementation of EUBDS entails the leakage of biodiversity risks. We drew on previous research that assessed possible production leakage from EUBDS (Schier et al., 2022). We based our study on the hypothesis that compared with EU countries, vulnerability and risks associated with roundwood production are higher in those non-EU countries that would compensate reduced EU roundwood production. The EUBDS would thus entail global leakage of risks to biodiversity. Working under this hypothesis, we examined whether globally available countrywise indicators show higher or lower vulnerability and risk to biodiversity loss for affected non-EU countries relative to EU countries.

THEORETICAL BACKGROUND

Leakage

Land-use systems are complex arrangements because drivers of land-use change operate directly and indirectly through dynamic interactions and feedbacks (Meyfroidt et al., 2018). Within the broad concept of telecoupling (Liu & al., 2018), we refer to land-use spillover as the process by which land-use changes or direct interventions in land use in one place have impacts on land use in another place. We also refer to land-use leakage as a form of land-use spillover caused by an environmental policy. The spillover has a negative effect and thus reduces the overall effectiveness of this intervention (Meyfroidt et al., 2020, 2018). Under our hypothesis, the implementation of EUBDS, including the shift of production to non-EU countries, could lead to the leakage of biodiversity loss and risk because the environmental risks would be higher than the positive effects in the EU and thus reduce the overall effectiveness.

Risk, hazard, and vulnerability

Risk is understood as comprising 3 elements: vulnerability, exposure to hazards, and frequency or severity of the hazard (Birkmann, 2007; Peduzzi & Herold, 2005). Vulnerability is described as the lack of capacity to prevent harm. The vulnerability concept has been continuously broadened into a comprehensive approach encompassing driving forces, susceptibility, coping capacity, and adaptive capacity (Birkmann, 2007) and can be measured through comparative indicators. Exposure is taken into account through the respective countries affected by a changed production of roundwood as a result of the EUBDS. Severity of the hazard can be quantified by the change in timber harvest. The exposure to hazard is thus all the greater as more roundwood has to be produced outside the EU to compensate for lower roundwood production inside the EU. Building on the 3 elements of risk, countrywise risk to biodiversity in our study is therefore quantified by values of biodiversity indicators of the exposed countries weighted by the change in timber harvest.

Conceptual framework

Our conceptual framework builds on Schier et al. (2022), who showed how an increase in protected forest areas in the EU leads to reduced roundwood production in the EU and a production leakage with increased roundwood production in non-EU countries. The roundwood production in EU and non-EU countries constitutes the severity of the hazard (white boxes in Figure 1) and has effects on biodiversity that depend on the vulnerability in both country groups. We described biodiversity with a modified and comprehensive pressure–state–response (PSR) indicator framework (OECD, 2013) (gray boxes in Figure 1), which relies on indicators that have been developed for global monitoring and reporting on biodiversity under the CBD, the Forest Resource Assessment (FRA), and the Sustainable Development Goals (SDG).

Following Geist and Lambin (2002), we differentiated pressures into direct and indirect drivers. We subdivided status indicators into forest status, comprising forest area and biomass, and biodiversity status in a stricter sense focusing on species

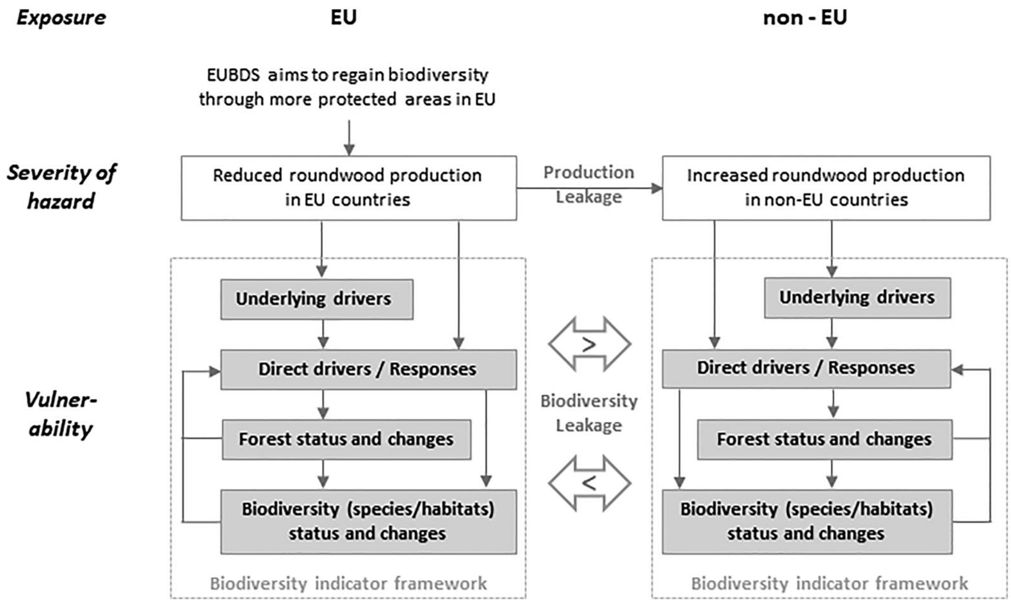

FIGURE 1 Conceptual framework to determine leakage of risks to forest biodiversity under the European Union Biodiversity Strategy 2030 (EUBDS) based on components of risk theory (Birkmann, 2007). Hazard severity is based on roundwood production volumes from Schier et al. (2022). Vulnerability is based on a modified pressure–state–response (Geist & Lambin, 2002; OECD, 1993) biodiversity indicator framework. Risk (not depicted) can be expressed through indicator values (vulnerability) weighted by the roundwood production (hazard). Leakage (Meyfroidt et al., 2020) occurs when biodiversity indicators point to a higher vulnerability or risks in non-EU countries and therefore to negative effects associated with increased roundwood production in non-EU countries. Greater than and less than symbols are indicator specific as specified in Table 1.

and habitats. In many cases, responses modify and change direct drivers. Related indicators can hardly be exclusively assigned to one or the other category. We thus summarized response and direct driver indicators. Leakage occurs when the comparison of vulnerability indicators shows significant differences and hence higher risks (as product of vulnerability and severity) in non-EU countries than in EU countries due to the implementation of EUBDS. It is thus necessary for each indicator to clarify whether higher or lower values indicate higher vulnerability and thus potentially negative effects (last column in Table 1).

METHODS

Indicator selection

We selected indicators mainly from adopted and published PSR (OECD, 1993) biodiversity indicator frameworks. In the context of the 2020 AICHI targets, such indicators were developed by the CBD (Butchart & al., 2010). The Biodiversity Indicators Partnership (BIP, 2022) lists 91 global biodiversity indicators relevant under CBD. These are currently being further developed under the Kunming–Montreal Global Biodiversity Framework (CBD, 2022b), which lists 26 headline indicators complemented by lists of component and complementary indicators. Global forest indicators were developed under the FRA (FAO, 2020), which comprises 22 forest-related indicators. Both the CBD-related and the FRA frameworks are in line with and linked to the SDG indicator framework.

From the 248 SDG indicators, 14 relate to SDG 15 “life on land” (UN, 2016). From the available lists and data repositories, we selected only published indicators for which we could construct a scientifically valid rationale linking forest management and roundwood production to biodiversity (Appendix S1). This implies use of forest-related indicators or indicators related to biomes that include forests (e.g., terrestrial biodiversity). From the scientific rationale, we determined whether smaller or bigger values for non-EU countries in comparison with EU countries indicated higher vulnerability and thus implied possible leakage (Table 1, right column). We selected indicators for which globally reliable, verifiable country-level data were publicly available for at least two thirds of each of the 2 country groups (data in Appendix S1). We used the latest available years as reference and 5-year periods for the analysis of temporal changes. To facilitate statistical evaluations, we used only indicators with data on continuous or at least 5-point Likert (1932) scales. Only in a few exceptional cases, did we amend indicators based on additional literature and our own previous work (Dieter et al., 2020), mainly to fill gaps in underlying drivers and to include economic aspects. Finally, we identified 26 indicators that substantiate our modified PSR indicator framework (Table 1).

Wood market modeling with the Global Forest Products Model

The Global Forest Products Model (GFPM) is a partial equilibrium model that simulates production, consumption, and trade of roundwood and wood-based products in 180 countries (Buongiorno et al., 2003; Schier et al., 2018). Schier et al. (2022) modeled possible roundwood production leakage under different EUBDS implementation scenarios from 2017 to 2050

TABLE 1 Indicators selected to quantify vulnerability of forest biodiversity.

Indicators	Unit	Year	Source/reference[a]				Potential
			AICHI	CBD22	FRA20	SDG	Leakage if[b]
Underlying drivers							
Forest area per capita	ha/person	2020	FRA2020 and data.un.org				Non-EU < EU
Mean governance	Indicator	2021	info.worldbank.org				Non-EU < EU
Biodiversity engagement	Indicator	2018	1				Non-EU < EU
Direct drivers and responses							
Forest area under a long-term management plan	%	2020			×	15.2.1	Non-EU < EU
Forest under certification scheme	%	2020	7	10	×	15.2.1	Non-EU < EU
Conservation as primary management objective	%	2020			×		Non-EU < EU
Protected area (PA) coverage	%	2022	11	3.1		15.1.2	Non-EU < EU
PA with management effectiveness evaluation	%	2022	11	3			Non-EU < EU
Strictly protected areas (IUCN category Ia)	%	2022	11				Non-EU < EU
Forest in legally established PA	%	2020			×	15.2.1	Non-EU < EU
Key biodiversity areas (KBAs) covered by PAs	%	2020				15.1.2	Non-EU < EU
Conservation spending	USD/ha	2001–2008	Waldron et al., 2013				Non-EU < EU
Forest status and changes							
Forest area as proportion of total land area	%	2020	5	A	×	15.1.1	Non-EU < EU
Forest area change rate	%	2015–2020	5	A	×	15.2.1	Non-EU < EU
Aboveground biomass in forest	t/ha	2020		8	×	15.2.1	Non-EU < EU
Change in aboveground biomass in forest	%	2015–2020		8	×	15.2.1	Non-EU < EU
Biodiversity (species, habitats) status and changes							
Biodiversity Habitat Index (BHI)	Indicator	2015	5	A; 2			Non-EU > EU
Change in BHI	%	2005–2015	5	A; 2			Non-EU < EU
Species Habitat Index (SHI)	Indicator	2019	5	A; 2.2			Non-EU > EU
Change in SHI	%	2014–2019	5	A; 2.2			Non-EU < EU
Red List Index (RLI)	Indicator	2020	4; 5; 12	A.3, 2		15.5.1	Non-EU < EU
Change in RLI	%	2015–2020	4; 5; 12	A.3; 2		15.5.1	Non-EU < EU
Bioclimatic Ecosystem Resilience Index (BERI)	Indicator	2015	15	A; 2			Non-EU < EU
Change in BERI	%	2005–2015	15	A; 2			Non-EU < EU
Intact forest landscapes	%	2016	globalforestwatch.org				Non-EU > EU
Proportion of land degraded	%	2015	15	10		15.3.1	Non-EU > EU

Abbreviations: AICHI, number of AICHI targets; CBD22, number of draft goals or targets or headline indicator in the Kunming–Montreal framework; FRA20, indicator in the Forest Resource Assessment; SDG, number of the Sustainable Development Goals.

[a]Indicators were selected from publicly available frameworks under the AICHI Targets (BIP, 2022; CBD, 2010), the Kunming–Montreal framework (CBD, 2022b), the Forest Resource Assessment (FAO, 2020), and the Sustainable Development Goals (UN, 2016).

[b]For each indicator, we define whether smaller of bigger indicator values for non-EU countries in comparison with EU qualify as a negative effect and thus as leakage, based on the rationale of each indicator (see Appendix S1).

with the GFPM (see Appendix S2). They modeled a moderate and an intensive EUBDS scenario to indicate lower and upper limits of the possible effects. As a result, they calculated country-specific shares but presented aggregated data only. We used these country-specific shares of the changes in total roundwood production inside and outside the EU following EUBDS implementation. Because there are hardly any differences in the shares of countries with increasing production between the 2 scenarios, we used only the moderate scenario, which can be regarded as conservative. We discarded Cyprus and Malta as countries with negligible roundwood production, also following Schier et al. (2022). We considered neither the Russian ban on log exports that went into effect in January 2022 nor possible consequences in production and trade of wood production due to the Russian military attack on Ukraine, which begun in February 2022.

Data treatment and tests

We extracted countrywise indicator data for single countries from publicly available databases (sources in Appendix S1;

TABLE 2 Percentage of national shares of decreasing roundwood production in EU countries[a] and of globally increasing roundwood production in non-EU countries[b] in 2050.

Countries with decrease (EU)	%	Countries with increase (non-EU)	%
Sweden	16.57	United States	17.0
Finland	15.72	Canada	15.5
Germany	11.14	Ukraine	11.6
France	10.64	Russian Federation	10.0
Poland	8.64	South Africa	7.8
Romania	4.90	China	7.0
Italy	4.15	Brazil	6.3
Spain	4.01	Australia	3.0
Austria	3.51	Chile	2.4
Portugal	2.61	Indonesia	2.3
Czech Rep.	2.46	United Kingdom	2.1
Latvia	2.44	Turkey	1.8
Estonia	1.84	Bosnia and Herzegovina	1.6
Bulgaria	1.64	Norway	1.5
Slovakia	1.48	Brunei Darussalam	1.2
Lithuania	1.35	Thailand	1.0
Croatia	1.31		
Hungary	1.25		
Slovenia	1.08		
Belgium	0.79		
Denmark	0.73		
Netherlands	0.59		
Ireland	0.57		
Greece	0.51		
Luxembourg	0.07		
Total	**100.00**	**Total**	**90.6**

[a]The 100% corresponds to an absolute annual reduction of 65 million m^3.

[b]Countries that contribute at least 1% and thus together account for 90.6% of the total increase in non-EU countries; 90.6% corresponds to an absolute annual increase of 36.8 million m^3 (also see Schier et al. [2022]).

countrywise data in Appendix S3). We then calculated the mean value for each indicator for the 2 groups of EU and non-EU countries. For 9 out of 26 indicators, we filled gaps in the country data with means per indicator and country group, assuming that countries with gaps are not biased toward more or less biodiversity. To derive the risk values (weighted means), we weighted each countrywise indicator value by the share that the respective country contributed to the reduced (for EU countries) or increased (for non-EU countries) felling volumes (Table 2). We then calculated the weighted indicator means per country group. We conducted tests of significance of mean differences for unweighted and weighted means. Based on Shapiro–Wilk *W* test results (Shapiro & Wilk, 1965), the normality of distribution was rejected for all indicators except for key biodiversity areas covered by protected areas, forest area as proportion of total land area, aboveground biomass in forest, and the Bioclimatic Ecosystem Resilience Index (BERI) values. We thus conducted the parametric *t* test of mean differences between the EU and non-EU countries for these 4 indicators only. For all the other variables that did not fulfil the normality assumption, we used the nonparametric Wilcoxon rank-sum test (Wilcoxon, 1945). For the comparison of weighted means, we used weighted *t* tests with the abovementioned shares because the shares of individual countries in reduced or globally increased roundwood production varied greatly. All statistical tests were conducted with Stata 16.1.

RESULTS

Development of roundwood production under EUBDS in- and outside the EU

The GFPM results of Schier et al. (2022) showed that for both, the reference and the moderate EUBDS implementation scenario, production, import, export, and consumption of roundwood increased until 2050. Thus, also with a moderate EUBDS implementation, production and consumption of roundwood were above the current level, but 65 million m^3 lower than in the business-as-usual (reference) scenario (Appendix S2). The country-specific disaggregated results (Table 2, left columns) showed that most of the reduction occurred in Sweden, which alone accounted for 16.57% of the EU's total reduction. The reduction in roundwood production in Luxembourg was predicted to be the smallest. The country accounted for 0.07% of the total EU reduction.

Under the moderate scenario, 62% of the decreased roundwood production in the EU was offset by production of an additional 40.6 million m^3 in non-EU countries. The remaining shares of the EU production deficit would probably no longer be produced and consumed worldwide. The countrywise disaggregation resulted in 81 countries with production increases. However, only 16 of these countries contributed at least 1% to this production increase, and together produced an additional annual volume of 36.8 million m^3, corresponding to 90.6% of the total increase of roundwood production in non-EU countries. We considered only these 16 countries and ignored the remaining 55 countries for practical reasons (Table 2, right columns). The United States contributed the largest shares of these additional felling volumes (17.0%). Among the countries contributing at least 1%, Thailand contributed the smallest share (1.0%).

With the exception of Bulgaria and Romania, all EU countries were classified as high-income countries (UN, 2023). Among the non-EU countries, there were 7 high-income, 7 upper-middle-income, and 2 lower-middle-income countries (Indonesia and Ukraine). None of the countries in our study were classified as a low-income country.

Vulnerability and leakage of risks to biodiversity

The comparison of indicator means showed that for 20 out of the 26 selected indicators, vulnerability and risk were higher in

TABLE 3 Vulnerability and risk for the groups of EU and non-EU countries as expressed by mean indicator values.

	Vulnerability (unweighted indicator means)				Risk (weighted indicator means)			
Indicators	**EU**[a]	**Non-EU**[a]	p[b]	**Leak**[c]	**EU**[a]	**Non-EU**[a]	p[b]	**Leak**[c]
Underlying drivers								
Forest area per capita (ha/person)	0.67	1.70	0.146		1.22	2.88	0.039	
Mean governance (indicator)	1.02	0.26	0.004	l	1.17	0.36	0.000	l
Biodiversity engagement (indicator)	5.62	5.04	0.631	pl	7.23	6.27	0.548	pl
Direct drivers and responses								
Forest area under long-term management plan (%)	82.95	60.21	0.008	l	78.95	64.75	0.044	l
Forest under certification scheme (%)	65.46	60.24	0.007	l	62.20	28.27	0.028	l
Conservation as primary management objective (%)	10.56	15.11	0.360		10.87	9.16	0.405	pl
Protected area (PA) coverage (%)	27.22	17.53	0.002	l	25.49	14.42	0.000	l
PA with management effectiveness evaluation (%)	6.08	3.99	0.431	pl	5.01	3.63	0.246	pl
Strictly protected areas (IUCN category Ia) (%)	3.31	13.96	0.002		4.46	5.72	0.510	
Forest in legally established PA (%)	22.62	16.46	0.019	l	20.79	12.81	0.019	l
Key biodiversity areas (KBAs) covered by PAs (%)	81.36	40.92	0.000	l	76.47	36.53	0.000	l
Conservation spending (USD/ha)	17.62	3.29	0.133	pl	6.91	2.66	0.473	pl
Forest status and changes								
Forest area as proportion of total land area (%)	36.10	35.01	0.832	pl	44.36	32.66	0.034	l
Forest area change rate (%)	0.13	0.12	0.805	pl	0.12	0.06	0.480	pl
Aboveground biomass in forest (t/ha)	132.10	122.49	0.587	pl	122.63	106.13	0.272	pl
Change in aboveground biomass in forest (%)	2.87	2.06	0.245	pl	3.08	1.90	0.116	pl
Biodiversity (species. habitats) status and changes								
Biodiversity Habitat Index (BHI)	0.49	0.59	0.005	l	0.55	0.63	0.039	l
Change in BHI (%)	−0.11	−0.10	0.375		−0.08	−0.06	0.443	
Species Habitat Index (SHI)	97.29	97.65	0.363	pl	96.82	97.50	0.984	pl
Change in SHI	−0.23	−0.93	0.009	l	−0.65	−0.99	0.585	pl
Red List Index (RLI)	0.93	0.86	0.004	l	0.94	0.88	0.006	l
Change in RLI (%)	−0.15	−0.84	0.005	l	−0.26	−0.62	0.149	pl
Bioclimatic Ecosystem Resilience Index (BERI)	0.30	0.41	0.000		0.33	0.43	0.004	
Change in BERI (%)	−0.16	−0.10	0.279		−0.10	−0.06	0.431	
Intact forest landscapes (%)	0.24	13.65	0.000	l	0.79	18.22	0.000	l
Proportion of land degraded (%)	9.88	20.83	0.008	l	9.03	24.59	0.000	l

[a]Indicator means for the groups of EU and non-EU countries.
[b]Values are for statistical tests for mean differences.
[c]Leakage: l, leakage (significant differences at a $p = 0.05$ and fulfilling the leakage-if assumption in Table 1); pl, indications for potential leakage (differences not significant, but fulfilling the leakage-if assumption in Table 1).

the group of non-EU countries than the EU countries (i.e., the "leakage if" assumption in Table 1 was fulfilled) (Table 3). Under the described EUBDS implementation scenario, the large majority of indicators thus showed significantly or at least potentially higher vulnerability and risk for non-EU countries. For vulnerability, these differences were statistically significant for 12 indicators, and for risk there were significant differences in 11 cases. These cases point to detrimental effects when roundwood production was transferred to non-EU countries. Only 5 indicators showed that transfer of roundwood production would not imply a leakage to more vulnerable countries. For the indicator conservation as primary management objective, vulnerability (unweighted mean) was higher for non-EU countries, whereas risk (weighted mean) was higher for EU countries. This was mainly due to Thailand, which reported a high share (82%) of such forests. However, this country accounted for a very low share (1%) of the increased roundwood production.

For most indicators, there were hardly any differences between vulnerability (unweighted indicator means) and risk (weighted indicator means), which showed that there were no systematic differences in indicator means between countries with high or low shares of the changed roundwood production volumes. On average, countries with high shares of production changes were neither more nor less vulnerable than those with low shares of production changes; weighting thus did not change the overall picture.

DISCUSSION

We relied on the well-established concepts of telecoupling and disaster risk theory. We use a novel combination of existing data for a new quantification of risks to forest biodiversity on a global level. For this, we created a specific PSR biodiversity indicator framework related to leakage effects of the EUBDS. Nearly 80% of our indicators pointed to higher vulnerability of forests in the affected non-EU countries and to associated risks of biodiversity loss due to roundwood production shifts from the EU into these countries.

Means of the forest area per capita indicator were higher in non-EU countries and were related to large countries with low population density and high forest cover. A shift of roundwood production to more remote areas in countries outside the EU could thus potentially reduce global pressure on forest biodiversity (Ferrer Velasco et al., 2020) and could support a concentration of protection measures close to densely populated areas, where biodiversity is usually valued highly (Bakhtiari et al., 2018). However, when considering the existence value of biodiversity in itself, protection measures would need to focus on areas with higher risks for biodiversity; these are to a large extent located outside the EU (see below).

The higher average values for the biodiversity engagement indicator for the EU might indicate a stronger political will for governments to act (Cooper et al., 2019). A strong political will in the EU is documented by the EU's earlier adoption of the 30% conservation target and by the requirement of an additional strict protection of one third of the totally protected area (EU, 2020), a protection level that is higher than that adopted by the UN (CBD, 2022a). The EU might thus be regarded as leading the way and pushing internationally for more protected areas. The adoption of the Kunming–Montreal Global Biodiversity Framework has been a success and a necessary safeguard for the EUBDS because unilateral action can provoke even more leakage.

Governance is essential for sustainable forest management and conservation measures (UN, 2019). High-quality governance is needed to ensure successful deforestation abatement (Fischer et al., 2021; Wehkamp et al., 2018) and nature protection. The lower values for mean governance in non-EU countries clearly indicated leakage risks, despite the establishment of the Kunming–Montreal framework, as roundwood production shifted to countries where governance aspects, such as government effectiveness, rule of law, and control of corruption (Kaufmann et al., 2010), are not as well established as in the EU.

Sustainable forest management is regarded as key to maintaining forest biodiversity during roundwood production (UN, 2008), and, given the increasing global roundwood demand, it is imperative to ensure the continued provision of multiple forest ecosystem services. The indicators long-term management plans and certification schemes provided clear indications that on the global average roundwood was less sustainably produced if under the given EUBDS conservation scenarios production was relocated to non-EU countries, which would challenge the maintenance of biodiversity during roundwood production.

Protected areas are regarded as the most commonly used tool for biodiversity conservation in developing countries (Miteva et al., 2012), and international indicator development has focused on them. Even though the effects of these measures are often reported as smaller than expected (Börner et al., 2020; Busch & Ferretti-Gallon, 2017; Seymour & Harris, 2019), we followed the rationale of the EUBDS, whereby increased forest conservation with larger shares of protected areas is essential to protect and conserve forest biodiversity. The 3 indicators with significant differences in protected areas showed that a further increase of conservation and forest protection areas in the EU would shift roundwood production to countries with still lower conservation efforts and thus risk counteracting EU conservation targets on the global level. Only scores of the indicator strictly protected areas were higher in non-EU countries. However, this difference was only significant for unweighted means because the share of strictly protected areas was mostly higher in those countries that contributed low shares of the increased non-EU roundwood production. The implementation of EUBDS would thus require an increase in strictly protected areas in those non-EU countries that account for the larger shares of production increase.

The status indicators forest area and aboveground biomass in forests were both lower in non-EU countries. Aboveground biomass is not only of economic relevance, but is also a key parameter in the multifunctionality of forest ecosystems (Eguiguren et al., 2020; Peters et al., 2023). Even though our results were mostly not statistically significant, they suggest that as a consequence of EUBDS implementation, roundwood production could be transferred to countries with lower forest biodiversity status in terms of extent and multifunctionality, including climate change mitigation potential.

Indicators for temporal changes showed that mean forest area and biomass increased in both country groups, which is an encouraging trend in both cases. Even though there were single countries in the non-EU country group with alarming deforestation (i.e., above 0.2% per year in Brazil, Indonesia, and South Africa), we found that roundwood production for the EU market was not necessarily linked to decreasing forest area or biomass. According to the forest transition hypothesis (Köthke et al., 2013; Mather, 1992), this may be due to the fact that most of the affected non-EU countries are, like the EU countries, more developed. Nearly all of them are high- or upper-middle-income countries. After earlier stages with low development and high deforestation, their higher development now coincides with mean increases in forest area. Deforestation no longer seems to be the main challenge in these countries (even though the means disguise countries in lower development stages where deforestation abatement is urgent). This has implications for the relevance of the EUDR. Beyond deforestation, this regulation has a very narrow definition of degradation and makes little mention of sustainable forest management. It only prohibits the importation of wood products from primary or natural forests that have been converted to plantations or planted forests. It does not apply to the management of forests that are not converted. But, as our indicators showed, additional roundwood production largely occurred in such forests, which are not covered by the EUDR. A stronger focus in the regulation on sustainable management of existing and newly established forests would have been required for a broader understanding of forest degradation.

Forest extent does not provide information on the ecological state and functionality of forests. Therefore, species information is a key element in monitoring compositional aspects of forests (Larsson et al., 2001) and ecosystem integrity (CBD, 2021; Hansen et al., 2021). The Biodiversity Habitat Index (BHI) and Species Habitat Index (SHI) are such indicators and showed on average more natural habitat in non-EU countries, which is in line with a higher proportion of the indicator intact forest landscapes. The averages of Red List Index (RLI) values showed that in the group of non-EU countries, species are on average under a higher risk of extinction. In summary, more natural and intact forests and more threatened species would be under pressure with increased roundwood production in non-EU countries, in the worst case leading to even higher proportions of land degraded. This is consistent with Rosa et al. (2023), who found that expanding set-asides to more than 25% of the currently managed forestland in the EU increases the global extinction risk relative to the continuation of current forest management practices in the EU. In contrast, the BERI indicated significantly lower vulnerability and risks for non-EU countries. From a resilience point of view, this supports relocation of roundwood production because ecosystems in non-EU countries are on average more resilient to climate change.

The temporal development of all 4 species-related indicators (BHI, SHI, RLI, BERI) showed a decrease over time in both country groups. This indicates an overall decline of species diversity and related ecosystem functions in both country groups. It is consistent with reports of a global decrease in species and habitat diversity and related functions (Newbold et al., 2015; Powers & Jetz, 2019; Tittensor et al., 2014) and calls for immediate action. However, decreases in RLI and SHI were significantly stronger in non-EU countries, and a transfer of more roundwood production into these might thus aggravate these imbalances.

Reduced roundwood consumption in general might be another option to reduce pressure on forest biodiversity. Indeed, our model results showed that only 62% of the decreased roundwood production in the EU would be offset by an additional production in non-EU countries; the remaining shares of the EU production deficit would no longer be consumed worldwide. Raw material consumption is a key underlying driver of biodiversity loss (Marques et al., 2019). An enforced reduction of roundwood production might therefore be regarded as a positive effect of EUBDS if it led to an overall demand reduction. However, together with increasing global population and income, the demand for raw material in general is likely to increase (Asada et al., 2020; Bithas & Kalimeris, 2022; Charlier & Fizaine, 2023; Vaden et al., 2020). Thus, a decreasing use of roundwood would rather stimulate substitution of wood products with other materials. There is clear evidence based on life cycle assessment studies that most wood substitutes are more greenhouse-gas intensive, which would result in increased greenhouse gas emissions (Geng et al., 2017; Hill, 2019; Hurmekoski et al., 2021; Myllyviita et al., 2021; Petersen & Solberg, 2005; Sarthre & O'Connor, 2010). This would thus again counteract aims of the European green climate policy. Decreasing roundwood production would foster displacement of environmentally friendly wood products and would hence have an additional negative impact on climate change mitigation on a global scale. Also, socioeconomic aspects of reduced roundwood production would need to be accounted for. For example, decreasing roundwood production would affect EU wood products markets in a way that would negatively affect, for example, EU wood-based industries, income, employment, and net trade (Schier et al., 2022).

Biodiversity indicator development is ongoing and includes remote sensing techniques (Hansen et al., 2021) and new modeling approaches (Jetz et al., 2022). New and revised indicators might change our results; thus, repeating our study might be worthwhile, specifically when indicators are consolidated and adopted under the Kunming–Montreal framework.

We had to restrict our analyses to the national level because no subnational data were available. Nevertheless, further spatial disaggregation would be of interest to show whether current and presumed future wood production would, for example, rely on primary, secondary, or plantation forests with their varying biodiversity status and trends. Data collection thus remains an ongoing task. There is a need for comparable subnational biodiversity and wood production data.

CONCLUSIONS

In our study, risk theory proved suitable to examine leakage effects of the implementation of the EUBDS. We found that increased forest conservation and protection in the EU could result in a shift of wood production into non-EU countries that are on average more vulnerable to the ecological risks of roundwood production. Our results provide clear indications that environmental policies under EUBDS risk producing negative effects on biodiversity elsewhere, which would thus counteract the overall effectiveness of the intervention.

We conclude that before more forests are conserved and protected under EUBDS, safeguards need to be in place to ensure that the shift of roundwood production to non-EU countries does not harm ecosystems elsewhere. The adoption of the UN Kunming–Montreal Global Biodiversity Framework is an urgent step in this direction because decreasing values of ecological indicators support the need for global conservation schemes. However, we argue that the Kunming–Montreal framework does not necessarily prohibit leakage effects. This is first because EUBDS aims are stricter and second because a comparison of governance and awareness indicators suggests that implementation of EUBDS might be faster and more effective. Nevertheless, regional strategies, such as EUBDS, can stimulate and even lead global conservation initiatives. However, unilateral implementation alone might prove counterproductive. Also, land-use planning needs to balance biodiversity conservation and roundwood production.

The EU regulation on deforestation-free supply chains might have only limited safeguard effects for the EUBDS because it does little to address sustainable forest management. As we have shown, related to wood production, deforestation is not the main threat to forest biodiversity in most of the affected non-EU countries. Instead, the challenge there, in mostly high- or upper-middle-income countries, is mainly to ensure the sustainable management of existing and newly established forests. Indonesia and Brazil are exceptions in that respect. The fact that they are on the list of countries for which higher roundwood production can be expected is alarming because they contain multiple biodiversity hotspots. From a global biodiversity perspective, one could argue that sustained roundwood production in the EU is needed to reduce pressure on more vulnerable ecosystems elsewhere, at least as long as forest management in non-EU countries is not as sustainable as in the EU.

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