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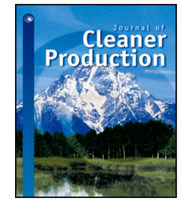

The effect of forest certification on conservation and sustainable forest management

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ABSTRACT

This study examined the effect of sustainable forest management schemes on forest conservation using remote sensing data on forest change. We applied fixed effect models focusing on two major sustainable forest management schemes: the Forest Stewardship Council and the Programme for the Endorsement of Forest Certification. Contrary to the findings from previous research, the regression results showed that expansion of the sustainable forest management area was uncorrelated with forest loss when controlling for the fixed effects of country and time. These findings were robust to the different definitions of a forest and country groups' OECD membership. Our estimations suggested that sustainable forest management increased forest loss in non-certified forest areas, indicating the leakage of forest loss from certified to non-certified forest areas. This implies that leakage effects should be considered when implementing forest management or protected forest schemes.

1. Introduction

Globally, deforestation has had major environmental and socioeconomic impacts, including climate change and biodiversity loss. The Intergovernmental Panel on Climate Change (IPCC) (2014) indicated that emissions from agriculture, forestry, and other land use sectors accounted for a quarter of all greenhouse gas emissions, mainly due to deforestation and agricultural emissions from livestock, soils, and nutrient management. In 1990, the world had 4128 million hectares (ha) of forest; this decreased to 4059 million ha in 2020 (FAO, 2020). Deforestation reduced the global share of forest area from 31.6% in 1990 to 30.6% in 2015, an annual net loss rate of 0.13%. Various measures have been introduced to prevent deforestation and/or implement sustainable forest management, including the United Nations Forest Forum, national efforts to reduce emissions from deforestation and forest degradation, conservation measures, sustainable forest management, the enhancement of forest carbon stocks (REDD+), the Sustainable Development Goals (SDGs), and the Montreal Process. Forest certification is one such initiative for sustainable forest management and includes Forest Stewardship Council (FSC) certification and the Programme for the Endorsement of Forest Certification (PEFC), as described in detail in Section 3.

This study examined the relationship between certification and forest loss using panel data analysis with country and year fixed effects models to evaluate whether forest management schemes promote global forest conservation. Although the previous literature relied on the cross-sectional approach, partly due to the limited data on forest loss (see Section 2), we regressed the forest cover loss on the area of certification along with country and year dummy variables and other observed economic characteristics by using the latest panel data on global forest loss as observed through satellite imagery. Controlling for the country and year fixed effects, the effects of the FSC and PEFC were identified by the intra-country variation in the change in forest cover. This approach provides more credible evidence regarding the effects of certification compared with previous approaches that relied on a subset of geographic areas (Brandt et al., 2014, 2016; Blackman et al., 2018) and a cross-sectional approach (Damette and Delacote, 2011). Our approach is essential for reliable estimation using the difference-in-differences method, which has been adopted in forest conservation studies such as those by Blackman (2013), Jones and Lewis (2015), Alix-Garcia and Gibbs (2017), and Simmons et al. (2018).

The remainder of this paper is structured as follows. Section 2 presents the literature review on forest management and the effects of certification. Section 3 briefly describes the FSC and PEFC schemes. The methodology—including the framework and data—is explained in Section 4. The results are presented and discussed in Section 5. Finally, Section 6 concludes with the key policy implications.

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[1] As each study examined various factors contributing to deforestation, citations have only been provided on the main topic of each study.

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2. Literature review

Since the 1990s, a variety of studies have analyzed the factors affecting deforestation from different perspectives and in different geographical areas, with most of them applying panel data regression. For example, Cropper and Griffiths' (1994) work, one of the earliest studies in this field, focused on the relationship between deforestation, on the one hand, and population and economic development, on the other, in Africa, Latin America, and Asia. Many other studies have also tested these two variables, although the effectiveness of these factors in explaining deforestation is mixed (Barbier and Burgess, 2001; Barbier, 2004; Barbier et al., 2005; Scrieciu, 2007; Culas, 2007; Arcand et al., 2008; Damette and Delacote, 2011; Culas, 2012; Damette and Delacote, 2012; Andrade de Sá et al., 2013; Faria and Almeida, 2016; Leblois et al., 2017; Panlasigui et al., 2018). Other factors that have been found to significantly affect deforestation are agricultural land and production (Barbier and Burgess, 2001; Barbier, 2004; Hosonuma et al., 2012; Gaveau et al., 2016), trade (Barbier et al., 2005; Faria and Almeida, 2016; Leblois et al., 2017), institutions (Culas, 2007), distance to settlement area (Mon et al., 2012; Getahun et al., 2013), and road (Newman et al., 2014).[1] Most recently, Leblois et al. (2017) evaluated the drivers of deforestation by updating deforestation data using the remote sensing data developed. Their panel data analysis of developing countries during 2001–2010 found that economic development, agricultural activity, and population pressure were the important drivers of deforestation. They also found that trade such as agricultural exports played a crucial role in driving deforestation, although the effect varied with the country's characteristics.

Empirical studies have also examined the relationship between forest protection policy and the prevention of deforestation. Haruna et al. (2014) showed that the impacts of protected areas on deforestation varied across space and time and discussed the importance of forward-looking plans in Panama. Robalino et al. (2015) evaluated the effect of interactions in forest conservation policies (protected areas and payments for ecosystem services) on deforestation in Costa Rica. The review paper of 35 studies by Busch and Ferretti-Gallon (2017) suggested that protected areas were consistently associated with lower deforestation. Nolte et al. (2013) found that strictly protected areas consistently avoided more deforestation than sustainable use areas, and indigenous lands were particularly effective at avoiding deforestation in locations with high deforestation pressure. Heino et al. (2015) indicated that the effects of protected areas on preventing deforestation were limited and differed by country.

Although these studies on protected forest areas have been carried out at national, regional, or global scales, research focusing on sustainable forest management remains limited, and the results are often inconclusive, leading to debate about the effects of forest management schemes on deforestation. At the local scale, previous studies have found that sustainable forest management, including the FSC and PEFC, is unlikely to be correlated with deforestation. Brandt et al. (2014) evaluated the relationship between investment sources and deforestation from 2000 to 2010 in Congo, where sustainable forest management was introduced in 2000. One of their findings was that such a policy did not always mitigate the degradation of tropical production forests. Similarly, Brandt et al. (2016) analyzed deforestation and timber production in Congo after the sustainable forest management policy was implemented and found that the policy did not reduce deforestation. Rather, it could potentially be associated with higher deforestation because of links with higher legal timber production, foreign capital, and international timber demand. Blackman et al. (2018) found no evidence that FSC certification affected deforestation in Mexico. Damette and Delacote (2011) found that the FSC and PEFC negatively affected deforestation (i.e., higher FSC/PEFC ratios decrease deforestation) at a global scale. They regressed deforestation on the FSC or PEFC (as a ratio of the certified area to the total forest area) and other control variables such as timber harvest volume/values, gross domestic product (GDP), GDP growth, population density, institution, and forest cover, using a multiple regression model targeting countries that introduced the FSC and PEFC. However, this estimate was subject to some shortcomings, such as the use of multiple regression analysis with old, single-year data. Thus, it is important to further understand the relationship between deforestation and forest management schemes at the global scale by using a recent multi-year dataset. Overall, the existing literature indicates that the effects of forest management schemes on forest loss remain contentious.

3. Sustainable forest management

Several forest certification systems have been established to improve sustainable forest management. Under such systems, independent organizations certify that forests or organizations satisfy certain standards from the perspectives of the environment, economy, and society. Certified forests are a worldwide phenomenon. However, the rate of certification is higher in European countries (Figs. 1 and 2). Such schemes contribute to the distribution of wood and wood products from certified forests, thus improving sustainable forest management. Forest certification systems include global standards such as the FSC and PEFC, which are the focus of this study, and domestic or local use (Rafael et al., 2018).

In 1993, environmental non-governmental organizations, led by the World Wildlife Fund, and other non-state actors established the FSC in Germany as an instrument to promote sustainable forest management through certification. The FSC is a global forest certification system established for forests and forest products. Certification authorities approved by the FSC examine forests with regard to 10 principles, including environmental impact, economic and social impact, and indigenous people's rights, as well as associated criteria that form the basis for all FSC forest management standards and certification.[2] To cover various forests and forest owners, the scheme has been modified so that the evaluation procedures for small organizations and country-based standards correspond to the national or regional situation. FSC International sets the framework for developing and maintaining international, national, and sub-national standards. The framework aims to ensure that the process for developing FSC policies and standards is transparent, independent, and participatory. As of December 2021, the total certified forest area worldwide is 230,080,286 ha (covered by 1801 certificates in 82 countries) (FSC International, 2021).

The PEFC was established in 1999 in Europe by the national forestry organizations of 11 countries, in response to the specific requirements of small and family forest owners, as an international umbrella organization providing independent assessment, endorsement, and recognition of national forest certification systems (PEFC International, 2018). Thus, in contrast to the FSC, the PEFC is a mutual recognition scheme. Although both schemes aim to enhance sustainable forest management, their approval procedures differ. FSC-certified forests are based on an international standard comprising the abovementioned 10 principles (FSC International, 2021), whereas the PEFC certifies independent forest management schemes in over 30 countries (PEFC International, 2018). The PEFC responded to the need for a mechanism enabling the independent development of national standards tailored to the political, economic, social, environmental, and cultural realities of the respective countries, while simultaneously ensuring compliance with internationally accepted requirements and global recognition.

PEFC could provide forest certification based on the requirements of the national sustainable forest management system. However, all national sustainable forest management systems must also meet several requirements, including: (1) maintenance, conservation and enhancement of ecosystem biodiversity, (2) protection of ecologically important

[2] Based on the 10 principles, the FSC aims at environmental effects, social benefits, and economically viable management. See https://fsc.org for details.

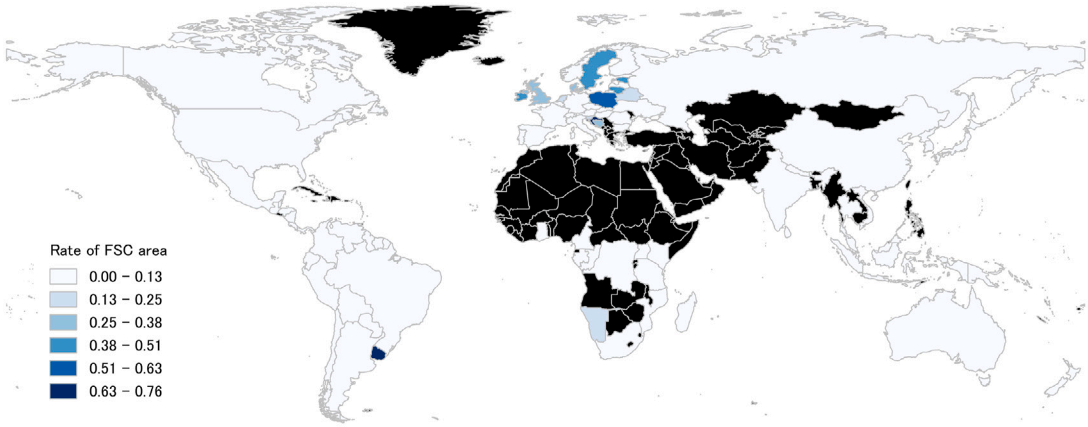

Fig. 1. Rate of FSC-certified forest area by country.
Source: UNEP (2018b).

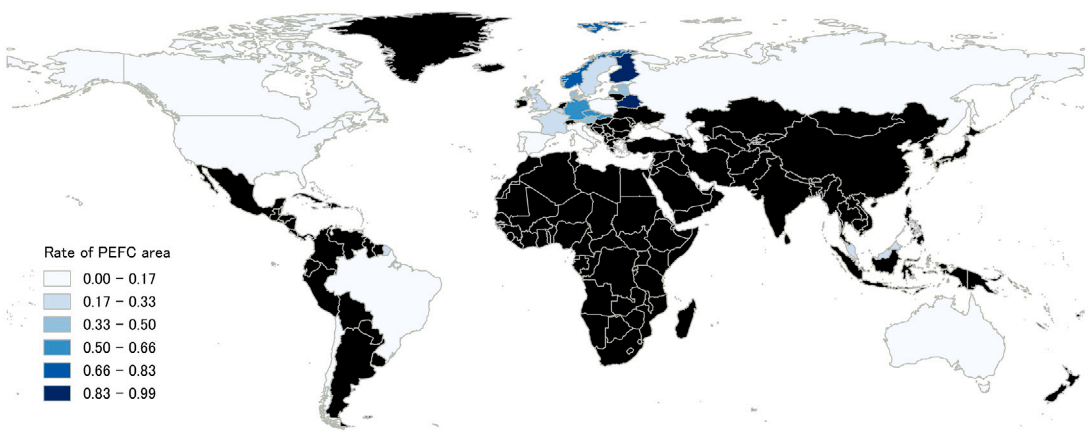

Fig. 2. Rate of PEFC-certified forest area by country.
Source: UNEP (2018b).

forest areas, and (3) provisions for consultation with local people, communities and other stakeholders.[3]

Countries outside Europe have also participated in this scheme since 2011. The PEFC is thus the largest forest certification system worldwide. At present, more than 313 million ha of forest area (with 49 national members and 39 endorsed national certification systems) are managed in compliance with the PEFC's internationally accepted sustainability benchmarks. In mid-2017, 431.4 million ha of forests had been certified by either the FSC or the PEFC standards, of which 71.1 million ha (or 16.5%) were double certified. Hence, despite their differences, the introduction of these forest certifications is considered a sustainable mechanism for protecting and managing forest areas.

4. Methodology

4.1. Empirical framework

We analyzed the effects of forest certification (i.e., the FSC and PEFC) on forest loss using a regression model with panel data. The following model was considered(Eq. (1)):

$$Loss_{it} = \beta_0 + \beta_1 Certification_{it} + \beta_2 X'_{it} + \theta_i + \zeta_t + \epsilon_{it}, \quad (1)$$

[3] See https://pefc.org/standards-implementation/standards-and-guides for details.

where $Loss_{it}$ is the net forest loss observed in country i in year t; $Certification_{it}$ is the certified forest rate given by the ratio of certified forests to forest area (FSC, PEFC, or total of the two); X_{it} is a vector of the observed characteristics of countries (GDP, GDP per capita, population, agricultural value, agricultural land, and institutional quality); θ_i is a country fixed effect; ζ_t is a year fixed effect; ϵ_{it} is an error term that is uncorrelated with the other variables; β_0 is a constant; and β_1 and β_2 are coefficients. The country fixed effect captures unobserved factors such as the demand for timber and other forest management in a country, whereas the year fixed effect captures factors that affect forest loss equally across the country in each year. For example, global demand for agricultural and logged timber products may be captured within the year fixed effect.

In addition, to estimate the effects of forest certification on forest loss in non-certified forests, the ratio of forest loss in non-certified forest areas, calculated by $Loss_{it}/Non\text{-}certified\ forest\ extent_{it}$ was applied, to Eq. (1) as a dependent variable.

The first analysis evaluated the effect of forest certification on the area of forest loss. The second analysis, which used the ratio of forest loss in non-certified forest areas as the dependent variable, evaluated how the change in forest certification affected forest loss in non-certified areas. The estimate captured the effects of the expansion of certified areas on forest loss outside the certified area. Furthermore, we implemented robustness checks, as explained in Sections 5.2 and 5.3.

The explanatory variables in our estimation were the ratio of FSC and PEFC area to country forest area (*FSC*, *PEFC*, or *Total certified*),

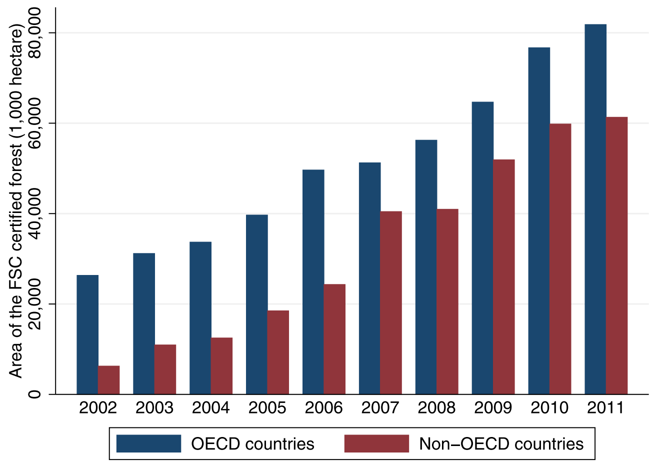

Fig. 3. FSC-certified forest area in OECD and non-OECD countries.
Source: UNEP (2018a).

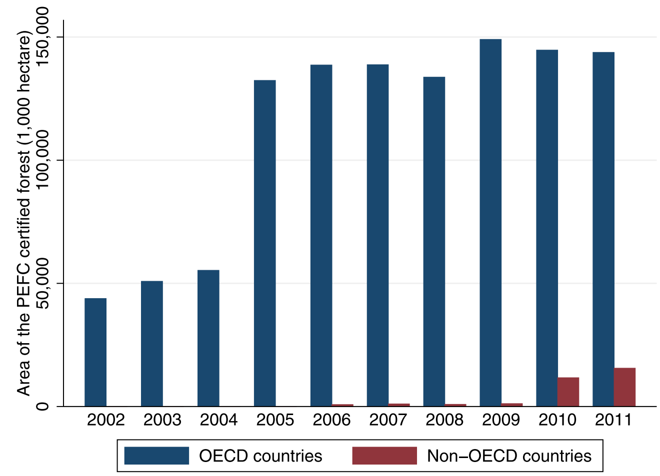

Fig. 4. PEFC-certified forest area in OECD and non-OECD countries.
Source: UNEP (2018b).

GDP (*GDP*), GDP per capita (*GDP per capita*), population (*Population*), agricultural value added to country GDP (*Agricultural value*), ratio of agricultural land to country area (*Agricultural land*), forest area in 2000 (*Forest extent*), and institutional quality (*Institutional quality*), which were selected based on previous studies. The variable selection followed Damette and Delacote (2011), who used country characteristics such as GDP, institutional quality, and population density as their explanatory variables to analyze the effects of certifications in the year 2005.

4.2. Data

Table 1 provides the summary statistics of the variables used for analysis. The data on forest certification area were obtained from the United Nations Environment Programme (UNEP, 2018a,b). The changes in certified areas and forest loss during the study period are reported in Figs. 3–5, respectively. Both the FSC and the PEFC's certification areas have increased over time, especially in the Organization for Economic Co-operation and Development (OECD) countries (see Figs. 3 and 4).

We considered the characteristics of each country that potentially affect forest management as the other control covariates. The variables are reported in Table 1. The GDP and GDP per capita are provided in real terms based on 2000 constant US dollars. Population and the agricultural demand variables act as proxy variables to reflect the forest development pressure. Institutional quality may be related to the country's enforcement level. *GDP* and *GDP per capita* are provided in real terms based on 2000 constant US dollars. The institutional quality data provided by Freedom House (2018) identify the levels of institutions' political rights and civil liberties on scales of 1 to 7 (1 = good and 7 = poor), respectively. We summed these two values for our estimation; thus, the minimum and maximum levels of institutional quality were 2 and 14, respectively.

The data on forest loss and forest area were obtained from the satellite observations provided by Hansen et al.'s (2013) dataset, which provides information on the global tree cover extent in the year 2000 and the subsequent forest loss 2001 onward.[4] This is a compilation of records of global forest loss and extent at a spatial resolution of 30 meters as observed from multi-spectral satellite images. For 30-meter pixels, the tree cover was defined as that comprising vegetation taller than five meters.[5] The dataset reported whether a specific pixel experienced forest loss (i.e., vegetation had been cleared in the pixel) in each year from 2001 to currently available until 2019 (Fig. 5 shows the deforestation rate by country from 2002 to 2011).[6] This unique dataset has been used in various research fields since its publication: environmental science (Bailis et al., 2015; Zhu et al., 2016; Romijn et al., 2018), ecology (Gonzalez et al., 2016; Pfeifer et al., 2017), agriculture (Dias et al., 2016; Abrahão and Costa, 2018), geography (Johnson, 2015; Macedo et al., 2018), economics (Alisjahbana and Busch, 2017; Berazneva and Byker, 2017; Chervier and Costedoat, 2017; Damania et al., 2017; Blackman et al., 2018; Gibson, 2018), political science (Cook et al., 2017), health science (Galway et al., 2018), and social sciences (Busch et al., 2015; Romijn et al., 2018). Among related studies, Richards and Friess (2016) used this dataset to identify the mangrove forest loss in the Southeast Asian countries. Identifying the factors of mangrove deforestation, they found country-specific differences. Similarly, Yamamoto et al. (2019) used the same forest data combined with socioeconomic data on agricultural households and found that deforestation decreased agricultural productivity in Indonesia. The dataset allowed us to estimate the trend of forest cover change by country. Table 2 shows the area of deforestation for OECD and non-OECD countries between 2002 and 2011. We considered a pixel with more than 10% of tree cover as a forest. This assumption may overestimate the effects of sustainable forest management because 10% is the least restrictive definition. Other definitions of forest have been tested later in our estimation.[7]

Hansen et al.'s (2013) dataset also reports the amount of vegetation gain in each country and year, allowing the consideration of the gross and net forest loss. In our analysis, we employed the net forest loss as the dependent variable, considering countries' forest loss and forest gain. The net forest loss in a year is the difference between the forest loss and the forest gain in each country for that year.[8] In the subsequent analysis, we define the gross forest loss as the forest cover loss.

[4] See https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.4.html.

[5] The Food and Agriculture Organization (FAO) defines a forest as land with tree crown cover of more than 10 percent and an area of more than 0.5 hectares, in which trees should attain a height of at least five meters (FAO, 2020). We tested whether the observed effects varied for different definitions of a forest by analyzing a range of 15–75 percent tree cover, as shown in subsection 5.3.

[6] This figure shows the gross forest loss and does not consider forest gain.

[7] Hansen's dataset offers pixel-based information for a tree cover range of 10%–75%.

[8] It was not possible to identify primary or secondary forest areas from the data for the year 2000. This means that the forest area reported in 2000 included not only primary and secondary (naturally regenerated) forests but

Table 1
Data sources and summary statistics.

Explanatory variables	Mean	Std. Dev.	Min.	Max.	Data sources
net-Loss (hectare)	107,530.5	404,508.9	0	3,926,871	Hansen et al. (2013)
Forest extent (hectare)	2.69e+07	9.03e+07	13	8.79e+08	Hansen et al. (2013)
Total certified (% country forest area)	0.022	0.095	0	0.959	United Nations Environment Programme[b]
FSC (% country forest area)	0.020	0.086	0	0.754	United Nations Environment Programme
PEFC (% country forest area)	0.002	0.032	0	0.819	United Nations Environment Programme
GDP[a]/1000	1,250,730	4,740,475	1,807,192	66,800,000	World Development Indicators[c]
GDP per capita[a]	5826	7932	194	49,616	World Development Indicators
Population /1000	40,501	157,208	47	1,344,130	World Development Indicators
Agricultural value (% country GDP)	16.07	13.408	0.037	79.042	World Development Indicators
Agricultural land (% country area)	40.031	21.577	0.449	85.287	World Development Indicators
Institutional quality	7.371	3.616	2	14	Freedom house[d]

The number of observations is 1579 across 165 countries, implying that the panel data is unbalanced.
[a]*GDP* and *GDP per capita* are based on 2000 constant US dollars.
[b]United Nations Environment Programme: https://geodata.grid.unep.ch/.
[c]World Development Indicators: https://databank.worldbank.org/source/world-development-indicators.
[d]Freedom House: https://freedomhouse.org/report/freedom-world.

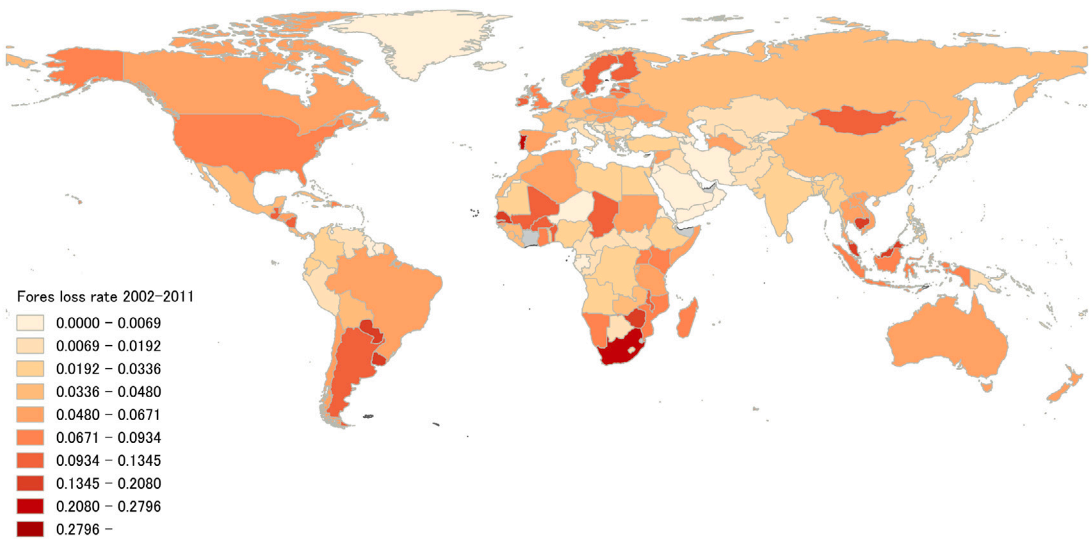

Fig. 5. Gross forest loss rate by country from 2002 to 2011.
Source: Hansen et al. (2013).

Using these data, we constructed country-level forest loss from 2002 to 2011. The forest loss data were merged with the control variables by country, corresponding to the year. Although it was possible to aggregate the deforestation data collected from satellite observations at various scales, we chose to estimate the effects at the country level for two reasons. First, district-level estimation may suffer from the effects of leakage. Once a forest area is certified, the forest loss may migrate to forests around the certified area.[9] Second, we wished to minimize a potential attenuation bias due to data quality and a lack of data. It is more difficult to obtain explanatory variables at the district level, and this could lead to unstable estimates.

5. Results

5.1. Effects of certification on forest loss

Table 2 presents the regression results.[10] The estimation results without controlling for the country and year fixed effects are shown in columns (1), (4), and (7) for total certification, FSC certification, and PEFC certification, respectively. The coefficients of total certification and FSC are negative and statistically significant at the 1% level, whereas that of PEFC is negative but not statistically significant. These results are consistent with the findings of a previous study (Damette and Delacote, 2011), which showed that the FSC had a greater effect on mitigating forest loss than the PEFC.[11] However, these negative relationships between forest loss and the expansion of certified forest area need not imply that certification had a causal effect on the mitigation of deforestation because the estimations could have been affected by unobserved country characteristics and annual world trends related to the agriculture and forestry sectors.

We further controlled for these effects by introducing dummy variables related to countries and years.[12] Using the country and year fixed effects variables, we explored the causal relationship between forest certification and the mitigation of forest loss. As a result, the coefficients of certification were no longer statistically significant, as shown in columns (2) for total certification, (5) for FSC certification, and (8)

also planted forests, such as plantations for agricultural production that existed in 2000.

[9] The leakage could also happen across countries. We tested this bias with an estimate of the effects of certification at the regional level in Section 5.4.

[10] Table A.1 presents the estimation results for the logarithm of forest loss and the ratio of forest loss as the dependent variables, respectively. There are no significant differences in the certification effects.

[11] Damette and Delacote (2011) used multiple regression and found that the mitigation of forest loss was correlated with the FSC and not the PEFC.

[12] This study employed unbalanced panel data. All the results were robust when the estimates were restricted to a strongly balanced sample. The results are available upon request.

Table 2
Effects of sustainable forest management on forest loss.

Certification type	Total			FSC			PEFC		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Total certified	−26 846.911***	−10 671.437	−8546.858						
	(9385.506)	(15 485.869)	(14 071.124)						
FSC				−39 476.349***	−19 887.581	−9318.552			
				(11 270.492)	(16 201.537)	(20 838.184)			
PEFC							−10 157.247	−5647.929	−8536.507
							(10 722.817)	(20 380.595)	(20 040.111)
GDP/1000	0.003***		0.015*	0.003***		0.015*	0.003***		0.015*
	(0.001)		(0.008)	(0.001)		(0.008)	(0.001)		(0.008)
GDP per capita	−1.717***		−2.675	−1.794***		−2.720	−1.855***		−2.746
	(0.467)		(2.683)	(0.476)		(2.686)	(0.474)		(2.652)
GDP per capita squared/1000	0.015***		0.016	0.014***		0.016	0.015***		0.016
	(0.004)		(0.023)	(0.004)		(0.023)	(0.004)		(0.023)
Population/1000	−0.094***		0.011	−0.095***		0.013	−0.094***		0.013
	(0.034)		(1.438)	(0.034)		(1.437)	(0.034)		(1.439)
Agricultural value	−144.172		1285.942*	−168.179		1279.677*	−145.141		1284.821*
	(162.789)		(717.279)	(162.482)		(716.348)	(162.770)		(716.659)
Agricultural land	206.410*		3696.247**	216.283**		3701.702**	196.787*		3695.820**
	(106.561)		(1456.775)	(107.351)		(1459.759)	(106.276)		(1457.679)
Forest extent	0.003***		0.033*	0.003***		0.033*	0.003***		0.033*
	(0.000)		(0.017)	(0.000)		(0.017)	(0.000)		(0.017)
Institutional quality	−5197.962***		−5405.656	−5221.542***		−5405.347	−5032.931***		−5397.615
	(1032.680)		(5847.893)	(1039.516)		(5849.679)	(1003.509)		(5845.492)
Intercept	40 467.810***	63 820.110***	−1 005 050.314**	41 148.498***	63 822.627***	−1 004 735.028**	39 551.491***	63 498.748***	−1 004 658.650**
	(10 479.924)	(5982.893)	(479 586.295)	(10 570.462)	(6197.726)	(479 600.177)	(10 359.384)	(6202.423)	(479 773.105)
Country and year FEs		✓	✓		✓	✓		✓	✓
Observation	1579	1579	1579	1579	1579	1579	1579	1579	1579
R^2	0.738	0.007	0.136	0.738	0.007	0.136	0.738	0.007	0.136

The numbers in parentheses represent standard errors clustered at the country level.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

for PEFC certification in Table 2.[13] In addition, when controlling for the observed country characteristics, the coefficients of certification were not statistically significant, as shown in columns (3) for total certification, (6) for FSC certification, and (9) for PEFC certification. The results with the fixed effects and control variables showed that the coefficients of certification were not statistically significant in any respect, indicating that the null hypothesis—that the expansion of certified forests does not affect forest loss at the country level—could not be rejected. Therefore, the negative correlation between certified area expansion and forest loss, observed in the models that did not control for the country and year fixed effects, was not a causal relationship but rather driven by unobserved country and year effects.

Among the country characteristics used as control variables, *Agricultural value* and *Agricultural land* had positive effects on forest loss (columns (3), (6), and (9) of Table 2). These results indicated that agricultural expansion led to deforestation, consistent with previous findings (Damette and Delacote, 2011). However, the coefficients of the other variables were not consistent with those of previous studies. For example, the coefficients for *Population* were not statistically significant in this study, even though population had been established as an important factor contributing to deforestation by Leblois et al. (2017).[14] This could be because the present analysis controlled for *Population* as well as *Agricultural value* and *Agricultural land*, which reflect the effects of agricultural demand or the pressure for agricultural expansion due to an increase in the country's population. As a result, *Population* was not statistically significant because of the dominant effect of the agriculture-related variables. In addition, the coefficients for *Institutional quality* were not statistically significant in our results. The effect of institutions or governance has been unclear in previous studies. For example, Leblois et al. (2017) found that institutional quality did not influence deforestation, whereas Damette and Delacote (2011) showed that institutions had an important impact on deforestation.

5.2. Robustness: regional and country status

The effects of forest certification on forest loss may differ depending on differences in factors such as the pressure driving deforestation, the regional context, and the income level. For example, Nolte et al. (2013) found that protected forests were effective in areas with high deforestation pressure. In addition, forest ecosystems support global biodiversity, with intact forests having a particularly large effect on biodiversity conservation (Morales-Hidalgo et al., 2015). Many herbivorous species are threatened by deforestation and forest degradation in tropical regions with intact forest cover (Ripple et al., 2015). Furthermore, the causes for deforestation and forest degradation are vastly different across regions. For example, commercial and subsistence hunting is a threat that leads to forest degradation in the tropics (Wilkie et al., 2011).

To address this concern, we disaggregated our estimations based on location, income level, and the subsistence of the intact forest to check the robustness of our findings in Section 5.1. Table 3 presents the estimation results for regions (temperate countries), incomes (high and low), and forest type (intact and high deforestation). Table A.2 lists the categorized countries. For the year 2000, we defined countries with a GDP per capita lower than USD1000 and higher than USD10,000 as low-income and high-income countries, respectively. In addition, we categorized the 65 countries that had an intact forest in 2000 as intact forest countries, as reported by Potapov et al. (2017). Kraxner et al. (2017) demonstrated that intact forests were located in tropical basins and boreal zones. Countries with high deforestation represented the top 30 countries identified by Global Forest Watch (2014).[15] The effects of forest certification were not statistically significant for high deforestation countries, similar to our main results (Section 5.1).

[13] The estimates without any controls addressed the multicollinearity problem. The coefficients of both certifications were not statistically significant, with or without control covariates.

[14] Population density and population growth have also been used in many studies. We tested both these variables and obtained similar results.

[15] Similar to the previous sections, we show only the variables related to forest certification here, although other variables and the country and year fixed effects have been controlled for.

Table 3
Effects across countries' categories.

Regions:	Tropics			Temperate		
Total certified	475 342.548**			4907.045		
	(182 536.315)			(7167.613)		
FSC		403 151.171			7752.615	
		(374 929.421)			(10 821.529)	
PEFC			627 922.409**			2618.521
			(297 782.839)			(7899.733)
Observation	718	718	718	799	799	799
R^2	0.312	0.310	0.312	0.305	0.305	0.305
Income:	Low			High		
Total certified	−2 668 231.238			2257.811		
	(2 566 246.498)			(12 919.833)		
FSC		−2 668 231.238			−19 295.900	
		(2 566 246.498)			(25 701.038)	
PEFC			–			14 557.372
			–			(22 660.093)
Observation	314	314		489	489	489
R^2	0.418	0.418		0.230	0.230	0.230
Forest:	Intact			High-deforestation		
Total certified	76 092.562			−280 769.583		
	(232 179.206)			(532 681.966)		
FSC		345 115.780			1 535 304.909	
		(347 100.504)			(2 274 626.986)	
PEFC			−34 888.657			−530 635.021
			(308 657.026)			(630 399.210)
Observation	575	575	575	254	254	254
R^2	0.174	0.174	0.174	0.240	0.242	0.241

The numbers in parentheses represent standard errors clustered at the country level.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
No observation shows a variation in the PEFC for a low-income country.
All regressions have been estimated using ordinary least squares (OLS) and include the country and year fixed effects as well as country characteristics such as GDP, population, agricultural value, and institutional quality.
Table A.2 lists each country.

5.3. Robustness: Defining a forest

Based on Sections 5.1 and 5.2, the FSC and PEFC, collectively and individually, were ineffective in mitigating the overall forest loss. We therefore adjusted the dependent variable, focusing on the definition of forests as an additional robustness check. Various definitions of a forest exist in terms of its vegetation coverage (see footnote 5 for detailed definitions). The United States National Vegetation Classification System defines a forest as an "area consisting of trees with overlapping crowns forming 60% to 100% cover" (Grossman et al., 1998). The forest data provided by Hansen et al. (2013) report the tree extent in an area with a tree cover percentage ranging from 0% to 100%. Therefore, we tested the robustness of the effects based on the definition of a forest by using a tree cover range of 10%–75%. The original analysis used a tree cover of 10% per pixel. The independent variables and fixed effects used in the previous analysis (see Table 2) were applied here as well.

Table 4 presents the results for the various definitions of a forest. Only the variables related to forest certification are shown as the statistical significances of the other variables were the same as in the main analysis. There are only minor differences between the findings in Table 4 and our main results (see Table 2). The coefficients for *Total certified*, *FSC*, and *PEFC* are not statistically significant for any definition, suggesting that forest certification does not tend to decrease total forest loss for any definition of a forest; this confirms the robustness of our main results.

The findings of this subsection suggest that certifications are less likely to reduce CO_2 emissions. A pixel with a lower tree cover ratio potentially includes agricultural land such as oil palm and coffee plantations, whereas that with a higher ratio tends to comprise primary forests. The CO_2 balance in the soil pool is different depending on the land management (Nave et al., 2010; Stiebert et al., 2019). In terms of the mitigation of CO_2 emissions, certification should be encouraged, and sustainable management should be promoted for higher tree cover or primary forest areas.

5.4. Loss in non-certified forest areas

Sustainable forest management schemes aim to maintain forests and sustainable forest use. We hypothesized that although forest certification protects certified areas, it can result in the leakage of forest loss to the surrounding non-certified areas, specifically with constant or increasing demand for forest goods. Strict forest management may reduce the supply of forest goods from logging, which may then be transferred to non-certified forests, offsetting the mitigation of forest loss in a country or region.[16] The impact of certification on such leakage varies. Pfaff and Robalino (2017) identified channels under which a program would fail to mitigate deforestation. For example, when use in a certain area is restricted, the land owner may use other unrestricted land. Alix-Garcia and Gibbs (2017) found that zero-deforestation agreements increased forest loss before their implementation, thereby canceling out their positive effects. However, Heilmayr and Lambin (2016) found no evidence that forest management schemes led to leakage in the regions surrounding protected forest areas in Chile. Therefore, we analyzed the effects of forest certification on non-certified forest areas worldwide. The effects of leakage differed depending on the country. To estimate the average effects of leakage, we regressed the forest loss per non-certified area by the ratio of the certification area, the same variable as used in Section 5.1. We assumed no deforestation in the certified area. Thus, the dependent variable estimated as forest loss divided by the non-certified area was interpreted as forest loss in non-certified forest areas. The results in Table 5 show that the coefficients are positive and statistically significant for *Total certified* and *PEFC* (columns (1) and (3)), indicating that the expansion of the PEFC increased forest loss in non-certified areas. This finding may be interpreted as the

[16] One way to avoid this offset may be to impose a price premium for certified forest goods (Mattoo and Singh, 1994; Sedjo and Swallow, 2002); however, only a small premium has been found by a previous study (Yamamoto et al., 2014).

Table 4
Effects of sustainable forest management based on the various definitions of a forest.

Tree cover:	With 15%	With 20%	With 25%	With 30%	With 50%	With 75%
Total certification						
Total certified	−8839.123	−7705.73	−7790.97	−7532.30	−4405.47	816.117
	(14 000.46)	(13 913.34)	(13 815.64)	(13 868.08)	(13 758.61)	(10 710.59)
R^2	0.130	0.128	0.127	0.124	0.100	0.053
FSC						
FSC	−9542.07	−9885.91	−9795.32	−9642.41	−9205.0	−3882.70
	(20 524.75)	(20 275.98)	(20 177.12)	(19 985.07)	(17 530.82)	(13 539.28)
R^2	0.130	0.128	0.1265	0.1236	0.1002	0.0528
PEFC						
PEFC	−8890.46	−6728.37	−6933.18	−6590.62	−1529.62	3927.39
	(19 859.76)	(19 508.79)	(19 440.41)	(19 206.17)	(17 214.02)	(14 298.31)
R^2	0.130	0.128	0.127	0.124	0.100	0.053

The numbers in parentheses represent standard errors clustered at the country level.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
All regressions have been estimated using OLS and include country and year FEs as well as country characteristics such as GDP, GDP per capita, population, agricultural value per GDP, agricultural land per country's land, forest extent, and freedom score.

Table 5
Effects of sustainable forest management on forest loss in non-certified areas.

Certification type	All country			OECD			Non-OECD		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Total certified	0.015***			0.015**			0.016**		
	(0.005)			(0.007)			(0.007)		
FSC		0.002			0.004			0.001	
		(0.003)			(0.005)			(0.003)	
PEFC			0.025***			0.021**			0.033***
			(0.006)			(0.008)			(0.005)
GDP	1.03e−11	−2.75e−12	−4.66e−12	−1.03e−10	−2.55e−10	−1.56e−10	1.32e−11	−1.47e−11	7.51e−12
	(3.84e−11)	(4.16e−11)	(4.56e−11)	(2.32e−10)	(2.73e−10)	(2.51e−10)	(2.82e−11)	(3.50e−11)	(2.83e−11)
GDP per capita/1000	5.23e−08	2.53e−07	1.22e−07	2.42e−07	1.89e−07	1.91e−07	−3.66e−08	5.09e−07	1.79e−07
	(1.14e−07)	(1.79e−07)	(1.23e−07)	(3.14e−07)	(3.95e−07)	(3.32e−07)	(1.99e−07)	(3.37e−07)	(1.75e−07)
GDP per capita squared/1000	8.20e−10	6.32e−10	3.65e−10	−1.29e−09	−2.40e−10	−5.89e−10	−3.84e−10	−6.79e−09	−2.63e−09
	(9.80e−10)	(1.39e−09)	(1.08e−09)	(1.64e−09)	(2.03e−09)	(1.75e−09)	(2.53e−09)	(4.46e−09)	(2.39e−09)
Population/1000	−4.09e−09***	−1.12e−08	−5.58e−09	−2.56e−07	−3.16e−07	−3.57e−07	−1.66e−09	−4.22e−09	−3.58e−09
	(7.20e−09)	(8.53e−09)	(6.91e−09)	(2.19e−07)	(2.16e−07)	(2.19e−07)	(6.17e−09)	(5.78e−09)	(5.65e−09)
Agricultural value	0.0000857***	0.0000989***	0.0000806	0.0003408	0.0001881	0.0003268	0.0000801***	0.0000889***	0.0000794***
	(0.0000297)	(0.0000305)	(0.0000289)	(0.0005127)	(0.0005823)	(0.0004784)	(0.0000294)	(0.0000302)	(0.000029)
Agricultural land	0.0001422 ***	0.0001331**	0.000149***	0.0003261	0.0002427	0.0002255	0.0001189**	0.0001333**	0.0001311**
	(0.0000538)	(0.0000543)	(0.0000519)	(0.0002397)	(0.0002192)	(0.0002332)	(0.0000561)	(0.0000551)	(0.000054)
Forest extent	4.06e−11	4.96e−11	3.58e−11	−2.09e−10	−3.73e−10	−3.77e−10	3.05e−12	3.37e−11	2.14e−11
	(8.02e−11)	(8.29e−11)	(7.98e−11)	(3.87e−10)	(3.62e−10)	(3.82e−10)	(9.95e−11)	(1.02e−10)	(9.52e−11)
Institutional quality	−0.000121	−0.0001353	−0.0001343	0.0006198	0.0001066	0.0007691	−0.0001166	−0.0001095	−0.0001507 *
	(0.0000884)	(0.0000908)	(0.0000869)	(0.0008503)	(0.0008256)	(0.0008771)	(0.0000865)	(0.0000886)	(0.0000856)
Intercept	−0.007 **	−0.0085619**	−0.0076395	−0.0057463	0.0109531	0.0087341	−0.0041946	−0.0078537 *	−0.005649
	(0.003)	(0.0037421)	(0.0033312)	(0.0190967)	(0.0179476)	(0.0174504)	(0.0038834)	(0.0042731)	(0.0036612)
Country and year FEs	✓	✓	✓	✓	✓	✓	✓	✓	✓
Observation	1579	1579	1579	311	311	311	1268	1268	1268
R^2	0.153	0.076	0.195	0.212	0.136	0.236	0.142	0.069	0.217

The numbers in parentheses are standard errors clustered at the country level.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

leakage of forest loss from certified areas to non-certified areas. Brandt et al. (2014) found that sustainable management led to deforestation alongside the managed area in a developing country and showed that deforestation increased after the implementation of sustainable forest management policy. Although our results showed a similar pattern to those of Brandt et al. (2014), the coefficients were not statistically significant for the FSC. One possible explanation is the difference between the FSC and PEFC schemes. As the FSC is a more prescriptive certification than the PEFC, it does not have the same consequences as the PEFC (Auld et al., 2008).

We then disaggregated our estimations into OECD and non-OECD countries. Because deforestation is often more severe in developing countries than in developed countries, we identified whether the effect of certification on deforestation differed by the level of economic development. Table 5 presents the estimated results for OECD and non-OECD countries in columns (4)–(6) and (7)–(9), respectively. The coefficients for *Total certified* and *PEFC* are positive and statistically significant for both OECD and non-OECD countries, indicating that forest certification increased forest loss in non-certified areas for both groups. Hence, there were no significant differences in the effects of certification on forest loss in non-certified areas between OECD and non-OECD countries.

Among the agricultural variables, *Agricultural value* and *Agricultural land* have positive and statistically significant effects on forest loss in non-certified areas for non-OECD countries, but not for OECD countries. These results indicate that agricultural expansion in developing countries had a negative effect on forests. For example, under the REDD+ mechanism, the cost of forest conservation is considered to be compensation for the forgone chance of agricultural development. Generally, such compensation relies on carbon prices and tends to be below agricultural revenue.

6. Conclusions

This study examined the effects of forest certification on forest loss by using a forest cover panel dataset based on satellite observations between 2002 and 2011. We found no evidence that forest cover loss was mitigated by the expansion of the certification area after considering country and year fixed effects. The estimates of previous studies that did not control for country and year fixed effects may be biased due to unobserved country- and year-specific characteristics. Our estimation, which considered such fixed effects, provides credible evidence regarding the effects of certifications.

Furthermore, previous studies indicate that the FSC mitigates forest loss, unlike the PEFC (Damette and Delacote, 2011). Such estimates identified using cross-sectional variations alone may be biased. Therefore, we analyzed FSC and PEFC certifications individually. Our estimation results yielded no evidence that either the FSC or the PEFC had decreased forest loss. This may be because both certification schemes focus on the enhancement of sustainable forest management rather than the mitigation of deforestation.

In addition, the null hypothesis that an increase in PEFC-certified areas led to forest cover loss in non-certified areas could not be rejected, supporting previous studies that have found that forest loss increases around the area that adopts sustainable forest management (Brandt et al., 2014, 2016). These findings have important implications for forest management policy formulation. In particular, policymakers should be mindful of the fact that increasing the area under sustainable forest management may not lead to forest conservation.

Although it cannot be concluded that certification mitigates forest loss at the country level, it is worth noting that forest certification has the potential to improve sustainable forest management. For example, certification contributes to enhancing forest biodiversity in terms of tree species richness and density (Kalonga et al., 2016).

Some limitations of this study that present scope for further research should be mentioned. First, we could not examine the detailed mechanisms that lead to an increase in forest loss in non-certified areas. Various factors may change with the establishment of sustainable forest management areas, such as new load construction and logging permissions. The implementation of sustainable forest management may not always promote forest conservation, as shown by Brandt et al. (2014, 2016). Second, as mentioned earlier, we could not clearly identify the causal mechanism between certification and forest loss in non-certified areas. Although leakage is one possible explanation, Blackman et al. (2018) could not identify the effect of the FSC on deforestation despite eliminating the spillover effects. Future studies should thus attempt to address the mechanisms and the magnitude of such leakage. Third, although we estimated the average effects of forest management schemes, none of the variables except *Total certified* and *PEFC* were significant for the OECD countries, indicating that the identification of deforestation drivers is difficult, especially in the OECD countries. Further estimations at the country level from geographical or political science perspectives are necessary to analyze the factors related to forest loss in more depth.

CRediT authorship contribution statement

Yuki Yamamoto: Conceptualization, Methodology, Formal analysis, Software, Writing – original draft, Writing – review & editing, Visualization. **Ken'ichi Matsumoto:** Conceptualization, Writing – original draft, Writing – review & editing, Visualization.

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

See Tables A.1 and A.2.

Table A.1
Regression results for the logarithm of forest loss and the ratio of forest loss.

Dependent variable	Log of forest loss			Ratio of forest loss		
	(1)	(2)	(3)	(4)	(5)	(6)
Total certified	0.901			0.002**		
	(0.681)			(0.001)		
FSC		0.182			0.002	
		(0.665)			(0.002)	
PEFC			1.311			0.002***
			(0.866)			(0.001)
Observation	1320	1320	1320	1579	1579	1579
R^2	0.122	0.118	0.123	0.092	0.090	0.092

The numbers in parentheses represent standard errors clustered at the country level.
** $p < 0.05$.
All regressions have been estimated using OLS and include the country and year fixed effects as well as country characteristics such as GDP, population, agricultural value, and institutional quality.

Table A.2
List of countries by categories.

Regions		Income		Forest	
Tropics	Temperate	Low	High	Intact	High-deforestation
Angola	Afghanistan	Afghanistan	Andorra	Angola	Angola
Antigua and Barbuda	Albania	Bangladesh	Antigua and Barbuda	Argentina	Argentina
Bahamas	Algeria	Benin	Australia	Australia	Australia
Barbados	Andorra	Burkina Faso	Austria	Belize	Bolivia
Belize	Argentina	Burundi	Bahamas	Bhutan	Brazil
Benin	Armenia	Cambodia	Bahrain	Bolivia	Cote d'Ivoire
Bolivia	Australia	Central African Republic	Barbados	Brazil	Cambodia
Brazil	Austria	Chad	Belgium	Brunei	Canada
Brunei	Azerbaijan	Comoros	Bermuda	Cote d'Ivoire	Chile

(*continued on next page*)

Table A.2 (*continued*).

Regions		Income		Forest	
Tropics	Temperate	Low	High	Intact	High-deforestation
Burkina Faso	Bahrain	Democratic Republic of the Congo	Brunei	Cambodia	China
Burundi	Bangladesh	Eritrea	Canada	Cameroon	Colombia
Cote d'Ivoire	Belarus	Ethiopia	Cayman Islands	Canada	Democratic Republic of the Congo
Cambodia	Belgium	Gambia	Croatia	Central African Republic	Finland
Cameroon	Bermuda	Guinea	Cyprus	Chile	India
Cayman Islands	Bhutan	Haiti	Czech Republic	China	Indonesia
Central African Republic	Bosnia and Herzegovina	India	Denmark	Colombia	Laos
Chad	Botswana	Kenya	Estonia	Costa Rica	Madagascar
Colombia	Bulgaria	Kyrgyzstan	Finland	Cuba	Malaysia
Comoros	Cape Verde	Laos	France	Democratic Republic of the Congo	Mexico
Costa Rica	Chile	Lesotho	Germany	Dominican Republic	Mozambique
Cuba	China	Liberia	Greece	Ecuador	Myanmar
Democratic Republic of the Congo	Croatia	Madagascar	Hong Kong	Equatorial Guinea	Paraguay
Djibouti	Cyprus	Malawi	Hungary	Ethiopia	Peru
Dominica	Czech Republic	Mali	Iceland	Finland	Russia
Dominican Republic	Egypt	Mauritania	Ireland	Gabon	Sweden
Ecuador	Estonia	Mozambique	Israel	Georgia	Tanzania
El Salvador	Fiji	Myanmar	Italy	Guatemala	Thailand
Equatorial Guinea	France	Nepal	Japan	Guyana	United States
Eritrea	Georgia	Niger	Kuwait	Honduras	Venezuela
Ethiopia	Germany	Pakistan	Liechtenstein	India	Vietnam
Gabon	Greece	Rwanda	Luxembourg	Indonesia	
Gambia	Hong Kong	Sao Tome and Principe	Macao	Japan	
Ghana	Hungary	Senegal	Malta	Kazakhstan	
Grenada	Iran	Sierra Leone	Netherlands	Laos	
Guatemala	Iraq	Tajikistan	New Caledonia	Liberia	
Guinea	Ireland	Tanzania	New Zealand	Madagascar	
Guyana	Israel	Togo	North Korea	Malaysia	
Haiti	Italy	Uganda	Norway	Mexico	
Honduras	Japan	Uzbekistan	Oman	Mongolia	
India	Jordan	Vietnam	Portugal	Myanmar	
Indonesia	Kazakhstan	Zambia	Puerto Rico	Nepal	
Jamaica	Kiribati		Qatar	New Zealand	
Kenya	Kuwait		Saint Kitts and Nevis	Nicaragua	
Laos	Kyrgyzstan		San Marino	Nigeria	
Liberia	Latvia		Saudi Arabia	Norway	
Madagascar	Lebanon		Singapore	Panama	
Malawi	Lesotho		Slovakia	Paraguay	
Malaysia	Libya		Slovenia	Peru	
Mali	Liechtenstein		Somalia	Philippines	
Mauritania	Lithuania		South Korea	Republic of Congo	
Mauritius	Luxembourg		Spain	Romania	
Mexico	Macao		Sweden	Russia	
Mozambique	Macedonia		Switzerland	Samoa	
Myanmar	Maldives		Syria	Solomon Islands	
Nicaragua	Malta		Trinidad and Tobago	Suriname	
Niger	Micronesia		United Arab Emirates	Sweden	
Nigeria	Moldova		United Kingdom	Tanzania	
Panama	Mongolia		United States	Thailand	
Paraguay	Montenegro		Venezuela	Uganda	
Peru	Morocco			United States	
Philippines	Namibia			Vanuatu	
Puerto Rico	Nepal			Venezuela	
Republic of Congo	Netherlands			Vietnam	
Rwanda	New Caledonia				
Sao Tome and Principe	New Zealand				
Saint Lucia	North Korea				
Saint Vincent and the Grenadines	Oman				
Senegal	Pakistan				
Seychelles	Papua New Guinea				
Sierra Leone	Poland				
Singapore	Portugal				
Somalia	Qatar				
Sudan	Romania				
Suriname	Saint Kitts and Nevis				
Tanzania	Samoa				
Thailand	San Marino				
Togo	Saudi Arabia				

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Table A.2 (*continued*).

Regions		Income		Forest	
Tropics	Temperate	Low	High	Intact	High-deforestation
Trinidad and Tobago	Serbia				
Uganda	Slovakia				
Venezuela	Slovenia				
Vietnam	Solomon				
Zambia	South Africa				
	South Korea				
	Spain				
	Sri Lanka				
	Swaziland				
	Switzerland				
	Syria				
	Tajikistan				
	Tonga				
	Tunisia				
	Turkey				
	Turkmenistan				
	Tuvalu				
	Ukraine				
	United Arab Emirates				
	United Kingdom				
	Uruguay				
	Uzbekistan				
	Vanuatu				
	Yemen				
	Zimbabwe				

Countries with GDP per capita lower than USD1000 (or higher than USD10,000) in 2000 are categorized as low-income (or high-income) countries.
Intact forest and high deforestation countries have been categorized based on Potapov et al. (2017) and Global Forest Watch (2014).

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