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The expansion and remaining suitable areas of global oil palm plantations

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Abstract

Non-technical summary. Oil palm has been criticized for being an environmentally unfriendly oil crop. In recent decades, oil palm plantations have extended into conservation landscapes, causing severe environmental damage and harming biodiversity. Nevertheless, oil palm remains a highly productive oil crop from which most of the world's vegetable oil is produced. Therefore, measuring the environmental impact of oil palm plantations and identifying suitable land to support its sustainable development is crucial.

Technical summary. To meet the rising global palm oil demand sustainably, we tracked annual land cover changes in oil palm plantation and mapped areas worldwide suitable for sustainable oil palm cultivation. From 1982 to 2019, 3.6 Mha of forests were converted to oil palm plantations. Despite a recent decline in overall conversion, the shift from forest to oil palm plantations has become increasingly more common over the last decade, rising from 14.1 to 34.5% between 2009 and 2019. During 1982–2019, 2.23 Mha of peatland and 0.1 Mha of protected areas were converted for oil palm plantations. The potential sustainable land amounts to 103.5–317.9 Mha (Asia: 44.6–105.1 Mha, Africa: 34.7–96.4 Mha, and Latin America: 35.2–116.5 Mha). Future oil palm expansion is anticipated to take place in countries like Brazil, Nigeria, Colombia, Indonesia, Ivory Coast, the Democratic Republic of the Congo, and Ghana, where more sustainable land is available for cultivation. Malaysia, on the other hand, is about to exceed the area of sustainable cultivation, and further expansion is not recommended. These findings can advance our understanding of the environmentally damaging impacts of oil palm and enhance the feasibility of sustainable oil palm development.

Social media summary. How should suitable land be chosen for the establishment of oil palm plantations to support the sustainable development of the oil palm plantation industry?

1. Introduction

Oil palm, which is only cultivated in tropical regions, produces high-quality oil, currently meets approximately 40% of the global demand for vegetable oil from 5 to 5.5% of cropland devoted to oil crop production (Carter et al., 2007; Cheng et al., 2018; Meijaard et al., 2020; Rizeei et al., 2018; Srestasathiern and Rakwatin, 2014; Yusoff et al., 2017). From 1982 to 2019, the area of oil palm plantations increased by 3.7 times, reaching an estimated 19.6 Mha globally as of 2019 (Descals et al., 2021; Du et al., 2022). Palm oil has rapidly expanded, emerging as a significant vegetable oil globally comparable to soybean oil. According to the Food and Agriculture Organization of the United Nations (FAO), in 2020, global exports of edible vegetable oil amounted to 87.8 million tons, of which palm oil accounted for 53.9%. However, palm oil production is most intense and geographically concentrated in Southeast Asia, especially in Indonesia and Malaysia (Cheng et al., 2017; Cheng et al., 2019; Sayer et al., 2012; Xu et al., 2020). FAO noted that in 2021, 83.8% of palm oil was supplied by Indonesia (27.0 million tons) and Malaysia (14.3 million tons). Thus, any restrictions on palm oil exports from these two countries will largely affect the global palm oil prices.

While oil palm plantations are expanding rapidly, there is significant controversy due to the environmental damage they cause. The proliferating expansion of unsustainable oil palm cultivation inevitably induced tropical deforestation and the loss of peatland, leading to a further decline in biodiversity and increased carbon emissions (Fitzherbert et al., 2008; Guillaume et al., 2018; Koh and Wilcove, 2008; Koh et al., 2011; Miettinen et al., 2016; Xu et al., 2020). However, outright trading boycotts of palm oil are not a feasible solution. Instead, minimizing environmental effects during the process of oil palm cultivation and promoting sustainable oil palm development may be a practical approach.

It is crucial to enhance our understanding of the impacts of oil palm expansion on the environment. The drastic expansion of oil palm plantations in recent decades has led to peatland degradation, resulting in a series of environmental issues and a substantial decline in biodiversity (Hoyt et al., 2020; Koh et al., 2011; Yu et al., 2022). Almost all of the land under oil palm cultivation formerly comprised tropical forests or carbon-rich regions (Vijay et al., 2016; Xu et al., 2022). Koh et al. (2011), who mapped the distribution of oil palm in Indonesia and Malaysia using the Moderate Resolution Imaging Spectroradiometer (MODIS) and Phased Array L-band Synthetic Aperture Radar (PALSAR) archives, found that by the early 2000s, approximately 6% of peatland in this region had been converted for oil palm plantations. Du et al. (2022) created a global map of oil palm expansion based on the years of plantation establishment and with a satisfactory spatial and temporal accuracy. This map will provide significant support for analyses of the environmental impacts of oil palm expansion.

Given the ongoing expansion of the area under oil palm cultivation each year, it is crucial to promote the exploration of suitable regions for potential oil palm expansion to sustain this trend. Rhebergen et al. (2016) assessed climatic, soil, and land use factors in Ghana to evaluate land suitability for oil palm cultivation. However, this study only considered few biophysical restrictions (water deficit, solar radiation, temperature, and slope). Whereas Pirker et al. (2016) mapped the global biophysical characteristics of oil palm. Although their study was informative, they overlooked the spatial variability of restriction thresholds applied for mapping oil palm suitability and discounted some significant constraining factors, such as solar radiation and soil pH values (Ogunkunle, 1993; Rhebergen et al., 2016). Moreover, mapping suitable land globally based on restriction thresholds derived from a literature review is controversial (Pirker et al., 2016), as it lacks the direct support from existing oil palm plantation distribution data.

Against the backdrop of the ongoing oil palm controversy, this study is aimed at clarifying the impacts of oil palm expansion on the environment and identifying potentially available land for oil palm cultivation globally. Our results can guide oil palm plantation companies to sustainably select only suitable areas for oil palm plantation and therefore help to reduce any potential harmful impact to the environment.

2. Materials and methods

2.1 Analysis of environmental impact

Du et al. (2022) developed a global oil palm dataset during 1982–2020 using the Landsat archive (Figure S1). This dataset is included in the global maps of plantations, with their planting years, and constitutes the first high-resolution dataset produced for global plantations at a 30 m spatial resolution. This dataset records the spatiotemporal dynamics in oil palm cultivation, utilizing Descals et al. (2021)'s 2019 global oil palm plantation dataset. It shows a satisfactory consistency in the planting year when compared to the map generated by Danylo et al. (2021). Further validation through validation samples confirms an F1 score of 86.83% for deviations within a ±5 year range.

First, we tracked the land conversion caused by the oil palm plantation expansion during 1992–2019 based on the global oil palm and ESA CCI Land Cover (SI Text 2, data from 1992 to 2019) datasets (Table 1, Figure 1[a]). The conversion of peatland and protected areas (categories I [Ia: nature reserves, Ib: wilderness areas] and II [national parks] in the World Database of Protected Areas [WDPA]) during the period 1982–2019 was also quantified (UNEP-WCMC, 2019).

2.2 Analysis of sustainability of oil palm cultivation

We subsequently utilized a global oil palm sample database to extract environmental restrictions pertaining to oil palm planting on a global, continental, and national levels (Figure 1[b]). Based on these data, we generated a global map highlighting land areas suitable for oil palm planting. Additional information regarding the environmental restrictions for oil palm planting at each level is available in Tables S3 and S4.

We considered climatic, soil, and terrain restrictions that significantly affect oil palm growth and yields (Pirker et al., 2016; Rhebergen et al., 2016; Yao and Kamagate, 2010) when mapping suitable land for oil palm cultivation (Table 1). Climatic restrictions were based on eight criteria derived from WorldClim (version 2.1). WorldClim contains a set of global climate variables at a spatial resolution of approximately 1 km from 1970 to 2000. We used the temperature, precipitation, daily solar radiation (DSR), wind, and water vapor pressure (WVP) as the climate restrictions. Data on soil-related factors were derived from the Harmonized World Soil Database (version 1.2). They covered soil depth, texture, pH, available water capacity (AWC), and organic carbon (OC). These factors represent soil nutrient and plantability, serving as essential indicators for guaranteeing oil palm growth and yield. Data on terrain restrictions comprised elevation, obtained using a digital elevation model, and slope data obtained from the Shuttle Radar Topography Mission (SRTM).

We used the oil palm sample database (SI Text 3) to extract the potential local climatic, soil, and terrain restriction thresholds for oil palm distribution. Based on these thresholds, we then predicted the suitable land for oil palm cultivation worldwide. These thresholds have global, continental, and national levels, corresponding to the values for extraction of global, continental, and national oil palm samples. Specifically, when determining the limiting factor thresholds for each country by utilizing that country's oil palm samples, the resulting value is utilized to generate national level map, as well as the creation of continental and global level maps. The thresholds for the three levels are inclusive, with the global thresholds being the broadest and the national

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Table 1. Restrictions applied for mapping the suitability of oil palm cultivation and their measurement

	Category	Criterion	Unit/description	Original spatial resolution	Dataset used
Climate	Temperature	Average annual temperature	°Celsius	30 arc seconds	WorldClim version 2.1 (Fick and Hijmans, 2017)
		Min annual temperature	°Celsius		
		Max annual temperature	°Celsius		
	Precipitation	Annual precipitation	mm/m^2		
		Number of dry months	Monthly precipitation <100 mm/m^2		
	Daily solar radiation (DSR)		MJ/m^2		
	Wind		m/s		
	Water vapor pressure (WVP)		KPa		
Soil	Effective soil depth		cm	30 arc seconds	HWSD (FAO/IIASA/ISRIC/ISSCAS/JRC., 2012)
	Texture	Sand	%		
		Silt	%		
		Clay	%		
	pH	Top	−log (H+)		
		Substrate	−log (H+)		
	Available water capacity (AWC)		mm/m		
	Organic carbon (OC)	Top	%		
		Substrate	%		
Terrain	DEM		Meters	30 arc seconds	NASA SRTM (Jarvis et al., 2008)
	Slope		Sloping degrees (°)		
Protected areas	Land already under use		Nature reserves (category Ia), wilderness areas (category Ib), and national parks (category II)	shpfile	WDPA (UNEP-WCMC, 2019)
Biomass	Above ground biomass (AGB)		>100 t/ha	30 arc seconds	(Avitabile et al., 2016)
Peatland	Peatland area			shpfile	(Xu et al., 2018)
Land cover	Land not possible to convert		Wetlands, water bodies, urban areas	10 m	ESA CCI Land Cover (ESA, 2017)

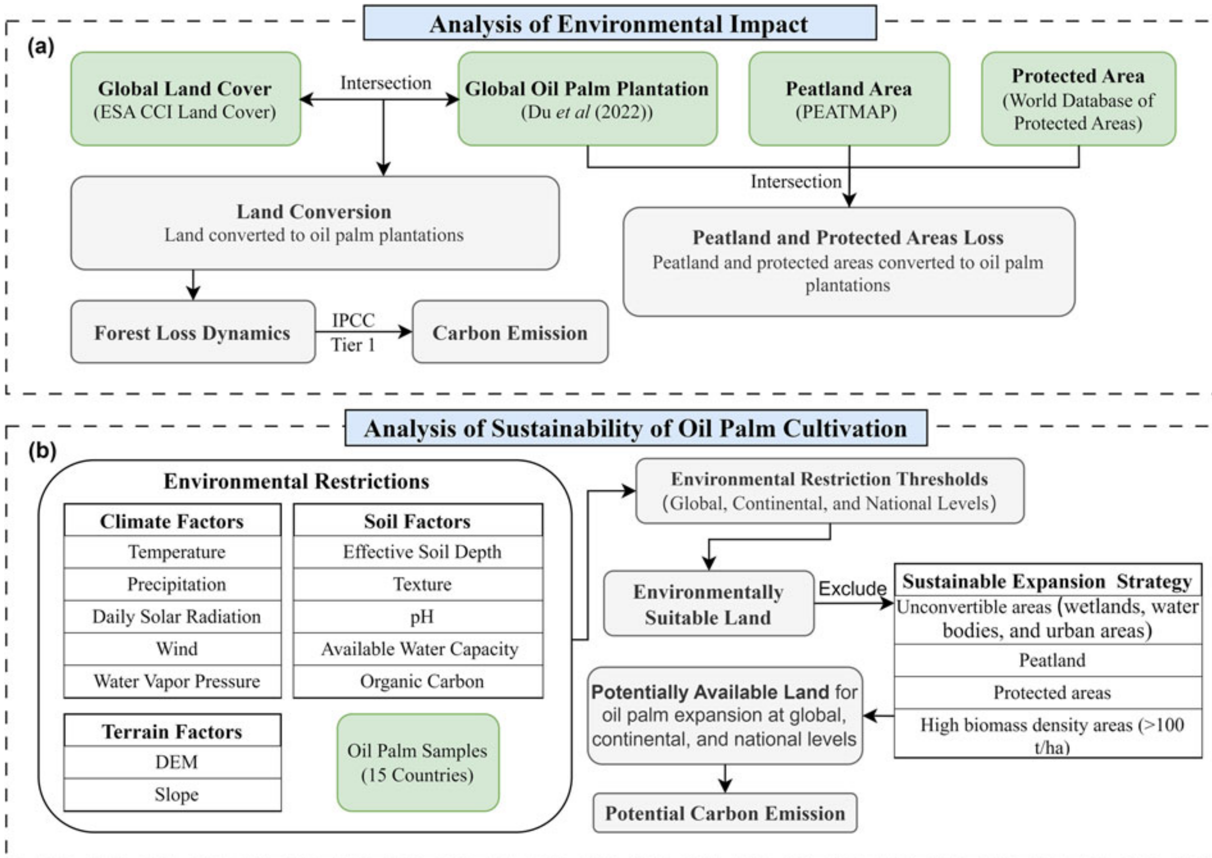

Figure 1. Flowchart of this study. (a) Flowchart of analysis of environmental impact. (b) Flowchart of analysis of sustainability of oil palm cultivation.

thresholds being the narrowest. We computed a suitable map for oil palm cultivation using restriction threshold values at global (maximum area), continental, and national (minimum area) levels. The national level threshold is better suited for determining the suitability of oil palm cultivation in a specific country, while the global level map can still provide guidance for oil palm cultivation on a worldwide scale. It's important to note that in cases where oil palm samples are only available in 15 countries, countries lacking oil palm samples are calculated using continental values.

Finally, to mitigate the associated environmental damage, we implemented an expansion strategy to promote a sustainable oil palm cultivation. This sustainable expansion strategy involved the application of a land mask, which excluded regions that are unsustainable for oil palm expansion, including unconvertible areas (wetlands, water bodies, and urban areas), peatland, protected areas, and high biomass density areas (>100 t/ha) (Table 1).

3. Results and discussions

3.1 Land conversion

During 1992–2019, 15.4 Mha of land was converted into oil palm plantations globally (Figure 2). The land types converted for oil palm plantations were mainly cropland (11.5 Mha) and forests (3.6 Mha), accounting respectively for 75.0 and 23.2% of the total expanded area (Figure S3). The expansion of oil palm cultivation is most prominent in Asia (14.1 Mha), followed by Latin America (0.9 Mha) and Africa (0.4 Mha) (Figure 3[a]). Southeast Asia evidenced a dramatic expansion of oil palm, with the greatest expansion occurring in Indonesia (9.4 Mha) and Malaysia (4.1 Mha) (Figure 2). Extensive grasslands were also converted for oil palm cultivation in countries such as Papua New Guinea and Colombia, where the land cover was mainly shrubland and grassland (Figure S4).

Since the 1980s, the annual expansion rate of oil palm has steadily increased, and Asia's oil palm expansion dominated the global oil palm expansion (Figure 3[b] and 3[c]). Although in recent decades, the expansion rate has fluctuated, as evidenced by one trough (2003; 0.20 Mha) and two peaks (1998, 0.91 Mha; 2012, 0.98 Mha) (Figure 3[a]). The trough in 2003 occurred globally and in Asia, while the trough in Latin America and Africa was not obvious (Figure 3[b]). After 2012, the rate of expansion gradually decelerated and eventually reached its lowest point in recent years, which was potentially correlating with the upward trend in palm oil prices (Gaveau et al., 2022). Cropland is the largest source of land for oil palm plantations, converting more than twice the area of forest (Figure 3(d)).

We estimated the global conversion of peatland (SI Text 45) and protected areas (SI Text 5) resulting from oil palm expansion in recent decades. Now globally, 2.23 and 0.1 Mha of oil palm plantations are established over peatland and protected areas, respectively.

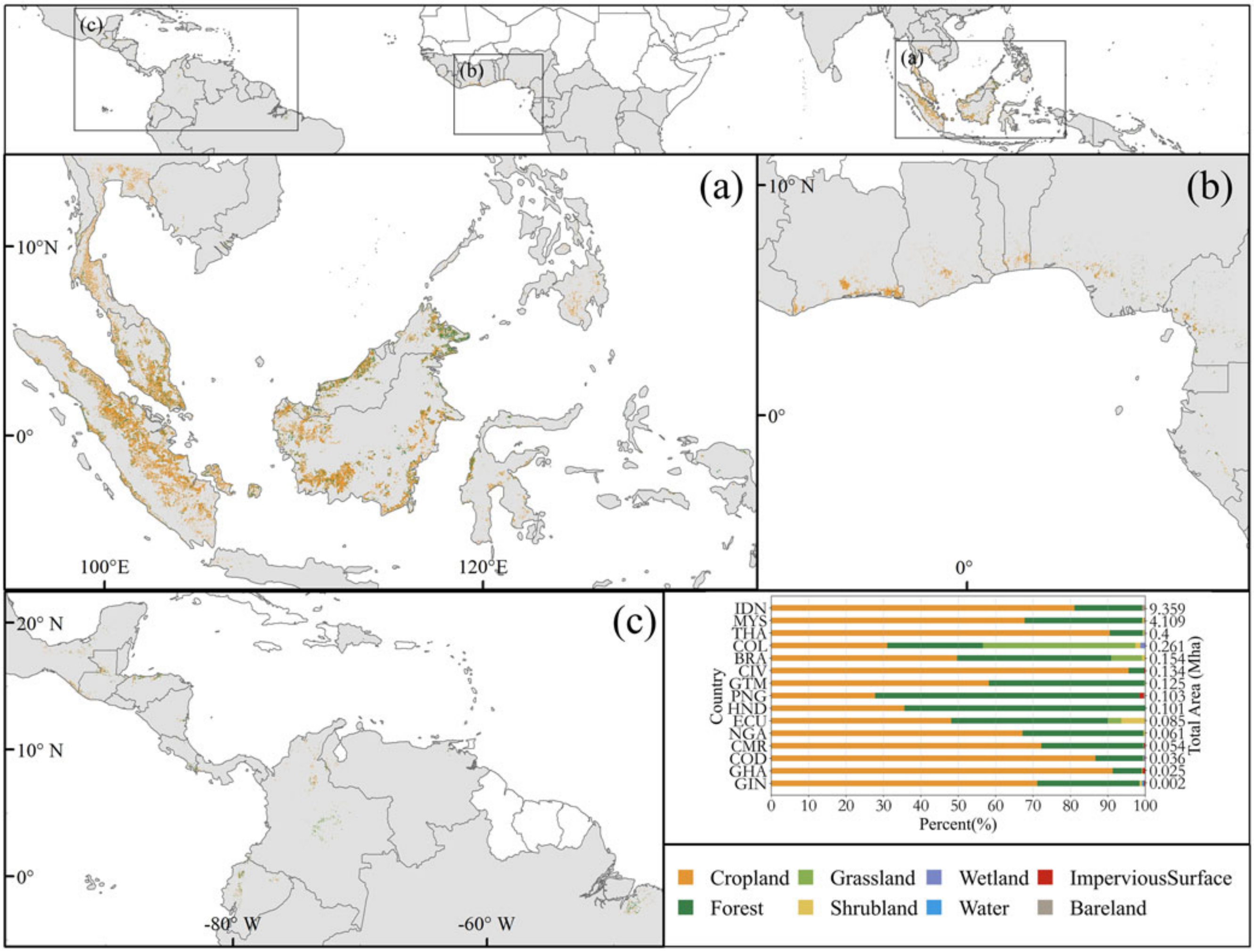

Figure 2. Land conversion by oil palm plantations in various countries. The stacked bar chart depicts the expansion of oil palm plantations from 1992 to 2019 in 15 countries. These countries are the ones for which oil palm sample data are available. BRA, Brazil; ECU, Ecuador; COL, Colombia; GTM, Guatemala; HND, Honduras; GIN, Guinea; GHA, Ghana; COD, the Democratic Republic of the Congo; CMR, Cameroon; CIV, Ivory Coast; NGA, Nigeria; THA, Thailand; MYS, Malaysia; IDN, Indonesia; PNG, Papua New Guinea.

3.2 Oil palm expansion into forests remains a significant concern

We tracked the expansion of oil palm plantations into different land uses and found that a total of 3.6 Mha of forests were affected in recent decades between 1992 and 2019 (Table S2). In Latin America, 41.8% (0.38 Mha) of oil palm plantations were formerly forested land (Table S2), and this was followed by Asia (22.2%) and Africa (15.0%). In Asia, a total of 3.2 Mha of forests were planted with oil palm, where Indonesia (1.7 Mha) and Malaysia (1.3 Mha) had the most expansion. Oil palm plantation expansion into forests peaked between 2008 and 2012, but gradually decreased from 2014 to 2019 (Figure 4[a]), mainly because of lower palm oil prices (Gaveau et al., 2022). Seymour and Harris (2019) and Austin et al. (2019) also indicated that tropical deforestation for the expansion of oil palm plantations has a notable decline in recent years. Although the proportion of forests covered by oil palm plantations showed a decreasing trend from 1992 to 2010, our results highlight that this trend was reversed in recent years (Figure 4[b]), implying the potential for more forest loss caused by oil palm expansion. Specifically, oil palm plantation expansion into forests remains severe in Indonesia, Malaysia, Honduras, Ivory Coast, Thailand, and Vietnam, while Colombia and Guatemala have been showing a decreasing trend (Figure S4). We did not distinguish between intact and logged forests, which is an essential distinction for assessing whether oil palm cultivation is a direct driver of deforestation (Gaveau et al., 2016).

Forest loss due to timber harvesting or conversion to other land uses including oil palm plantations is always linked with loss of carbon sink potential, CO_2 emission, and temperature increase and warming effects. In this study, we evaluated the impact of forest loss due to oil palm expansion on CO_2 emission by employing the standard method of CO_2 emission from the Intergovernmental Panel on Climate Change (IPCC) Tier 1 (Eggleston et al., 2006) (SI Text 6). The historical carbon emissions resulting from the annual oil palm expansion during 1992–2019 was calculated and the results are shown in Figure 5. As shown in Figure 5(a), the establishment of oil palm plantations did not cause excessive reduction in carbon stock as this was the result of various land use conversions. The carbon loss (emission) due to forest loss was 501 (408–811) Tg C for the period between 1992 and 2019 (Table S5). Indonesia and Malaysia

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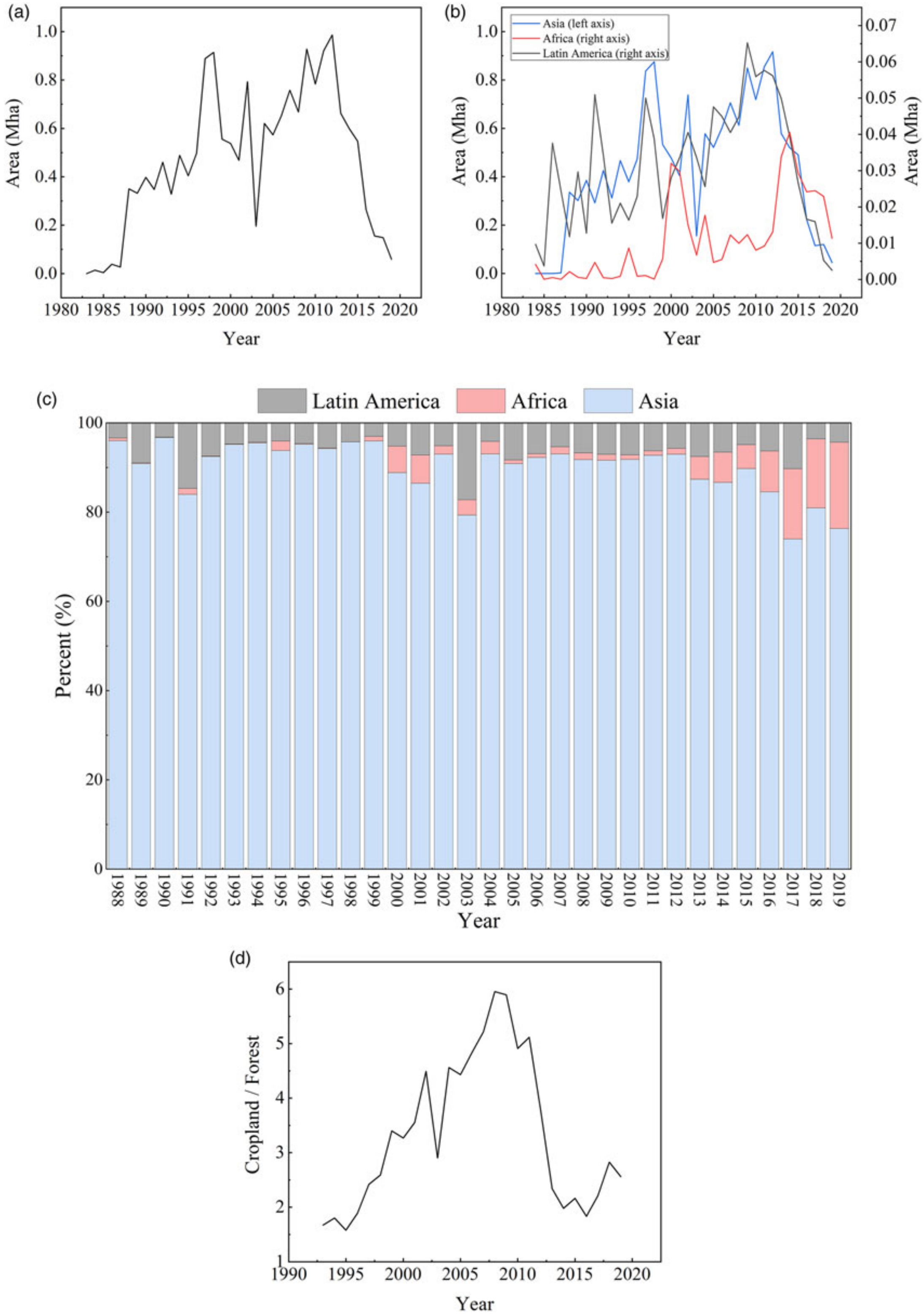

Figure 3. The characteristics of oil palm expansion. (a) Global annual expansion of oil palm plantations. (b) Continental expansion of oil palm plantations, including Asia (left *Y* axis), Africa (right *Y* axis), and Latin America (right *Y* axis). (c) The percentage of oil palm plantation expansion areas in each continent relative to the total expansion area for each year. (d) The ratio of converted agricultural land to forest area is a critical measure.

were the countries with the most drastic carbon stock loss, contributing 46.0 and 32.1% of the total reduction, respectively. The ratio of carbon emissions from oil palm plantation expansion reached its peak (2.5%) in 2013 and then decreased sharply (Figure 5[c]). Although forest loss caused by oil palm expansion is significantly reduced in recent years, it remains an issue in carbon losses (Guillaume et al., 2018), especially in Indonesia and Malaysia.

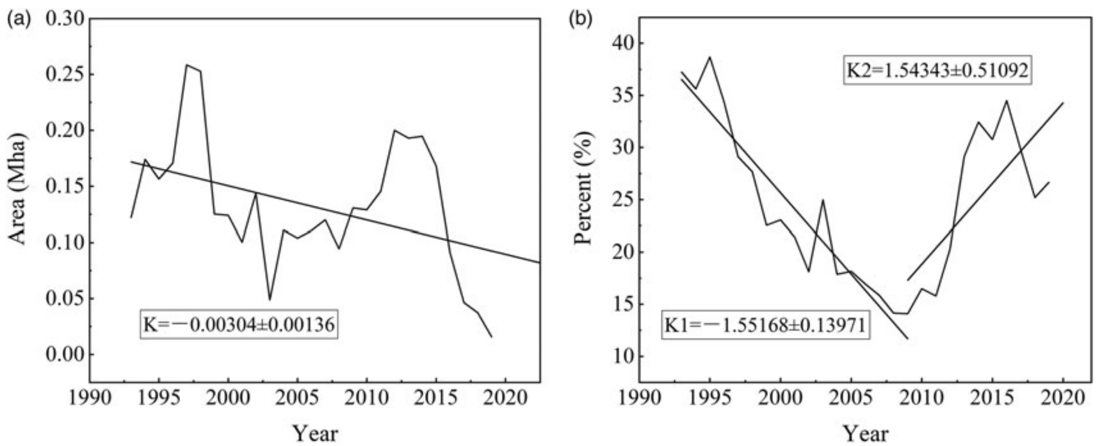

Figure 4. The characteristics of oil palm plantation expansion into forest. (a) The area of forest was converted to oil palm plantations. (b) The proportion of forest covered by oil palm plantations.

Consequently, stringent international and governmental regulations are still needed to protect forests from the invasion of oil palm plantations. Since its establishment in 2004, the Roundtable on Sustainable Palm Oil has made great efforts to promote the sustainable development of oil palm, including through the promotion of sustainability certification. Carlson et al. (2018) found that certified growers have stopped expanding oil palm plantations at the expense of forest but has not positively impacted the loss of peatland forests. Many countries promote oil palm concessions, but without an optimal legal framework, biodiversity and high carbon stock areas cannot be effectively protected (Assidiq et al., 2021; Busch et al., 2015).

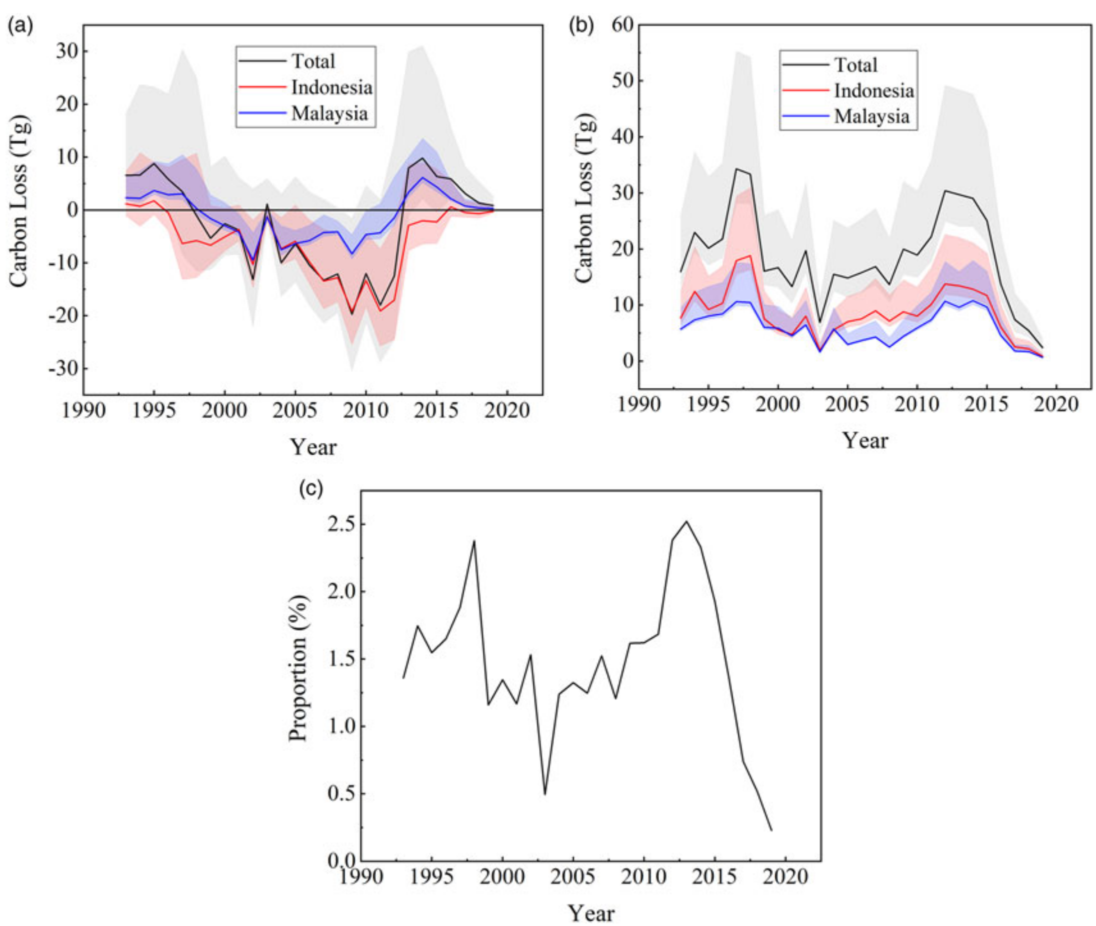

Figure 5. The characteristics of changes in carbon stocks. (a) Total carbon emissions caused by oil palm expansion. (b) Carbon emissions from the invasion of forests by oil palm plantations. (c) The ratio of carbon emissions resulting from oil palm plantation expansion into forests to global carbon emissions caused by land use change (Friedlingstein et al. 2022).

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Table 2. Suitable climatic factors for oil palm cultivation in different countries

	Temperature (°C)			Precipitation		DSR	Wind	WVP
	Min (°C)	Max (°C)	Mean (°C)	Annual rainfall (mm)	Dry season	(MJ/m^2)	m/s	(kPa)
Global	**19.0–24.3**	**27.9–35.2**	**23.7–29.5**	**965–4080**	**0–7**	**11.9–20.1**	**0.8–3.9**	**2.3–3.0**
Central America	**19.1–23.6**	**27.9–34.5**	**23.7–28.6**	**1079–3984**	**0–7**	**11.9–20.1**	**1.0–3.9**	**2.3–3.0**
Brazil	21.4–22.2	30.3–31.3	25.9–26.5	2122–2574	4–6	15.4–16.3	1.2–1.8	2.8–2.9
Ecuador	18.4–21.9	26.7–29.9	23.7–25.8	1346–3650	0–6	11.9–13.6	1.0–1.9	2.5–2.9
Colombia	21.8–23.6	29.5–34.3	25.7–28.6	1079–3096	0–6	13.4–19.5	1.1–3.9	2.7–3.0
Guatemala	19.1–21.7	28.7–34.5	23.9–28.0	1499–3984	1–6	18.3–19.8	1.4–2.6	2.3–2.8
Honduras	19.5–23.0	28.9–32.5	24.2–27.5	1159–3035	2–6	18.9–20.1	1.5–3.5	2.4–2.8
Central Africa	**19.0–24.3**	**28.1–35.2**	**24.3–29.5**	**965–3453**	**1–7**	**13.8–19.2**	**0.9–2.9**	**2.3–3.0**
Guinea	22.6–24.3	32.2–35.2	24.7–29.5	2038–3453	4–7	16.0–19.2	1.5–2.9	2.3–2.7
Ghana	21.2–24.0	29.4–31.6	25.3–27.7	965–1967	4–7	15.1–17.1	1.2–2.3	2.7–3.0
Democratic Republic of the Congo	19.0–20.9	29.1–30.6	24.3–25.6	1569–1901	1–4	14.7–16.7	0.9–1.3	2.4–2.6
Cameroon	20.5–23.4	28.1–30.9	24.5–27.1	2073–3089	3–4	13.8–14.5	1.1–2.3	2.5–3.0
Ivory Coast	21.7–23.5	29.1–31.2	25.5–27.0	1195–1846	4–7	16.6–18.1	1.1–2.3	2.6–3.0
Nigeria	20.7–23.1	29.6–31.7	25.1–27.4	1209–2992	3–6	14.2–15.9	1.3–2.0	2.4–3.0
Southeast Asia	**19.1–24.1**	**28.5–32.5**	**23.8–28.1**	**1261–4080**	**0–7**	**15.2–19.7**	**0.8–3.1**	**2.4–3.0**
Thailand	21.6–24.1	29.8–32.5	25.7–27.8	1261–3568	3–7	17.5–19.2	1.1–2.3	2.6–2.9
Malaysia	20.5–23.6	29.0–32.0	24.7–27.6	1801–3600	0–3	15.6–17.7	1.1–2.3	2.6–3.0
Indonesia	19.1–24.0	28.5–32.4	23.8–28.1	1472–4009	0–6	15.2–18.2	0.8–2.4	2.5–3.0
Papua New Guinea	19.7–23.0	28.7–32.0	24.8–27.0	2006–4080	0–3	15.5–19.7	1.2–3.1	2.4–3.0

3.3 Potentially available global land for oil palm plantation expansion

After excluding areas considered inappropriate because of climatic, soil, and terrain restrictions (Tables 2 and 3), spanning from national level to global level, the land suitable for cultivating oil palm amounted to 358.2–1,064.7 Mha. This suitable land is distributed across Southeast Asia, the west coast of Central Africa, the Congo Basin, Central America, and the Amazon region (Figure S6). The most suitable countries for oil palm cultivation are Brazil (0.3–233.6 Mha) and Indonesia (70.9–121.6 Mha), followed by the Democratic Republic of the Congo (COD) (9.4–104.4 Mha) and Colombia (5.8–73 Mha). Some areas are still suitable for oil palm cultivation in Malaysia (9.7–25.5 Mha) and Papua New Guinea (1.9–21 Mha). However, these areas include land use types that cannot be converted and areas requiring protection.

Following the filtration of the land mask, potentially available land remaining for oil palm expansion globally amounted to 103.5–317.9 Mha (Asia: 44.6–105.1 Mha, Africa: 21.3–96.4 Mha, and Latin America: 35.2–116.5 Mha) (Figure 6). Substantial areas of suitable available land remaining for oil palm expansion were found in Brazil (0.1–53.8 Mha), Thailand (0.7–23.9 Mha), COD (1.2–20.2 Mha), Colombia (2.3–19.5 Mha), Nigeria (1.9–19.1 Mha), Indonesia (7.2–17.3 Mha), India (6.8–15.5 Mha), Ivory Coast (1.3–15.1 Mha), Venezuela (9.9–13.1 Mha), and Ghana (0.4–10.9 Mha) (Table S4).

The national level map conformed more closely to oil palm plantation distribution, enabling precise mapping of potentially available land for oil palm expansion globally (Figure 6). The stringent application of the land mask reduced the suitable areas for oil palm cultivation by 74% (from 404.8 to 103.5 Mha). Among them, protected, peatland, unconverted, and areas that have high biomass density account for 70.1, 16.2, 11.3, and 277.8 Mha, respectively. Asia has the largest expanse of land available for oil palm expansion, making it the primary region prioritizing oil palm cultivation over other continents. Of the 15 countries where oil palm samples are distributed, Indonesia (7.2 Mha), Colombia (2.3 Mha), Nigeria (1.9 Mha), Ivory Coast (1.3 Mha), and COD (1.2 Mha), are suitable for oil palm plantation expansion (Table S4). However, on the national level map, countries with little potentially available land, such as the Brazil (0.05 Mha), Papua New Guinea (0.05 Mha), and Guinea (0.08 Mha), are not suitable for substantial expansion of oil palm plantations (Table S4).

This study included 15 countries where oil palm samples were distributed. As Figure 6 shows, land cover in areas of potential oil palm expansion is dominated by forests (10.4 Mha; 61.9%), grasslands (3.7 Mha; 22.0%), and cropland (1.8 Mha; 10.5%), while smaller areas of shrubland (0.7 Mha; 4.2%) and bare land (0.2 Mha; 1.4%) are suitable for oil palm cultivation. Indonesia has the most potential for expanding oil palm plantations. Indonesia has the most land available for oil palm expansion (7.2 Mha), and forests, cropland, and grassland account for 70.0,

Table 3. Suitable soil and terrain factors for oil palm cultivation in different countries

	Depth	Texture (%)			pH		AWC	OC		Terrain	
	(cm)	Sand (%)	Silt (%)	Clay (%)	Top (–log[H+])	Substrate (–log[H+])	(mm)	Top (%)	Substrate (%)	DEM (m)	Slope (°)
Global	10–100	**8–94**	**1–57**	**3–59**	**3.8–8.1**	**3.8–8.2**	**150–15**	**0.4–30.7**	**0.2–34.8**	**2–727**	**0.03–9.55**
Central America	**100**	**8–94**	**3–57**	**17–37**	**3.8–8.0**	**3.8–8.1**	**150–100**	**0.4–7.3**	**0.2–2.9**	**2–727**	**0.03–9.25**
Brazil	100	46–80	3–17	17–37	3.8–5.2	3.8–4.8	150	1.0–1.6	0.4–0.6	8–69	0.07–0.97
Ecuador	100	8–54	20–57	15–59	4.3–7.0	4.1–7.8	150	0.5–3.1	0.2–2.5	14–585	0.07–2.37
Colombia	100	13–94	4–39	2–54	4.5–5.6	4.6–6.7	150–100	0.5–3.9	0.2–1.7	9–161	0.3–1.27
Guatemala	100	24–55	24–45	14–37	5.5–8.0	5.4–8.1	150	0.5–7.3	0.3–2.9	11–644	0.03–2.19
Honduras	100	24–44	27–33	23–49	5.1–7.0	5.1–7.3	150	0.7–2.5	0.3–1.0	3–727	0.03–9.25
Central Africa	**10–100**	**8–89**	**1–48**	**6–58**	**4.1–7.7**	**4.2–7.9**	**150–15**	**0.4–30.7**	**0.2–34.8**	**2–588**	**0.04–5.3**
Guinea	10–100	8–77	9–34	14–58	4.8–7.6	4.2–5.0	150–15	0.6–2.6	0.3–3.5	2–402	0.06–1.84
Ghana	10–100	16–89	5–41	6–53	4.6–7.7	4.8–7.9	150–15	0.4–1.6	0.2–0.6	2–232	0.05–2.14
Democratic Republic of the Congo	100	29–86	1–13	13–58	4.1–5.1	4.3–5.2	150	0.7–1.2	0.2–0.5	354–588	0.10–3.32
Cameroon	10–100	34–79	7–48	14–26	4.8–7.7	4.8–7.9	150–15	0.6–7.4	0.3–3.3	9–517	0.14–5.28
Ivory Coast	100	26–89	5–39	6–41	4.4–6.2	4.5–5.7	150–50	0.4–30.7	0.2–34.8	7–174	0.06–1.72
Nigeria	100	26–82	7–40	8–49	4.8–6.2	4.8–6.3	150–50	0.6–1.5	0.3–0.5	15–483	0.05–2.13
Southeast Asia	**10–100**	**8–90**	**6–48**	**3–59**	**4.4–8.1**	**4.2–8.2**	**150–15**	**0.4–30.7**	**0.2–34.8**	**2–525**	**0.03–9.55**
Thailand	100	8–83	11–43	6–58	4.4–6.6	4.2–6.7	150–50	0.5–30.7	0.3–34.8	5–237	0.03–9.55
Malaysia	10–100	8–83	11–34	6–59	4.4–8.1	4.2–8.2	150–15	0.5–30.7	0.3–34.8	2–332	0.03–8.32
Indonesia	100	17–90	6–48	3–55	4.4–6.4	4.5–6.4	150–50	0.4–30.7	0.2–34.8	2–480	0.03–6.20
Papua New Guinea	100	11–47	29–39	19–55	5–6.4	5.1–7.0	150	0.9–3.4	0.4–1.5	6–525	0.07–9.27

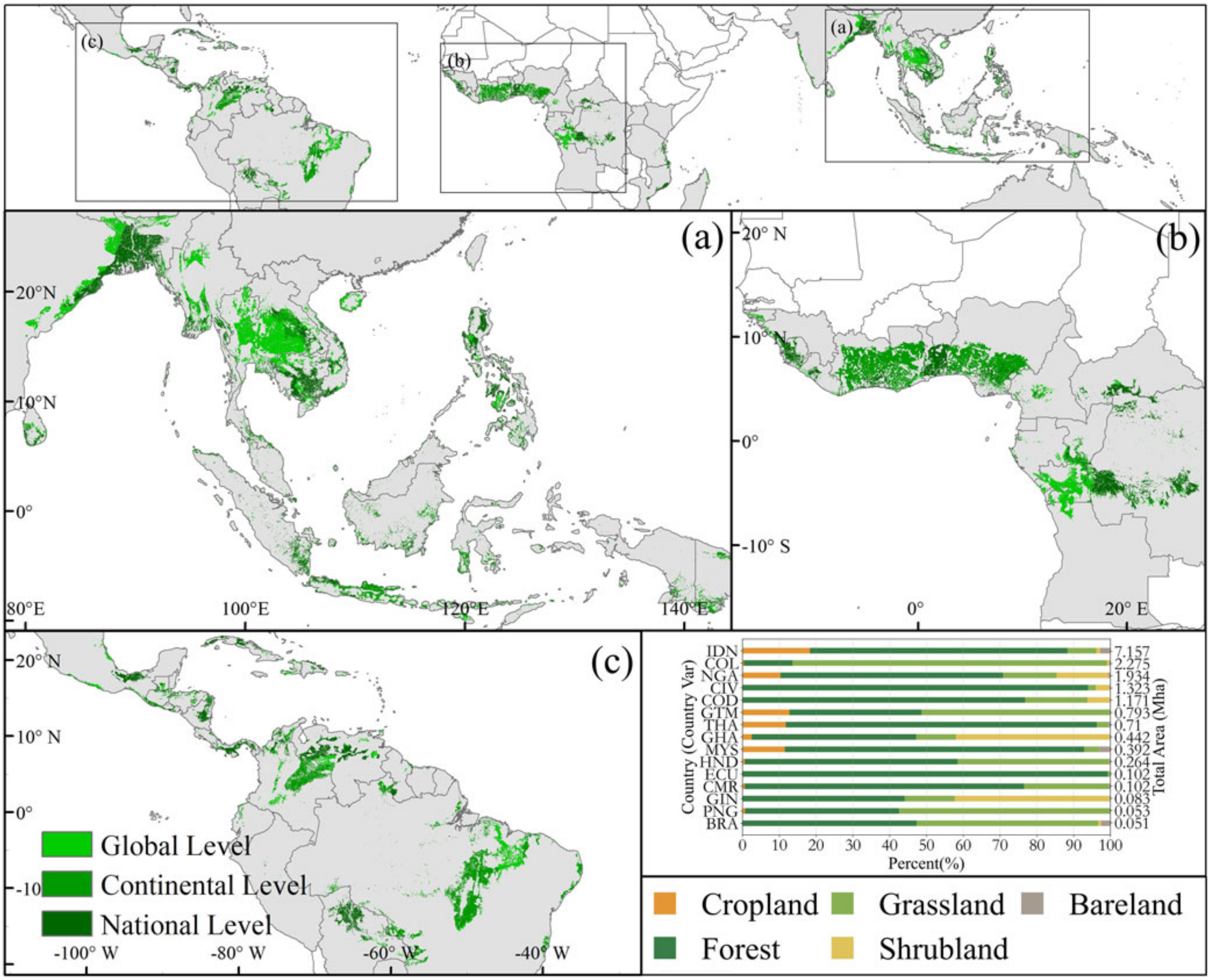

Figure 6. Potentially available land for oil palm expansion at global, continental, and national levels under different restrictions. Unconvertible areas (wetlands, water bodies, and urban areas), peatland, protected areas, and high biomass density areas were excluded from the potentially available land. The stacked bar chart illustrates the potentially available land area at the national level in 15 countries, which are the countries where oil palm samples are available.

18.4, and 7.8%, respectively. Colombia's potential expansion area, mainly grasslands, covers 85.5% of the total. However, with an existing planted area of 5.1 Mha, Malaysia is about to exceed the area of sustainable cultivation. Only 0.4 Mha of suitable land with national thresholds for sustainable oil expansion remains in Malaysia, which is well below the existing oil palm area in Malaysia (8%).

3.4 Availability of oil palm sustainability maps

Although irrigation, fertilization, and sound management (such as effective foliage pruning and pest control) can reduce the adverse impacts of oil palm cultivation on unsuitable land, they will increase production costs. Thus, we extracted thresholds for climatic, soil, and terrain restrictions to map suitable areas worldwide for oil palm cultivation (Tables A3 and A4). Most of the extracted thresholds were within the range presented by Goh (2000), Corley and Tinker (2008), and Pirker et al. (2016) and match more perfectly with the optimal thresholds within the literature. For example, the optimal average annual temperature for oil palm cultivation ranges between 26 and 29 °C, and the suitable average annual temperature range reported in the literature is 17–36 °C (Table S5). Our value, extracted using Brazil oil palm samples, ranged between 25.9 and 26.5 °C. Some maximum or minimum values, such as the number of dry months, were not within the proposed range. The restriction thresholds that we extracted were more suited regionally, as they were derived from the existing oil palm plantations, enabling a more precise mapping of suitable areas for oil palm cultivation.

We used IPCC methodology to calculate the potential carbon stock changes resulting from future oil palm plantation expansion into forests, croplands, and grasslands in 47 countries (Table S6–S8). The results showed that potential carbon stock changes were significantly reduced following filtration of land mask. The potential carbon emissions per unit area will be reduced by 61.6% (from 77.0 to 29.6 Tg C/ha), 57.3% (from 73.4 to 31.3 Tg C/ha), and 54.9% (from 56.7 to 25.6 Tg C/ha) in the global, continental, and national level maps, respectively. Carbon stock changes caused by forest loss were respectively 10,230 (2,538–19,927) Tg C, 8,037 (1,972–15,653) Tg C, and 2,679 (698–5,184) Tg C in

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the global, continental, and national level maps, compared with the pre-filtration values: 85,035 (15,199–155,704) Tg C, 60,956 (11,408–112,264) Tg C, and 19,209 (3,839–37,814) Tg C. This positive effect of the sustainable expansion strategy was more pronounced in protected, carbon-rich forests. For example, on the continental level map, the total potential carbon losses decreased by about 87.4% following filtration of land mask. The emissions per unit area of invaded forests decreased from 103.9 to 81.8 Tg C/ha, which significantly improved over historical carbon emissions caused by oil palm expansion (139.4 Tg C/ha). Furthermore, cultivating oil palm on grasslands does not result in carbon emissions (Germer & Sauerborn, 2008; Goodrick et al., 2015).

The suitable land with national thresholds is more appropriate for local oil palm growers to expand plantations. However, the oil palm samples were only distributed in 15 countries, making it impossible for most countries to map areas suitable for oil palm cultivation. The remaining suitable land depicted in this map was less than that reported in other studies, except for Indonesia and Malaysia. For Indonesia, an area of about 17.26 Mha (7.16 Mha plus existing oil palm plantations [11.54 Mha] and minus affected protected areas [0.03 Mha] and peatland [1.41 Mha]) is close to the estimation (18.19 Mha) from Pirker et al. (2016). The remaining suitable land in Malaysia amounts to only 0.39 Mha on the national level map. However, Pirker et al. (2016) argued that Malaysia had exceeded the area for sustainable production, this is because they did not spatially exclude existing oil palm plantations. National level maps depicted sustainable land based on areas of existing oil palm plantations and the number of samples in the country. However, the usual practice of planting oil palm first in optimal land affected the assessment. We identified 0.44 Mha in Ghana, which is far below the amount previously identified (6.7 Mha by Rhebergen et al. [2016]) but approximately equal to the area of optimal land (0.41 Mha by Pirker et al. [2016]). Colombia, Nigeria, Ivory Coast, and COD have considerable amounts of land available for oil palm expansion, but far less than the area proposed by Pirker et al. (2016). Our national level maps show that potentially available land is sparse in other countries.

The global and continental level maps showing still availably suitable lands for oil palm cultivation are significant inputs supporting sustainable oil palm expansion. We identified 53.8 and 41.2 Mha, respectively, in Brazil, using the global and continental maps, with these values respectively being approximately 10.5 Mha more and 2.2 Mha less than the highly suitable area obtained by Pirker et al. (2016). However, the remaining suitable land in Brazil calculated from the national values was only 0.05 Mha, which is well below the values calculated using the global and continental level maps. This is because of the small sample size (90) and the preference of local growers to expand oil palm on perfectly suitable land, leading to narrow restriction thresholds in Brazil. This finding suggests that restrictions in the targeted land could be relaxed for the future expansion of oil palm plantations in Brazil. A similar condition is found in Nigeria, Colombia, Ivory Coast, COD, and Ghana. Countries with larger potential areas for expansion in the continental level map were mostly located in Latin America and Africa (Brazil, Nigeria, Colombia, Indonesia, Ivory Coast, COD, Ghana). These countries could be the primary areas of future oil palm expansion.

The national level map is more instructive than the global and continental level maps for oil palm cultivation at national scales. An increase in sample size is, however, crucial for improving the map's credibility. Findings for Indonesia and Malaysia, which are currently the centers of oil palm plantation (containing 57% of the samples), are more convincing. For other countries, the values in the continental and global maps are similar to those reported in previous studies, indicating that this approach is highly feasible and that the credibility of the assessment results would improve by increasing the oil palm sample size. Subsequent studies should consider increasing the sample size in each country, but a legitimate increase in sample size may require more precise oil palm dataset and higher-resolution validation data. Furthermore, we did not use geospatial information on market accessibility and planters' social and cultural characteristics, which are complicated but essential influencing factors in expanding plantations. Future studies should include these factors into the analysis to find suitable land for oil palm expansion.

4. Conclusion

Oil palm is a productive oil crop that requires less land area on a yield basis relative to other oil crops to meet the increasing global demand for vegetable oils. However, it is undeniable that inappropriate oil palm cultivation has caused severely negative environmental impacts, primarily as a result of planters' negligence for biodiversity conservation and the environmental protection. In our study, oil palm plantations extended into large areas of conservation landscapes, especially forests. Despite the annual decrease in the total area of oil palm planting, the proportion of the oil palm plantation expansion into forests shows a divergent trend, indicating that the oil palm expansion still threatens the forested land. We also mapped the global land suitability for sustainable oil palm production, showing the remaining land potentially available for oil palm expansion. Continued expansion of the oil palm industry is appropriate in some countries, such as Indonesia, whereas oil palm expansion in other countries, such as Malaysia, is no longer recommended. Considering multi-level maps, even without considering the most favorable planting conditions in the country, Brazil, Thailand, COD, Colombia, Nigeria, Indonesia, India, Ivory Coast, Venezuela, and Ghana have larger amount of areas suitable for oil palm and therefore they could explore large-scale oil palm production.

A rational approach to solve issues related to unsustainable production of oil palm is necessary rather than boycotting products of oil palm in the international market. Selecting only the most suitable areas for oil palm production and increasing the yield of oil palm would be alternative methods for sustainable production of oil palm industry. This study could guide oil palm growers to identify suitable areas and expand oil palm only on those areas. In this way, areas that have high conservation values can be avoided from expanding oil palm.

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