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Does forest management certification halt forest loss at country level? A global analysis

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ABSTRACT

Forests play a vital role in regulating the global climate, supporting biodiversity, and sustaining the livelihoods of approximately 1.6 billion people. However, unsustainable forest management continues to drive widespread forest loss. Certification schemes such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) evolved to promote sustainable forestry practices, yet evidence of their effectiveness in reducing deforestation and forest degradation remained inconclusive. This study employed generalised additive models to assess whether increased FSC and PEFC certification coverage was associated with reduced permanent and temporary forest loss, using annual data from 2005 to 2019 across more than 113 countries while controlling for other drivers of forest change. No significant association between certification coverage and forest loss reduction was found at the country level. These findings were limited by the lack of publicly available data on certified forests at high spatial resolution and the use of aggregated country-level certification coverage, which might obscure regional (sub-country) effects. Improved transparency and finer-scale data are needed for more definitive assessments of certification's impact. Furthermore, for achieving global goals such as halting deforestation by 2030, additional strategies beyond voluntary certification are needed.

1. Introduction

Forests cover roughly one-third of the Earth's terrestrial area and represent one of the most vital ecosystems globally. They play a key role in regulating the World's climate, provide habitat for approximately 80% of amphibian, 75% of bird, and 68% of mammal species, and support the livelihoods of over 1.6 billion people (FAO and UNEP, 2020; Luther et al., 2020; Newton et al., 2020; Tyukavina et al., 2022). Yet, between 2000 and 2020, 459 million hectares of tree cover were lost equivalent to 12% of the global tree cover present in 2000 (Hansen et al., 2013; World Resources Institute, 2023). Even after accounting for natural forest regeneration and replanting, net global tree cover loss remains substantial, amounting to 101 million hectares over the same period (Potapov et al., 2022).

Tree cover loss can be either temporary or permanent. Temporary loss can result from natural disturbances (e.g., fires, storms, pests), anthropogenic degradation (e.g., shifting agriculture or overexploitation), or planned forest management operations (e.g., clearcuts or regeneration harvests). In contrast, permanent loss is mainly associated to the concept of deforestation, which refers to human-caused, permanent removal of trees (e.g., conversion of forests to agriculture). Deforestation is a major contributor to greenhouse gas (GHG) emissions, estimated to account for 12–20% of annual GHG emissions globally (Watson and Schalatek, 2020), as well as a leading cause of habitat destruction and biodiversity loss (Diaz et al., 2019; FAOUNEP, 2020).

Globally, land-use change for commodity production (e.g., beef, soy, palm oil) accounts for about 27% of forest loss, followed closely by forestry at 26% (Curtis et al., 2018). These drivers vary regionally: in boreal and temperate forests, forestry operations dominate, whereas in tropical regions, commodity-driven deforestation and shifting agriculture are more prevalent (Curtis et al., 2018). In 2021, 145 countries signed a pledge at COP26 in Glasgow to end deforestation and land degradation by 2030 (Gasser et al., 2022). However, despite this

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commitment, tropical primary forest loss remains persistently high, with annual losses ranging from 3.8 to 4.1 million hectares over the past four years, an area comparable to the size of Switzerland disappearing each year (World Resources Institute, 2024). These trends raise questions about the effectiveness of existing tools to curb forest loss.

Forest management certification emerged in the 1990s as a market-based response to growing concerns about tropical deforestation (Rametsteiner and Simula, 2003). It aims to incentivise environmentally and socially responsible forest management by promoting practices such as legal compliance, the protection of high-biodiversity areas (e.g., primary forests), reduced illegal logging, improved labour conditions, and the involvement of local communities in decision-making (Clark and Kozar, 2011; Rametsteiner and Simula, 2003). The Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) are the two most prominent global certification schemes (Depoorter and Marx, 2022; Paluš et al., 2021). As of 2019, FSC covered over 200 million hectares of forest in 84 countries, while PEFC certified 320 million hectares in 38 countries, amounting to approximately 5% and 7.9% of global forest area, respectively (FSC, 2023a; PEFC, 2023a). Although certification originally emerged to tackle tropical deforestation, around 85% of certified forest areas are located in Europe and North America, thus primarily covering temperate and boreal regions (Bösch, 2025).

This study evaluated the effectiveness of forest management certification in reducing tree cover loss, both permanent and temporary, at the national level. Previous research on the sustainability outcomes of certification had produced mixed findings and has typically focussed on smaller case studies at regional level (Burivalova et al., 2017; Di Girolami et al., 2023; Komives et al., 2018). This paper contributed to resolving these inconsistencies by (1) distinguishing between permanent and temporary forest loss, (2) providing rare empirical insights into the outcomes of PEFC certification, and (3) evaluating the potential of forest management certification to halt deforestation at large scale. The latter is relevant when certification such as FSC and PEFC is discussed as means to achieve international commitments such as the COP26 pledge to end deforestation by 2030. To this end, the study used annual certification data from FSC and PEFC alongside three complementary global datasets on tree cover loss (Curtis et al., 2018; Hansen et al., 2013; Potapov et al., 2022), covering a 15-year period and more than 113 countries. It employed generalised additive models (GAMs), incorporating control variables from the World Bank and FAOSTAT to account for confounding drivers of forest loss, following a similar approach as Dröge et al. (2024) evaluating the environmental outcomes of food commodity certification. With this approach, this study extends the work of Yamamoto and Matsumoto (2022) by using two more nuanced tree cover loss datasets and seven more years of observation. Yamamoto and Matsumoto (2022), using the Hansen dataset for the years 2002–2011, found that FSC and PEFC forest management certification do not influence forest loss while controlling for other factors potentially influencing deforestation (e.g., economic development, population growth).

Given that forest loss encompasses both permanent and temporary changes, three datasets were used. The Hansen dataset captured all tree cover loss regardless of cause or permanence. The Curtis dataset allowed for the isolation of loss attributed to forestry, typically representing temporary loss in managed and plantation forests. The Potapov dataset provided estimates of net forest cover change over two decades, capturing both loss and regrowth, although without annual resolution.

It was hypothesised that certification would reduce permanent forest loss by discouraging illegal logging (Giurca et al., 2013; Guan et al., 2019). It was also expected that certified management would promote more sustainable harvesting methods, such as selective logging and reduced-impact logging, which could minimise canopy disturbance and reduce temporary losses in managed forests (Bicknell et al., 2014; Morel et al., 2019; Schulze and Zweede, 2006). Furthermore, it was anticipated that certification could support ecosystem restoration and post-harvest regeneration, thus reducing net forest loss over time. Lastly, given its higher stringency, it was hypothesised that FSC would be more effective than PEFC in reducing both permanent and temporary forest loss (Depoorter and Marx, 2023). The theoretical framework for these expectations, along with background on certification standards, is detailed in Section 2.1.

2. Research background

2.1. Forest management certification

Certification schemes, often referred to as voluntary sustainability standards (VSS), are private, transnational, market-based instruments designed to promote sustainable management and production systems. VSS set sustainability-related standards, verify compliance through conformity assessments, and issue certificates to compliant actors (UNCTAD, 2023). Economic actors voluntarily adopting VSS benefit from enhanced market access, reputational gains, and in some cases, price premiums for certified products (Marx et al., 2022; Marx and Wouters, 2014). Forest management certification is a sector-specific type of VSS that aims to ensure the social, economic, and environmental sustainability of forest use.

Schemes such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) aim to address forest loss through several causal pathways (Blackman et al., 2018; Tritsch et al., 2020). Originally conceived to reduce illegal logging and deforestation, these schemes ensure legal compliance in wood extraction and safeguard primary forests and other high conservation value areas. They also promote sustainable forest management practices, including selective and reduced-impact logging, non-destructive felling techniques, sustainable harvest rates, ecosystem restoration and set-aside areas (Lehtonen et al., 2021; Villalobos et al., 2018).

These silvicultural approaches, which maintain continuous forest cover, help reduce environmental impacts by preserving canopy integrity and limiting tree mortality from fragmentation and exposure (Bicknell et al., 2014; Morel et al., 2019; Schulze and Zweede, 2006). As a result, they are expected to reduce temporary forest loss. These outcomes might not only be observed in certified areas but also beyond through spillover effects (Oya et al., 2018). Certification also seeks to improve local livelihoods, which can reduce incentives for deforestation and support transitions toward less land-intensive economic activities, though this relationship remains complex (Blackman et al., 2018; Moonen et al., 2016). Additionally, compliance audits and external scrutiny by NGOs or the media help ensure that certified forest operations implement sustainable practices effectively (Haack and Rasche, 2021). Based on these mechanisms, the following hypothesis was formulated:

H1. Countries with a higher share of certified forest area have lower rates of permanent and temporary forest loss.

The two leading global forest certification schemes, FSC and PEFC, both pursue sustainable forest management and rely on the mechanisms described above to reduce forest loss. However, despite a degree of convergence over time (Overdevest, 2010; Tricallotis et al., 2019), important differences remain between the schemes that may influence their effectiveness. FSC is generally perceived as more stringent and credible than PEFC (Lopatin et al., 2016).

First, the schemes differ in origin. FSC was founded in 1993 by a coalition of environmental NGOs in response to the lack of intergovernmental action on deforestation (Auld, 2014). PEFC, by contrast, was established in 1999 by European forestry industry associations as a more flexible, industry-friendly alternative (Damette and Delacote, 2011; Fischer et al., 2005).

Second, governance structures vary significantly. FSC's General Assembly operates through a tripartite system consisting of Environmental, Social, and Economic chambers, each further divided into North and South sub-chambers, to ensure balanced representation and influence (FSC, 2014). PEFC's General Assembly, by contrast, grants voting rights to National Governing Bodies and international members, many closely aligned with industry interests (PEFC, 2023b).

Third, the two schemes differ in how they set standards. FSC defines 10 international principles and 57 performance-based forest management criteria. These include requirements to maintain, conserve, or restore ecosystem services, protect threatened species, prohibit conversion of natural forests or high conservation value (HCV) areas, and safeguard representative samples of native ecosystems (FSC, 2023b). While these can be adapted into national standards, they act as a minimum threshold globally. PEFC, on the other hand, uses a more bottom-up, system-based approach: national certification bodies develop their own standards, which are endorsed by PEFC if they meet the requirements outlined in the PEFC benchmark standard (PEFC, 2018). While this may allow for stronger adaptation to local contexts, it can also result in weaker requirements that reflect existing industry norms (Damette and Delacote, 2011; Fischer et al., 2005).

Fourth, although both schemes prohibit illegal logging and forest conversion and promote sustainable harvesting, biodiversity protection, and ecosystem restoration (FSC, 2015; PEFC, 2018), they differ in how these standards are implemented. Both rely on third-party audits to verify compliance, but FSC provides more training opportunities for forestry operators and enforces stricter rules to ensure the independence of auditors (Depoorter and Marx, 2023).

Finally, FSC enjoys greater recognition in terms of credibility. It is a member of the ISEAL Alliance, a global organization for credible sustainability standards, and complies with ISEAL's Codes of Good Practice for standards-setting, assurance, and impact evaluation (ISEAL, 2024). PEFC is not an ISEAL member.

These structural and procedural differences led to the second hypothesis:

H2. FSC certification is more effective in reducing permanent and temporary forest loss than PEFC certification.

Before testing these hypotheses, an overview of the existing empirical evidence on the relationship between forest management certification and forest loss is provided in Section 2.2.

2.2. Existing empirical evidence on reduced forest loss and degradation through forest management certification

Several studies have evaluated the impact of forest certification on forest loss and degradation, with most focusing on FSC certification, while fewer examine the effects of PEFC. In Chile, FSC certification resulted in a 13% reduction in the conversion of natural forests to forest plantations (Heilmayr and Lambin, 2016). The authors of that study used a matched difference-in-difference analysis to ensure comparability of pixels. Also using a matching approach, comparing villages with certified and non-certified logging concessions in Indonesia, Miteva et al. (2015) found that villages with FSC certification in Indonesia experienced lower rates of forest loss and adopted reduced-impact logging practices (e.g., selective logging) compared to similar non-certified villages. In the Brazilian Amazon, Rana and Sills (2024) observed that FSC certification reduced the likelihood of deforestation. The authors controlled for selection effects also using a matching approach. Damette and Delacote (2011), analysing data from 87 countries for the year 2005, found a negative relationship between FSC certification and deforestation, although this was not the case for PEFC. This study relied on FAO forest data, which are self-reported by countries and accounted for other factors potentially influencing deforestation including institutional quality, economic growth, population density, the remaining forest cover and the timber harvest value (Damette and Delacote, 2011). Boubacar and Sissoko (2025), using FAO forest cover data for 70 countries from 2000 to 2021, concluded that FSC certification enhances forest cover, particularly in low- and middle-income countries. Both studies controlled for other deforestation drivers, including population and economic growth, timber harvests, and agricultural expansion. However, as both rely on FAO's Global Forest Resources Assessment (FRA) data, which are based on self-reported national statistics, their findings may diverge from analyses using remotely sensed data such as that provided by Global Forest Watch (GFW) (Carter et al., 2023).

Other studies reported smaller effects. In Peru, Rico et al. (2018) found a 0.1% reduction in forest loss in one of three study regions due to FSC certification. Similarly, in Cameroon, Panlasigui et al. (2018) found a modest 0.03% reduction in forest loss in one of four regions after forests received FSC certification. In both studies, the authors used a matching approach to ensure comparability of certified and non-certified pixels and employed panel regression accounting for other factors potentially influencing deforestation (Panlasigui et al., 2018; Rico et al., 2018). Other environmental benefits included narrower skid trails and roads in certified forests in Gabon, as well as a trend of smaller declines in aboveground biomass and reduced damage to unfelled trees in certified forests (Medjibe et al., 2013).

However, several studies found no significant differences in forest loss between certified and non-certified forests. For example, Blumröder et al. (2020, 2019) did not find FSC certification to lead to ecological improvements in Russian boreal forests; the amount of timber harvested, and the prevalence of large-scale clearcutting were similar in both certified and non-certified sites. In Sweden, Villalobos et al. (2018) found that neither FSC nor PEFC certification reduced forest degradation. Blackman et al. (2018) found that FSC certification did not reduce deforestation in Mexico. Anderson et al. (2019) similarly found no difference in deforestation rates between FSC-certified and non-certified logging concessions in the Peruvian Amazon. In the studies in Sweden, Mexico and Peru, the authors all applied a quasi-experiment approach, matching certified and non-certified forests to ensure comparability accounting for selection effects (Anderson et al., 2019; Blackman et al., 2018; Villalobos et al., 2018).

3. Methods

3.1. Data

Three tree cover loss datasets (Curtis et al., 2018; Hansen et al., 2013; Potapov et al., 2022) were used and implemented in three Generalised Additive Models (GAMs) (Table 1). In all three GAMs, the percentage of tree cover loss was used instead of hectares to account for countries varying in size and forest area. The percentage of tree cover loss was calculated using the forest extent in 2000 as reference (Hansen et al., 2013).

The first GAM utilised the Hansen dataset (with a canopy cover threshold of 30%), which is based on Landsat satellite imagery at a 30-m resolution and LiDAR data (Fig. 1A). This dataset defines tree cover as all vegetation greater than 5 m in height, including both natural and plantation forests (Hansen et al., 2013). It includes annual tree cover loss (both permanent and temporary) due to factors such as deforestation, harvesting, fire, disease, and storm damage, reported at the country level.

The second GAM incorporated the Curtis dataset, which reports annual forest loss at the country level, categorised by the dominant driver of loss (Curtis et al., 2018) (Fig. 1B). This dataset identifies the five primary drivers of global forest loss, derived from Google Earth imagery for 10 x 10-km grid cells. Forest loss attributed to forestry was selected, focusing on temporary losses observed in managed forests and plantations, which are typically caused by harvesting followed by forest regrowth in subsequent years. To address the positive skew in both the Hansen and Curtis datasets, a log transformation was applied.

Annual tree cover gain data for the covered years was not available. To include forest regrowth, the dataset of (Potapov et al., 2022) was used, which reports net forest change over a 20-year period (from 2000 to 2020) (Fig. 1C). This dataset is based on Landsat imagery and Global

Table 1
Overview on data used in GAMs, the data source as well as basic descriptive statistics. All variables were annual data except for the forest extent which reports the forest extent for the year 2000 and the net forest cover change which compares 2000 to 2020. Descriptive statistics for the 122 countries (see Table I, Supplementary Information) included in the GAMs. Data visualised in Figures I to III in the Supplementary Information.

Explanatory variable	Mean	Std. Dev.	Min.	Max.	Data sources and explanation
Forest loss [% of forest area]	0.57	0.57	0.00	7.55	Hansen et al. (2013), annual data, all forest loss independent of driver, reference forest area for the year 2000
Forest loss temporary [% of forest area]	0.22	0.38	0.00	6.09	Curtis et al. (2018), annual data, forest loss attributed to forestry, reference forest area from Hansen et al. (2013) for the year 2000
Net forest cover change [% of forest area]	−1.58	8.05	−26.00	54.00	Potapov et al. (2022), net forest change over 20 years (2000–2020), reference forest area from Hansen et al. (2013) for the year 2000
FSC coverage [% of forest area]	7.72	16.74	0.00	153.76	FSC, annual data, reference forest area from Hansen et al. (2013) for the year 2000
PEFC coverage [% of forest area]	7.49	18.62	0.00	103.42	PEFC, annual data, reference forest area from Hansen et al. (2013) for the year 2000
Population density [people/km^2]	241.91	892.58	2.65	7965.88	The World Bank (2022), annual data
Population growth [%]	1.19	1.12	−2.26	6.57	The World Bank (2022), annual data
GDP per capita [current USD]	14903.55	20039.79	151.68	118823.60	The World Bank (2022), annual data
GDP per capita growth [%]	2.42	3.61	−22.31	33.00	The World Bank (2022), annual data
Agriculture, forestry, fishing, value added [% GDP]	10.48	10.82	0.03	66.03	The World Bank (2022), annual data
Forest products export value [% GDP]	0.80	1.55	0.00	31.02	The World Bank (2022), annual data
WGI corruption indicator	0.06	1.02	−1.67	2.47	World Governance Indicators, (Kaufmann et al., 2011)
Forest extent 2000 [% of country area]	41.84	26.16	0.16	97.84	Hansen et al. (2013)

Ecosystem Dynamics Investigation (GEDI) lidar forest structure measurements and was implemented in the third GAM. The combination of these three datasets enables an examination of forest management certification outcomes from different perspectives and causal pathways, as outlined in Section 2.1.

Annual data on forest management certification from FSC and PEFC were obtained for the years 2005–2019. Certification coverage for each Voluntary Sustainability Standard (VSS), country, and year was calculated by dividing the certified hectares by the country's forest extent as reported for the year 2000 (Hansen et al., 2013) (Fig. 2).

To account for other factors that could influence forest loss, the study included the following variables from the World Bank: GDP per capita (current USD), GDP per capita growth (annual %), population density (people/km^2), population growth (annual %), the "control of corruption" indicator from the World Governance Indicators (WGI) dataset, and the value added by the agriculture, forestry, and fishing sector (as % of GDP) (Kaufmann et al., 2011; The World Bank, 2022) (Figs. I-III, Supplementary Information). In addition, to reflect a country's economic reliance on forestry, the export value of forest products from the FAOSTAT database was included, calculated as a percentage of GDP (FAOSTAT, 2024) (Fig. I, Supplementary Information). Previous studies, such as Allen and Barnes (1985), Damette and Delacote (2012), Dávalos et al. (2011), Ewers (2006), Leblois et al. (2017) and Waldron et al. (2017), highlight the importance of these variables in explaining variation in forest loss.

Additional governance indicators from the World Governance Indicators (WGI), such as rule of law and regulatory quality, were initially considered, but found to be highly correlated with the control of corruption indicator. Therefore, the control of corruption indicator was selected as a proxy for broader institutional quality, capturing key governance dimensions relevant to forest management. This approach aligned with studies such as Yamamoto and Matsumoto (2022), which similarly used institutional quality measures to account for governance-related influences.

3.2. Statistical analysis

R version 4.0.5 (R Core Team, 2022) was used, and three generalised additive models (GAMs) were applied to assess the relationship between forest management certification and both permanent and temporary forest loss. GAMs were chosen for their flexibility in modelling non-linear relationships. The models were implemented using the gam function from the mgcv package, with thin plate regression splines applied as smoothers for all independent and control variables (Wood, 2017).

In the first and second GAMs, the Tweedie distribution with a log-link function was employed to account for heteroscedasticity. The first

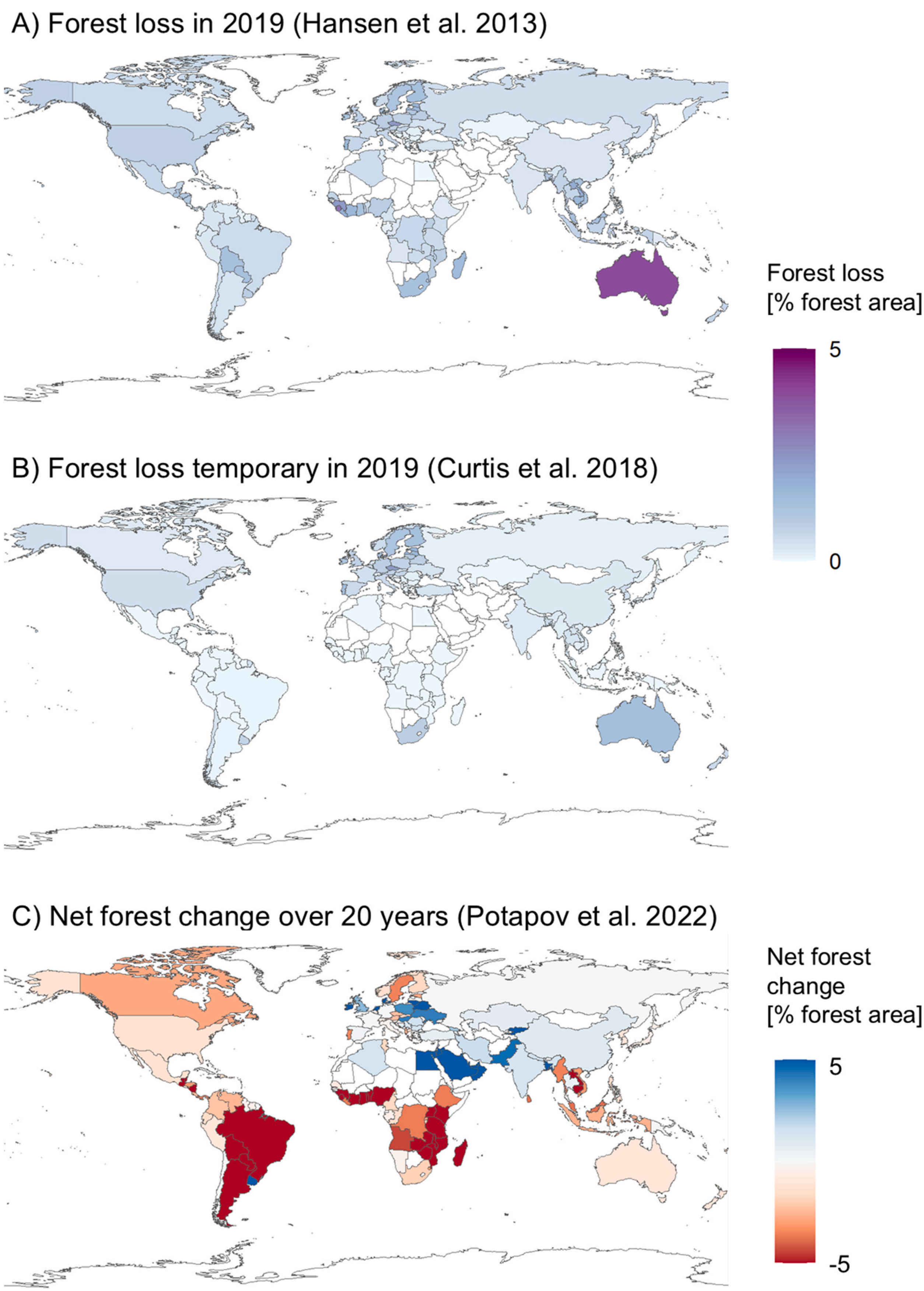

Fig. 1. Global visualisation of forest loss datasets used in this study. A) Tree cover loss including both permanent and temporary loss due to human activity and natural disturbances (Hansen et al., 2013), B) temporary forest loss in managed and plantation forests attributed to forestry operations (Curtis et al., 2018), and C) net forest change over a 20-year period which also accounts for forest regeneration.

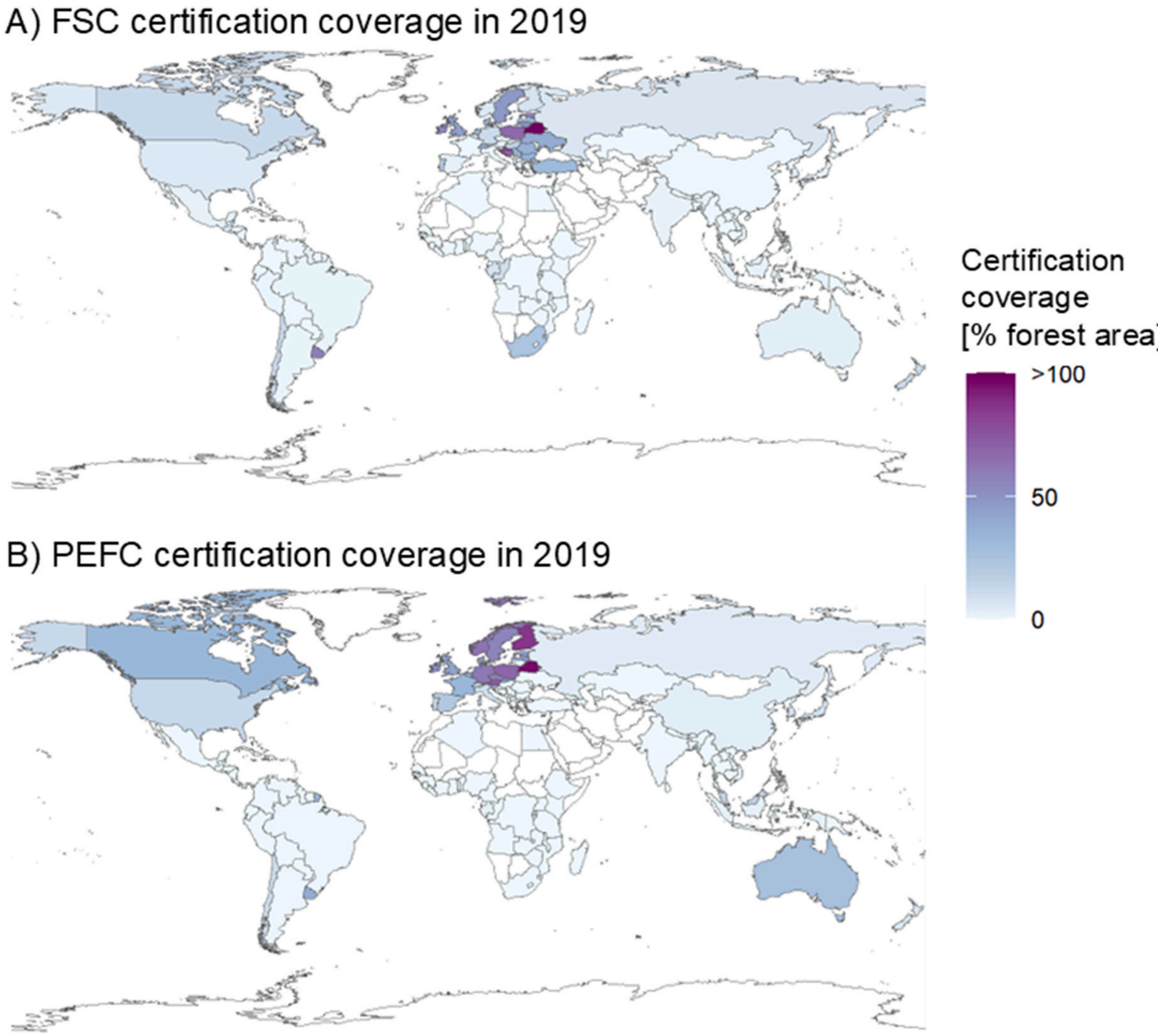

Fig. 2. FSC (A) and PEFC (B) forest management certification coverage in 2019 calculated as percentage of forest area certified. The forest extent in 2000 (Hansen et al., 2013) served as reference for calculation. Most of the forest management certification was found in the global north.

model utilised the Hansen dataset, which reports both permanent and temporary tree cover loss, while the second model employed the Curtis dataset, filtered to include only temporary loss attributed to forestry activities. In both models, FSC and PEFC certification coverage (expressed as a percentage of forest area) were included as explanatory variables, alongside control variables obtained from the World Bank and FAOSTAT. Forest extent in 2000 (as a percentage of total country area) was included to account for initial differences in forest cover, and the previous year's forest loss (log-transformed) was added to account for temporal lag effects. A country random effect was included to capture unobserved, country-specific factors.

The third GAM employed the Potapov dataset, which provides net forest change over the period 2000–2020. As annual data were not available for this dataset, mean values for FSC and PEFC certification coverage, as well as for all control variables, were calculated for the period 2005–2019. A scaled t-distribution was used in this model to account for the presence of heavy-tailed data.

Model fit was evaluated using the gam.check function (Wood, 2017). Diagnostic plots indicated the presence of influential outliers. Cook's distance was therefore calculated, and observations exceeding the threshold of 4/sample size were excluded (Nieuwenhuis et al., 2012). Countries with no recorded forest loss or missing World Bank or FAOSTAT data were also excluded. As a result, 122 countries were included in the first and second GAMs, and 113 in the third GAM (see Tables I and II, SI).

4. Results

In 2019, FSC was present in 84 countries while PEFC was present in 38 countries. FSC covered over 200 million hectares of forest (5% of the global forest area) while PEFC certified 320 million hectares (7.9% of global forest area). About 1.8% of global forest area is certified by both FSC and PEFC. The majority of certified forests were located in the global north (Fig. 2). Consequently, forest management certification did not coincide with hotspots of forest loss, particularly if looking at the net forest cover change between 2000 and 2020 (Fig. 1C).

A correlation between forest management certification and forest loss, both permanent and temporary, was identified in two of the three generalised additive models (GAMs). In the first GAM, which assessed total tree cover loss (including both permanent and temporary loss due to human activity and natural disturbances), a statistically significant positive correlation was observed for PEFC certification coverage (Fig. 3). In the second GAM, which focused on temporary forest loss in managed and plantation forests attributed to forestry operations, significant positive correlations were found for both FSC and PEFC certification coverage (Fig. 4). However, the effect sizes were small: a 10% increase in certification coverage was associated with an increase in forest loss of less than 0.01%. In the third GAM, no significant

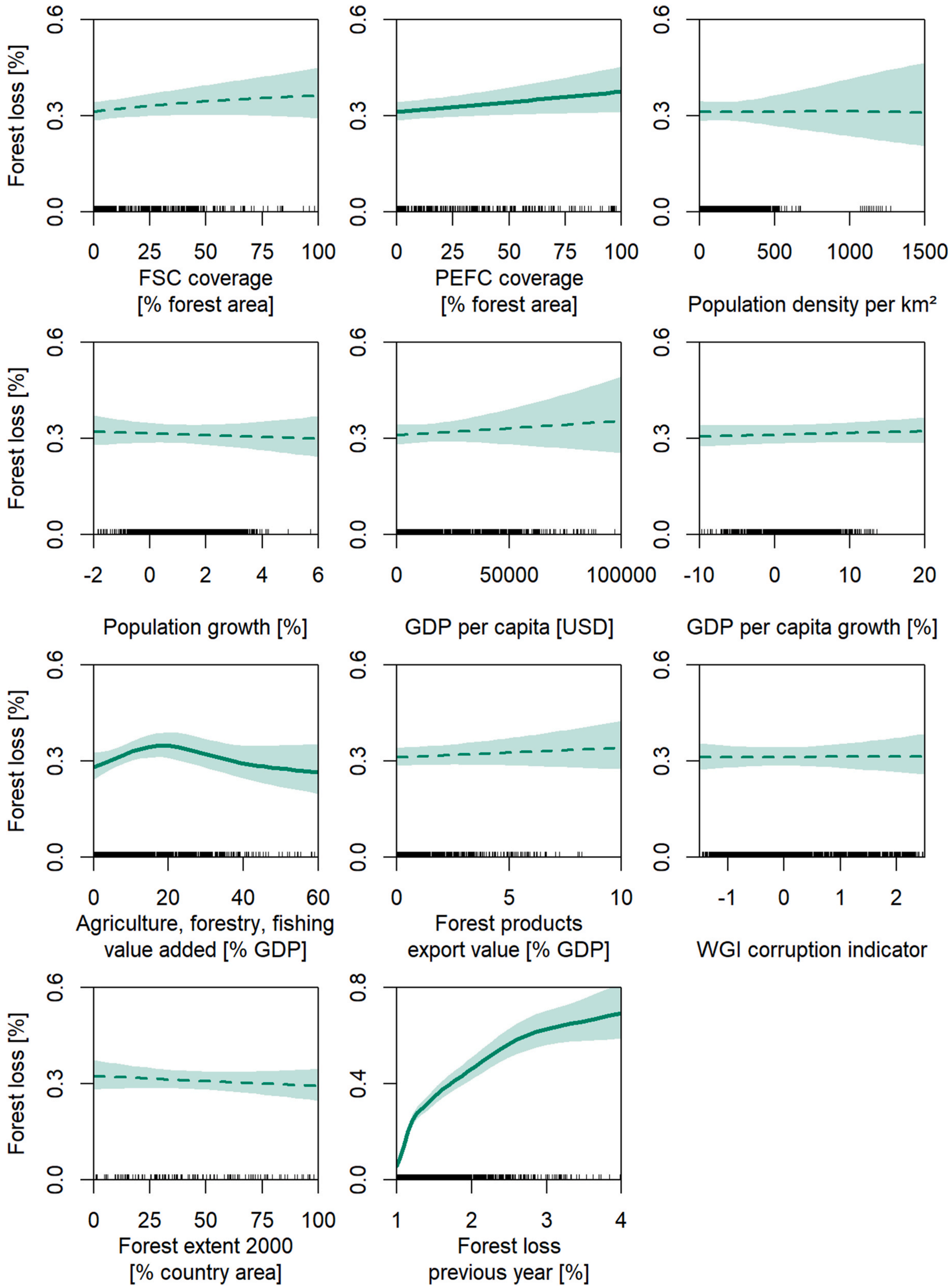

Fig. 3. Summed effect plots for the generalised additive model (GAM) using the Hansen dataset (Hansen et al., 2013). It comprised the total tree cover loss including both permanent and temporary loss due to human activity and natural disturbances. Summed effect plots show the effect of each independent variable on the outcome variable while other predictors are set to median value or reference level and random factors are dropped. Significant variables are shown with solid, non-significant variables with dashed lines. Light green area represents 95% confidence intervals. Rug at plot bottom shows distribution of data.

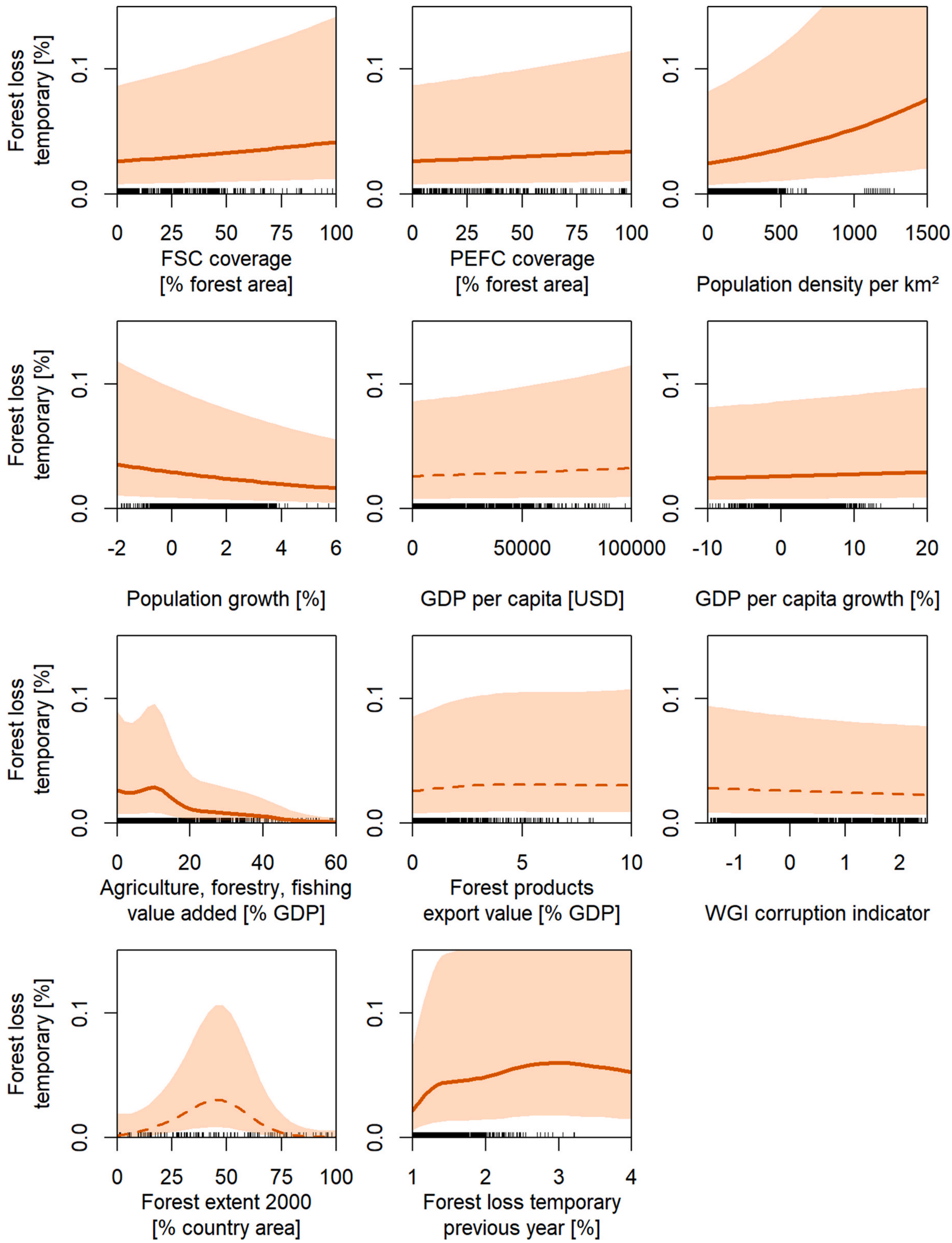

Fig. 4. Summed effect plots for the generalised additive model (GAM) using the Curtis dataset (Curtis et al., 2018). It comprises temporary forest loss in managed and plantation forests attributed to forestry operations. Summed effect plots show the effect of each independent variable on the outcome variable while other predictors are set to median value or reference level and random factors are dropped. Significant variables are shown with solid, non-significant variables with dashed lines. Light orange area represents 95% confidence intervals. Rug at plot bottom shows distribution of data.

correlation was found between FSC or PEFC certification coverage and net forest change over the 20-year period (Fig. 5). Detailed model output is given in Table III in the Supplementary Information.

Among the control variables, the economic value added in the agriculture, forestry, and fishing sectors proved significant across all three GAMs, with a general trend indicating greater forest loss in countries with higher value added in these sectors (Figs. 3–5). Human population density and population growth were significant in the second and third GAMs. Specifically, higher population density was associated with increased temporary forest loss and greater net forest change,

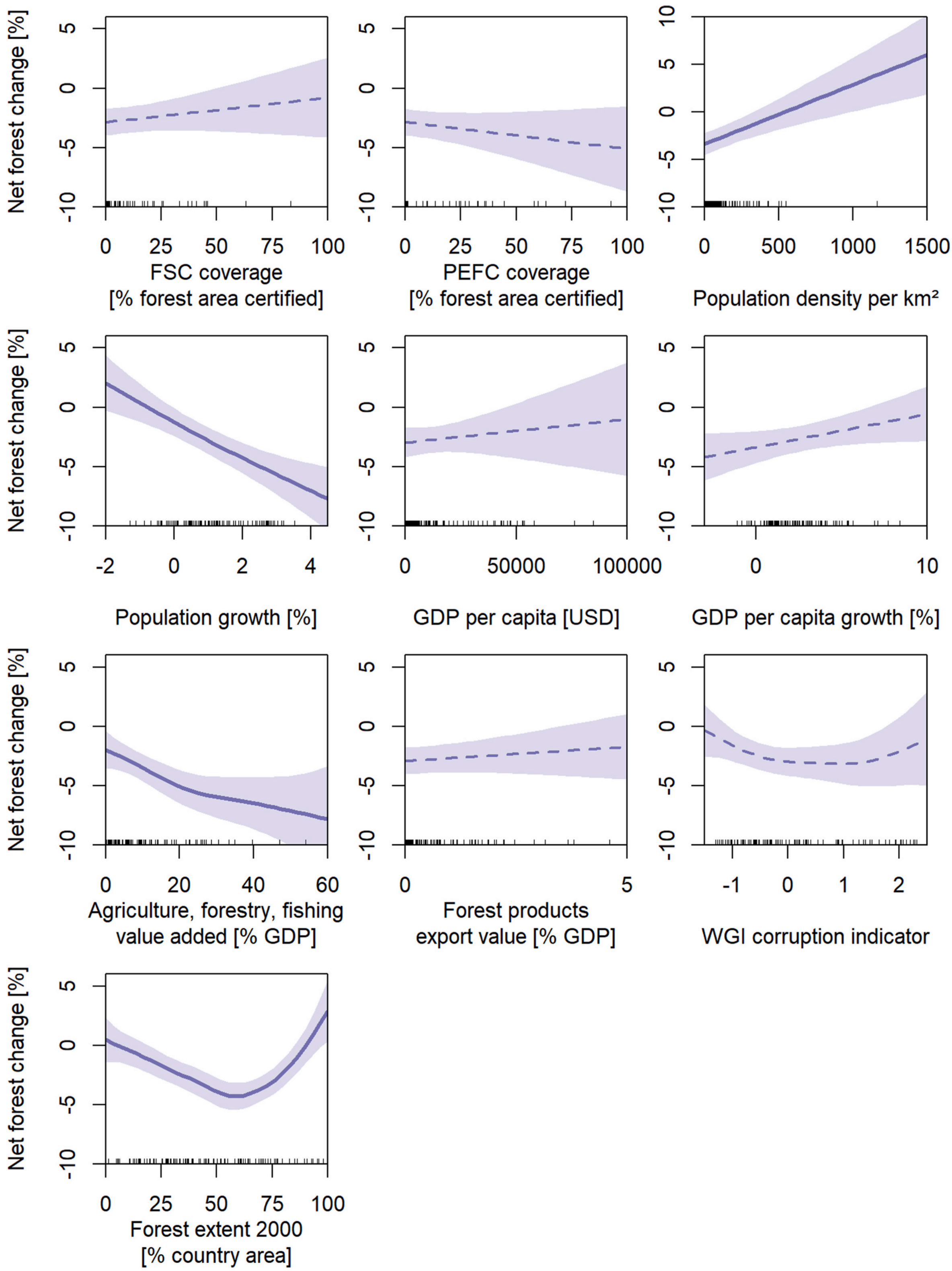

Fig. 5. Summed effect plots for the generalised additive model (GAM) using the Potapov dataset (Potapov et al., 2022). It comprises the net forest change over a 20-year period. Summed effect plots show the effect of each independent variable on the outcome variable while other predictors are set to median value or reference level. Significant variables are shown with solid, non-significant variables with dashed lines. Light purple area represents 95% confidence intervals. Rug at plot bottom shows distribution of data.

whereas lower population growth corresponded with reduced temporary forest loss and net forest change (Figs. 4 and 5). The lagged forest loss variable reached significance in the first and second GAMs, where countries with high forest loss in previous years also experienced high forest loss in subsequent years (Figs. 3 and 4). Forest extent was significant in the third GAM, exhibiting an initial decline in net forest change as forest extent approached 50% of the country's area, followed by an increase in net forest change beyond this threshold (Fig. 5).

5. Discussion

5.1. Certification does not reduce forest loss at national scale

No evidence was found that FSC or PEFC forest management certification reduced total tree cover loss or deforestation, nor did certification reduce temporary loss attributed to forestry operations in managed and plantation forests. Consequently, Hypothesis H1 that countries with a higher share of certified forest area experience lower rates of permanent or temporary forest loss was rejected. No difference in effectiveness was identified between FSC and PEFC; both schemes were positively associated with temporary forest loss attributed to forestry operations. Therefore, Hypothesis H2 that the higher stringency of FSC (as outlined in Section 2.1) leads to stronger effects than PEFC was also rejected.

This analysis, covering more than 113 countries, contributed to a growing body of literature suggesting that forest management certification has limited measurable impact on forest loss at the global or national scale. Komives et al. (2018), in their systematic review, concluded that most studies using remote sensing and robust empirical designs do not detect statistically significant effects of FSC certification on forest loss. For example, Blackman et al. (2018) used a quasi-experimental approach combining propensity score matching and difference-in-differences estimation to compare deforestation rates in FSC-certified and comparable non-certified forest areas in Mexico. They found no significant effect of certification between 2000 and 2012 on deforestation. Similarly, Panlasigui et al. (2018) employed panel regression with pixel-level matching to control for observable and unobservable heterogeneity in forest conditions across Cameroon, finding that FSC certification reduced forest loss only in one out of four regions studied by a marginal 0.03%. Rico et al. (2018) combined panel regression and matched pixel-level analysis to assess the impact of FSC certification in Peru, showing a minor effect (0.1% forest loss reduction) in just one of three regions.

The findings of the present study were also consistent with those of Yamamoto and Matsumoto (2022), who analysed the effect of FSC and PEFC certification on forest loss across multiple countries using a global panel dataset and linear regression. They found no significant association between certification and forest loss, based on national-level certification coverage and Hansen's global tree cover loss dataset. While the present study adopted a similar macro-scale approach, it extended their work by incorporating more recent data (2005–2019) and applying generalised additive models (GAMs) to better capture nonlinear effects and improve model flexibility.

The lack of significant associations between FSC or PEFC certification and reduced forest loss observed in this study contrasts with findings from previous analyses based on FAO's Global Forest Resources Assessment (FRA) data (Boubacar and Sissoko, 2025; Damette and Delacote, 2011). This discrepancy likely stems from fundamental differences in data sources and forest definitions. FRA relies on self-reported national statistics and applies a land-use-based definition of forest, meaning that areas remain classified as forest even after logging, provided they are designated for continued forest use (Carter et al., 2023). As a result, clear-cutting within certified areas may not be recorded as deforestation in FRA data, particularly if replanting is anticipated. In contrast, this study used data published via GFW which is based on independent, consistently applied satellite observations of tree cover loss. GFW data are globally comparable, reducing variability introduced by national reporting (Carter et al., 2023). Furthermore, FRA data may obscure forest degradation and plantation expansion, and often reflect optimistic policy targets rather than observed outcomes (Grainger, 2008; Keenan et al., 2015; Sloan and Sayer, 2015). Consequently, using FRA data may overestimate the positive effects of certification, whereas GFW provides a more transparent and ecologically meaningful basis for assessing certification's impact on forest ecosystems.

5.2. Explaining limited national-scale effects of certification

Several factors might explain why forest management certification had limited measurable effects on deforestation at the national level. Similar to Yamamoto and Matsumoto (2022), the study acknowledges that institutional, legal, and contextual factors influence both forest outcomes and the efficacy of certification schemes. Forest management certification was predominantly implemented in the Global North (Fig. 1), where institutional frameworks are stronger, and deforestation rates lower (Auld et al., 2008; Bösch, 2025; Marx and Cuypers, 2010). In these cases, reverse causality might be at play, with stronger national governance and legal frameworks ensuring forest protection and generating a self-selection bias into certification (Gibson et al., 2000; Rayner et al., 2010). As a result, the measurable impact of certification on reducing illegal or permanent forest loss was limited in such settings. The present study's finding that certification does not significantly reduce permanent forest loss at the global scale should therefore be interpreted with caution. Certification might yield greater effects in tropical forest countries with higher baseline deforestation, but uptake in these contexts was low due to high transaction costs and weaker governance (Bösch, 2025; Durst et al., 2006; Sommer, 2017, 2018).

Second, forest management certification schemes were designed specifically for managed forests and sustainable forest management practices, rather than for strictly protected areas. Consequently, temporary forest loss (e.g., driven by sustainable forestry operations such as selective logging or ecological silvicultural practices) is an expected component within certified forests and does not necessarily indicate degradation. Additionally, temporary loss can result from natural disturbances like wildfires, insect outbreaks, or windthrow, which are beyond the scope of certification to control. This complicates the interpretation of temporary forest loss as an indicator of certification effectiveness. Incorporating forest management and forest disturbance specific control variables (e.g., share of production forest, wildfire incidence) might better capture these nuances but such data remain limited or inconsistent globally, posing challenges for macro-scale analyses like the present study.

5.3. Data and methodological constraints

The limited evidence of forest management certification reducing forest loss at national scale might partially be attributed to methodological limitations, mostly attributed to data constraints. The present study was conducted at the country level, which might obscure regional or site-specific impacts of certification, particularly where certified areas represent a small fraction of national forest area. Thus, the absence of detectable effects at the national scale cannot be interpreted as evidence that certification is universally ineffective. Instead, it underscored inherent limitations of global observational studies in detecting potentially meaningful but context-specific certification outcomes. Neither FSC nor PEFC provided precise georeferenced data, which precluded the use of spatially explicit impact evaluation methods such as matched pair analysis commonly applied in recent studies at subnational levels. As a result, the study relied on aggregate national-level certification coverage, which might dilute or obscure the effects of certification in countries where coverage is low or highly concentrated.

Another methodological limitation related to the selection of control variables. Although aligned with prior macro-scale analyses (e.g., (Damette and Delacote, 2011; Dröge et al., 2024; Yamamoto and Matsumoto, 2022), the selection was constrained by data availability across the 122 countries included in the analysis. While the selected control variables account for drivers commonly related to forest loss, such as economic and population growth, they might not adequately capture governance dimensions central to sustainable forest management (e.g., tenure security, rule enforcement, stakeholder engagement) as such data was not available.

Finally, the use of lagged deforestation rates in the panel models helped to account for temporal autocorrelation, but might also absorb persistent effects of earlier certification, potentially underestimating long-term impacts. Sensitivity analyses excluding the lag term yielded slightly reduced model fit but similar results, suggesting robustness. Future studies need finer spatial data to disentangle the outcomes of forest management certification which will then also allow the exploration of more advanced panel econometric techniques, such as dynamic models or instrumental variable approaches, and the use of revised set of control variables.

5.4. Environmental co-benefits beyond forest loss reduction

Despite the absence of significant effects on forest loss at the national level, prior research showed that certification deliver important environmental co-benefits at the local scale. Kalonga et al. (2016) using a quasi-experimental design in Tanzania showed that FSC-certified forests had higher tree species richness, density, and diversity. A global meta-analysis by Matias et al. (2024) found that FSC certification was positively associated with mammal abundance, tree and shrub species richness, and the presence of threatened species, although overall biodiversity effects were taxon-specific and often neutral. Zwerts et al. (2024) observed greater abundance of large mammals in FSC-certified forests in Gabon and the Republic of Congo. Particularly critically endangered species, such as the African forest elephant *(Loxodonta cyclotis)* and the western lowland gorilla *(Gorilla gorilla),* benefitted from certification (Zwerts et al., 2024). In a separate study in Gabon, however, the soundscape saturation did not differ, indicating a similar richness of vocalising species in certified and non-certified forests (Zwerts et al., 2022)

According to a review by Burivalova et al. (2017), certified forests and forests under reduced-impact logging outperformed conventional forestry in 76% of environmental outcomes reviewed, particularly for biomass retention, road density, and conservation set-asides (e.g., Imai et al., 2009; Medjibe et al., 2013; Sollmann et al., 2017). These findings suggest that certification might not reduce forest loss when measured at country level but can still produce environmental gains within certified concessions.

6. Conclusions

Deforestation and forest degradation remain key drivers of global biodiversity loss and greenhouse gas emissions. Forest management certification schemes, such as those of the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC), evolved to mitigate these impacts by promoting sustainable forestry practices, including the protection of high conservation value areas, designation of conservation set-asides, and implementation of restoration measures. However, despite their growing uptake, particularly in the Global North, robust empirical evidence on their effectiveness in reducing forest loss remained limited and mixed.

This study presented the most comprehensive global analysis to date on the relationship between forest certification and forest loss. Using annual data from more than 113 countries across a 15-year period, and accounting for both permanent deforestation and temporary forest removal associated with logging, no statistically significant association was found between national-level certification coverage and reductions in forest loss. This conclusion held for both FSC and PEFC, with no systematic difference in effectiveness between the two schemes. Methodologically, this study advanced prior work by (1) distinguishing permanent and temporary forest loss, (2) extending the time horizon of analysis, and (3) applying flexible generalised additive models (GAMs) to evaluate national-level effects globally.

At the same time, these results were interpreted with caution given key limitations. Most notably, the absence of data on certified forests at high spatial resolution restricted the ability to conduct subnational or concession-level impact evaluations. As a result, any regional environmental benefits of certification might be obscured when evaluated at country level, particularly where certification coverage remained low or highly clustered. Furthermore, the study’s reliance on macro-level control variables constrained by global data availability might not fully capture governance or enforcement factors central to the success of certification.

These findings nevertheless carried several implications for policy and research. First, while certification conferred other environmental and social benefits not captured in tree cover metrics (e.g., enhanced biodiversity) it appeared insufficient on its own to reverse forest loss trends at national scale. Second, achieving international targets such as the COP26 pledge to halt deforestation by 2030 cannot be achieved by individual instruments alone but will require additional, more comprehensive and coordinated strategies that go beyond voluntary certification, but to which voluntary sustainability standards as FSC and PEFC can contribute (Cosimo et al., 2024; Macdonald et al., 2024). This might include jurisdictional approaches, financial incentives such as REDD+, market access regulations like the EU Deforestation Regulation (EUDR), and strengthened national forest governance.

Juridical approaches are emerging collaborative, multi-stakeholder efforts to achieve various sustainability goals across an entire administrative area such as a district, province, or country, by aligning public policies, private sector actions, and community initiatives within that jurisdiction (Macdonald et al., 2024). These instruments offer avenues to tackle local complex root causes of deforestation through a systemic approach. In addition, initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation), developed under the UNFCCC, can provide financial incentives and technical support to countries that reduce forest emissions, helping to shift incentives toward forest conservation. Furthermore, market access regulations like the EUDR prohibit the import of deforestation-linked commodities and require companies to prove legal and sustainable sourcing, creating market-based incentives to refrain from deforestation (Schilling-Vacaflor and Gustafsson, 2024). Lastly, strengthened national forest governance, including law enforcement, land tenure clarity, and inclusive decision-making, is essential for effective implementation of any effective anti-deforestation strategy. Together, these instruments could potentially offer complementary pathways to address deforestation (Schleifer and Fransen, 2022).

Finally, greater transparency from certification schemes, particularly in making locations of certified areas at higher spatial resolution publicly available, is needed. It will be essential for future studies enabling rigorous evaluations and is, moreover, crucial to ensure the credibility and accountability of certification schemes in the years ahead.

CRediT authorship contribution statement

Saskia Dröge: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Charline Depoorter:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Axel Marx:** Writing – review & editing, Supervision, Methodology. **Bart Muys:** Writing – review & editing, Supervision, Methodology.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors used AI assisted tools (ChatGPT-4) to enhance writing and clarity of the manuscript text during the revision process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clpl.2025.100104.

Data availability

The data that has been used is confidential.

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