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Carbon emissions from forest conversion by Kalimantan oil palm plantations

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Oil palm supplies >30% of world vegetable oil production[1]. Plantation expansion is occurring throughout the tropics, predominantly in Indonesia, where forests with heterogeneous carbon stocks undergo high conversion rates[2–4]. Quantifying oil palm's contribution to global carbon budgets therefore requires refined spatio-temporal assessments of land cover converted to plantations[5,6]. Here, we report oil palm development across Kalimantan (538, 346 km^2) from 1990 to 2010, and project expansion to 2020 within government-allocated leases. Using Landsat satellite analyses to discern multiple land covers, coupled with above- and below-ground carbon accounting, we develop the first high-resolution carbon flux estimates from Kalimantan plantations. From 1990 to 2010, 90% of lands converted to oil palm were forested (47% intact, 22% logged, 21% agroforests). By 2010, 87% of total oil palm area (31,640 km^2) occurred on mineral soils, and these plantations contributed 61–73% of 1990–2010 net oil palm emissions (0.020–0.024 GtC yr^{-1}). Although oil palm expanded 278% from 2000 to 2010, 79% of allocated leases remained undeveloped. By 2020, full lease development would convert 93, 844 km^2 (~90% forested lands, including 41% intact forests). Oil palm would then occupy 34% of lowlands outside protected areas. Plantation expansion in Kalimantan alone is projected to contribute 18–22% (0.12–0.15 GtC yr^{-1}) of Indonesia's 2020 CO_2-equivalent emissions. Allocated oil palm leases represent a critical yet undocumented source of deforestation and carbon emissions.

Oil palm (*Elaeis guineensis*) plantations in Sumatra and Kalimantan produce ~50% of palm oil worldwide[1], and Indonesia plans to double national palm oil production primarily by expanding landholdings in Kalimantan and Papua[7]. In 2010, Indonesian palm oil and palm kernel oil production generated ~US$11.1 billion (ref. 1). Yet, Indonesia ranks among the top national greenhouse-gas (GHG) emitters, largely from land-based carbon emissions including deforestation and forest degradation[8]. Although fires are the dominant cause of Indonesia's emissions during droughts[9], oil palm's contribution to deforestation and emissions is uncertain. Over 50% of oil palm was planted from 2000 to 2010 (ref. 10), yet automated analysis of remote-sensing products has proved insufficient to detect young (<10 yr) or small-scale (<200 ha) oil palm agriculture[11,12]. Recently developed plantations remain undocumented across mineral soils[13], which comprise 88% of Kalimantan's land area. Accounting for past and potential near-term emissions from plantation expansion is essential to estimate the contribution of oil palm to global carbon emissions, as well as to assess the potential market value of Indonesia's forest carbon.

Kalimantan harbours diverse land covers containing highly variable carbon stocks. Accurate emissions assessments therefore require tracking multiple land cover pathways to oil palm, including transitions from logged lands and agroforests[6]. Despite ~40% loss of lowland forest (<300 m above sea level; a.s.l.) across Kalimantan and Sumatra from 1990 to 2005 (refs 4,14), Indonesia maintains the third most extensive tropical forest among nations[8]. Residual intact Kalimantan forests support considerable above-ground carbon (AGB, tC ha^{-1}; refs 2,6). Yet, since the 1980s, ~80% of Kalimantan forests were under federally managed industrial timber concessions[14,15]; this extensive logging reduced carbon stocks. Mosaics of community-managed agroforests and agricultural fallows may also have relatively high AGB (ref. 16). In addition, Kalimantan contains ~13% of the world's tropical peatlands[17,18], with substantial stores of below-ground carbon. Peat draining and burning for oil palm threaten these peatland carbon storage systems[19–21].

Here, we quantify oil palm extent across Kalimantan from 1990 to 2010, assess land cover types converted to oil palm, and estimate net carbon emissions (carbon flux) from oil palm agriculture. Oil palm plantation lease maps, representing government-approved plantations at several stages of the permitting and development process, were compiled and compared with our digitized oil palm maps. Using these allocated leases to constrain future oil palm expansion, we evaluate outcomes generated from three oil palm development scenarios, including business-as-usual (BAU) and two reduced emissions from deforestation and forest degradation (REDD+) initiatives, from 2010 to 2020.

Across Kalimantan, areas cleared for, or planted with, oil palm were digitized from Landsat satellite images (~30 m, $n = 35$ scenes) in 1990, 2000 and 2010 eras (Fig. 1 and Supplementary Figs S1 and S2 and Supplementary Information S1). In 1990, oil palm covered 903 km^2. From 1990 to 2000, plantations expanded by 746 km^2 yr^{-1} to occupy 8,360 km^2. Since 2000, clearing rates increased 212% to 2,328 km^2 yr^{-1}. By 2010, plantations covered 31,640 km^2, with 87% on mineral soils and 13% on peatlands, roughly proportional to Kalimantan's land area on mineral and peat soils, respectively. Peatland conversion to oil palm increased from 3% in the 1990s

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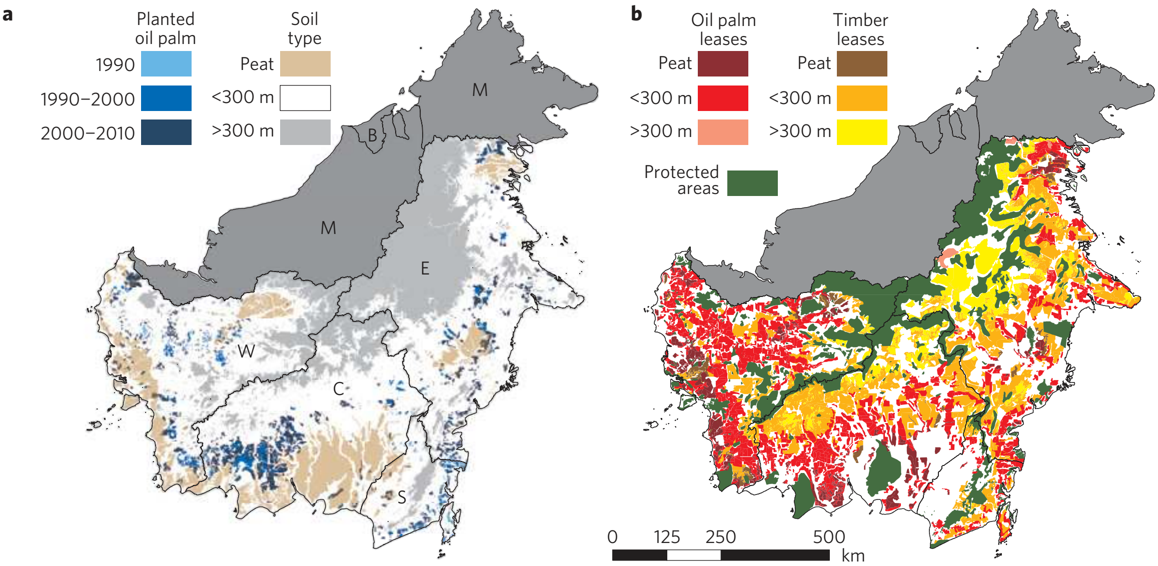

Figure 1 | Planted oil palm, oil palm leases, timber leases and protected areas in Kalimantan. Malaysian Federated States of Sarawak and Sabah (M) and Brunei (B) are dark grey. Mineral soils are distributed among elevation classes <300 m a.s.l. and >300 m a.s.l.; >99% of peat soils are <300 m a.s.l. **a**, From 1990 to 2010, oil palm expanded from 903 km^2 to 31,640 km^2, occupying 9% of lowlands (<300 m a.s.l) outside of protected areas, distributed among West (W; 28%), Central (C; 40%), South (S; 8%) and East (E; 23%) Kalimantan provinces. **b**, In 2010, 64% of Kalimantan's lowland area was allocated as follows: planted oil palm and awarded plantation leases (30%); logging concessions and pulp and paper plantations (Timber Leases, 24%); protected areas (10%). Residual lands, depicted in white, comprise only 31% of Kalimantan's total land area.

to 16% in the 2000s. In 2010, oil palm plantations occupied 9% of Kalimantan's lowlands outside of protected areas.

The median lease area is 127 km^2 across all allocated lease polygons, with several conglomerates holding $>1{,}000$ km^2 ($n=838$ polygons, 118,085 km^2 total area, 83% on mineral soils, Fig. 2). In 2010, 21% of lease area contained oil palm. Over 23% of planted oil palm occurred outside leases. These anomalies probably result from incomplete or outdated records provided by government agencies and lease maps generated without field data. Assuming all awarded leases are converted to oil palm under BAU, 2010 plantation area increases ~300% to occupy 125,484 km^2, including 34% of Kalimantan's lowlands outside of protected areas. When logging concessions and pulp and paper plantations are combined with leases, >54% of Kalimantan's lowlands are controlled by extractive land-based industries (excluding mining), with another 10% in protected areas.

To determine the land cover types converted to plantations (Supplementary Table S1), we classified 1990- and 2000-era Landsat data using the Carnegie Landsat Analysis System-lite (CLASlite) with a decision tree algorithm[22]. From 1990 to 2010, oil palm converted primarily intact (47%) and logged forests (22%) as well as agroforests (21%, Fig. 3). Only 10% of plantations were established on non-forested lands. Under BAU, all unplanted areas within allocated oil palm leases are developed by 2020. On the basis of these awarded leases, oil palm is projected to clear a further 93,844 km^2, comprising 90% forested lands (41% intact, 21% logged, 27% agroforest) and 10% non-forests. Over 18% of projected conversion occurs on peatlands.

We evaluated the contribution of oil palm plantation development to Kalimantan deforestation by comparing our findings with estimates of 2000–2008 forest loss (~2,812 km^2 yr^{-1}; ref. 3). By projecting this mean annual deforestation rate to 2010 and combining our intact and logged forest land covers to approximate the forest class of ref. 3, we estimate that oil palm plantations were directly responsible for ~57% of 2000–2010 deforestation (15,949 km^2).

The carbon flux from oil palm agriculture was estimated by combining land cover conversion results with measures of AGB, emissions from peatland draining and burning, and sequestration

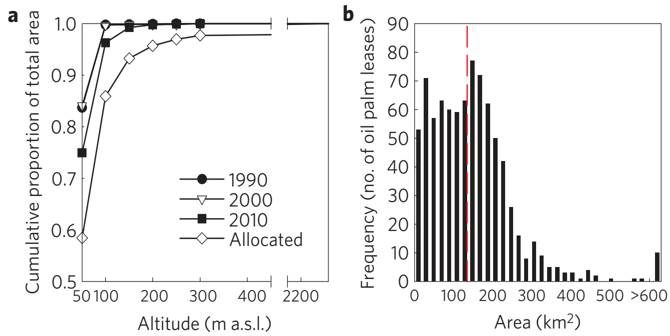

Figure 2 | Distribution of planted and allocated oil palm by altitude and plantation lease area. a, Applying a digital elevation model (90 m) across Kalimantan (sea level to 2,294 m a.s.l.) indicated that in 2010, 96% of planted and 86% of allocated oil palm occurred on lands <100 m a.s.l. Proportions are cumulative, and represent total area occurring within each elevation class. **b**, Lease areas were estimated by compiling provincial maps (Supplementary Methods). Across all plantation lease polygons with unique names or no name ($n=838$), the median area indicated by the red dashed line was ~127 km^2 (range 1–1,596 km^2).

from oil palm growth (Supplementary Table S2). By assuming that all AGB was emitted the year of conversion, but calculating emissions from peatland soils on an annual basis, we employ a hybrid annual balance/net committed emissions approach[23]. Thus, we underestimate emissions from peat draining, because these emissions continue as long as peatlands remain dry[17,19,21]. Many oil palm companies cleared lands with fire in the 1990s (ref. 20) and field observations suggest that present prohibitions on burning to clear peatlands are often unenforced. We therefore run scenarios assuming that fire is applied to either all or none of these peatlands during plantation development. We report only carbon flux sourced directly from oil palm development.

Conservatively assuming that peatland soils are not burned during oil palm development, from 1990 to 2000, cumulative net

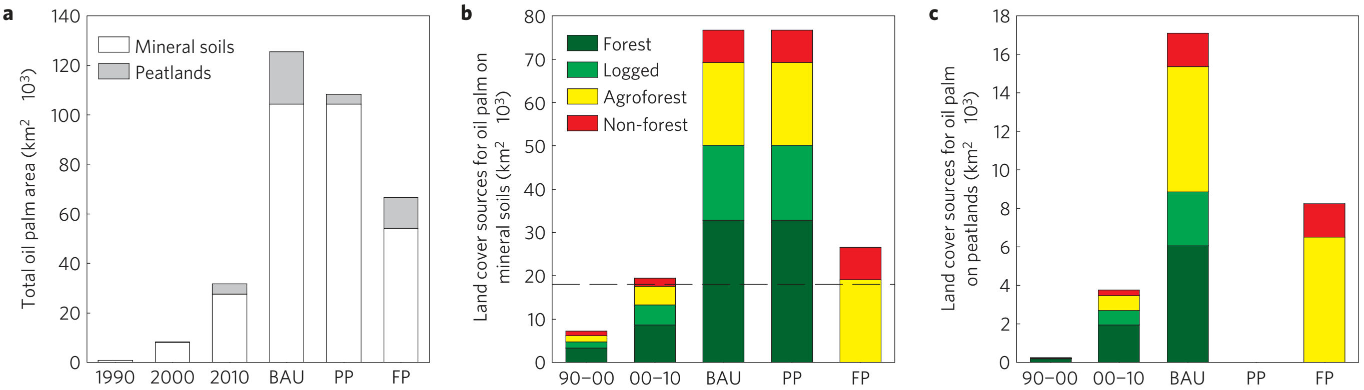

Figure 3 | Oil palm area planted and land cover converted, 1990–2020. **a**, Planted oil palm area in 1990, 2000 and 2010, and projected under 2010–2020 scenarios across peat and mineral soils. **b**,**c**, From 1990 to 2010, 39% of oil palm was established in intact forests on mineral soils (**b**) with 13% on peatlands (**c**). The BAU scenario assumes all oil palm leases are converted, without any further leases granted; Peatland Protection (PP) prohibits peatland conversion within leases; Forest Protection (FP) prohibits clearing intact and logged forests within leases. The dashed line in **b** denotes the top of the *y* axis in **c**.

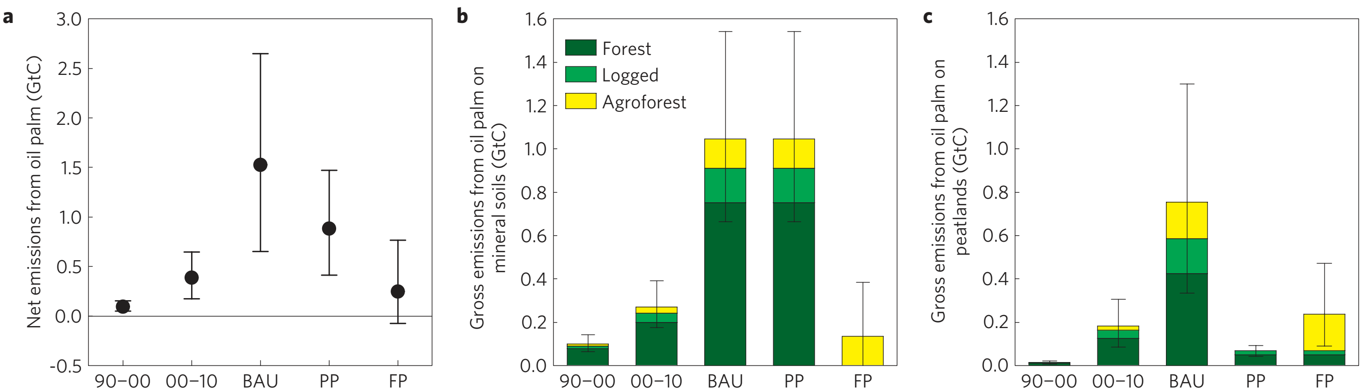

Figure 4 | Carbon emissions from oil palm plantations, 1990–2020. Estimates assume peatlands are burned for plantation development. **a**, Net carbon emissions in two previous decades with future 2010–2020 scenarios. **b**, Mineral soils contributed 65% of 1990–2010 gross emissions. **c**, Peatlands generated 26% of these emissions through peatland draining and burning, and 9% from above-ground biomass conversion. BAU assumes all awarded plantation leases are developed; Peatland Protection prohibits peatland conversion within leases; Forest Protection prohibits intact and logged forest clearing within leases. Error bars represent estimates generated from low and high carbon bookkeeping model inputs (Supplementary Methods).

carbon emissions from land conversion to plantations totalled 0.09 GtC (0.05–0.14; Fig. 4 and Supplementary Table S3 and Supplementary Information S2). From 2000 to 2010, these emissions increased to 0.32 GtC (0.15–0.51). Clearing intact forests on mineral soils generated 56% of 1990–2010 gross oil palm emissions (that is, excluding sequestration from oil palm growth). Peatland conversion contributed 25% of gross emissions. With all awarded leases developed, 2010–2020 projected net emissions reach 1.21 GtC (0.54–2.06).

If plantations apply fire to clear peatlands, 1990–2020 cumulative net carbon emissions increase 24% above the non-fire scenario. Cumulative carbon flux totalled 0.09 GtC (0.05–0.15) and 0.39 GtC (0.17–0.65) from 1990 to 2000 and 2000 to 2010, respectively. From 1990 to 2010, 49% of gross carbon emissions were sourced from intact forests on mineral soils, and 35% were from peatlands. Peat burning alone may have contributed ~13% of gross emissions. Net cumulative carbon emissions sourced directly from plantations are projected to reach 1.52 GtC (0.65–2.65) from 2010 to 2020.

More than 75% of Indonesia's CO_2-equivalent emissions (~0.56 GtC yr^{-1} in 2005) are attributed to land cover change[24]. If all allocated leases are developed without fire, from 2010 to 2020, carbon emissions from Kalimantan oil palm plantations increase 284% and generate 27% of Indonesia's projected 2020 land-based emissions (Table 1). Assuming fire is used to prepare peatlands for oil palm, Kalimantan plantations contributed 21% of Indonesia's total emissions from land cover change in the mid-1990s, and 9% in the mid-2000s. If all awarded leases are developed, oil palm in Kalimantan alone would generate 34% of Indonesia's 2020 land-sourced emissions. Indirect land cover change (for example, wildfires, logging, displaced smallholder farmers) is not incorporated here but could create a further and potentially substantial carbon source[25,26]. Carbon emissions solely from oil palm industries may therefore constrain opportunities to meet Indonesia's pledged 26% reduction below projected 2020 GHG emissions levels[27].

To assess the relative potential of policies aiming to reduce land-based carbon emissions (for example, refs 28,29), we explore two alternative scenarios of oil palm development within allocated leases. Peatland Protection prevents peatland conversion within oil palm leases, thereby protecting ~17,100 km^2 of peatlands. Forest Protection prohibits clearing intact and logged forests for oil palm, but allows agroforest and non-forest conversion and thus retains ~59,000 km^2 of forested lands (Fig. 3). Implementation of such policies requires that awarded plantation development permits in forest or peatland areas be restricted or revoked, options that are not being considered in Indonesia at present.

In contrast with BAU, the Peatland Protection scenario yields 37–45% emission reductions, whereas the Forest Protection scenario decreases emissions 71–111%, resulting in 0.25 GtC

Table 1 | Contribution of Kalimantan oil palm development to Indonesia's national CO_2-equivalent emissions, 1990–2020.

Era	Scenario	Annualized emissions (GtC yr^{-1}): Indonesia Total	Indonesia LULCC	Kalimantan oil palm No Fire	Kalimantan oil palm Fire	Kalimantan oil palm emissions (percentage of Indonesia's national CO_2-equivalent emissions): Total No Fire	Total Fire	LULCC No Fire	LULCC Fire
1990–2000		0.13	0.04	0.01 (0–0.01)	0.01 (0–0.02)	7 (3–11)	7 (4–11)	20 (10–32)	21 (11–34)
2000–2010		0.56	0.44	0.03 (0.01–0.05)	0.04 (0.02–0.06)	6 (3–9)	7 (3–12)	7 (3–12)	9 (4–15)
2010–2020	BAU			0.12 (0.05–0.21)	0.15 (0.06–0.26)	18 (8–30)	22 (9–38)	27 (12–47)	34 (15–60)
2010–2020	Peat protection	0.69	0.44	0.09 (0.04–0.15)	0.09 (0.04–0.15)	13 (6–21)	13 (6–21)	20 (9–33)	20 (9–33)
2010–2020	Forest protection			0.01 (−0.01–0.05)	0.02 (−0.01–0.08)	2 (−2–7)	4 (−1–11)	3 (−3–12)	6 (−2–17)

Indonesian carbon emissions, converted from CO_2-equivalent GHG emissions, were derived from the First National Communication to the United Nations Framework Convention on Climate Change that assessed 1994 emissions[30], and Indonesian National Council on Climate Change 2005 estimates and 2020 projections[24]. We report net national emissions (Total), and net emissions sourced from land use/land cover change (LULCC), and compare scenarios assuming fire is applied to all (Fire) or none of the peatlands (No Fire). Low and high estimates, in parentheses, were developed by including low and high range carbon model inputs (Supplementary Methods). BAU, business-as-usual.

(−0.07–0.77) net emissions from 2010 to 2020 (Table 1). If fire is not used to clear peatlands, the best-case Forest Protection scenario generates 0.12 GtC in net carbon sequestration as a result of carbon stored by maturing plantations. These initiatives require protecting forests and peatlands from all proximate causes of land cover change, especially fires and logging[6].

Land management decisions are influenced by the distribution of benefits among diverse actors with asymmetrical influence[28]. Therefore, land cover outcomes may reflect land use value accrued to dominant agents, rather than net market value. Where REDD+ displaces oil palm agriculture, Indonesia's central government receives REDD+ funds, but forgoes palm oil export taxes. To assess the opportunity costs of implementing REDD+ at the national level, we compare oil palm export tax revenues (Supplementary Fig. S3 and Table S4) with gross revenues from avoided emissions generated by the Peatland Protection and Forest Protection scenarios for a 26-year plantation life cycle. With a 15% palm oil export tax, revenue from oil palm is US\$10,000 ha^{-1}. Applying US\$10 tCO_2^{-1} and assuming no burning for plantation development, avoided emissions revenue is US\$6,800 ha^{-1} or US\$7,100 ha^{-1} in the Forest Protection or Peatland Protection scenarios, respectively. If avoided emissions assessments incorporate peatland burning, Forest Protection revenues total US\$8,000 ha^{-1}. Only Peatland Protection benefits (US\$13,800 ha^{-1}) exceed export tax revenues from oil palm.

By providing high-resolution maps of plantations at all stages of development, we document 288% greater oil palm extent across Kalimantan than the most recent ~2000-era estimate[12]. Although our results confirm that oil palm increasingly is established on peatlands[6,13,20], we demonstrate that from 1990 to 2010, mineral soils received 87% of plantation development and generated 65–75% of gross emissions from Kalimantan oil palm. Despite representing <1% of Indonesia's land area, conversion of intact forests on mineral soils (12,072 km^2) contributed ~6% of Indonesia's national land-based 1990–2010 GHG emissions. Under certain market conditions and land management practices, REDD+ initiatives aimed at mitigating these emissions may generate national government revenues similar to oil palm export revenues.

Yet, allocated plantation leases now occupy 32% of lowlands outside protected areas. Oil palm companies are not required to account for forest loss or carbon emissions generated during plantation development. Moreover, leases are awarded without independent assessments of land use and carbon, and are not available for public review. Carbon emissions from undeveloped leases have therefore remained concealed and excluded from national emission projections. Kalimantan's leased plantation lands represent a significant near-future source of deforestation and associated carbon emissions. Increased transparency by the plantation sector is essential and urgently required for inclusion of oil palm agriculture in land management and emissions mitigation efforts.

Methods

Land cover classification and validation. Our land cover classification was developed from 1990- and 2000-era Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus images. To maximize cloud-free coverage, we compiled satellite data from 1990 to 2000, as well as images ±4 years from these target years. Multiple images per scene in a single era were often included in the data set, which consisted of 116 Landsat scenes spanning 1988–1994 ($n = 52$), and 1999–2002 ($n = 64$). CLASlite software was used to pre-process raw data to reflectance, and to apply a probabilistic spectral un-mixing model yielding fractional cover, consisting of photosynthetic vegetation, non-photosynthetic vegetation, and soil[22]. Before classification, cloudy areas and pixels with ≥15° slope were masked, and single-era images were mosaicked.

A decision-tree algorithm, originally developed to detect deforestation and disturbance in Peru[26], was applied to classify CLASlite mosaics into intact forest, logged forest, agroforest and non-forest land covers. Where we had ground-based validation data and/or very high-resolution IKONOS or Quickbird images (~14,000 km^2 coverage), this algorithm was modified to detect land cover under various atmospheric and geometric conditions as well as across diverse vegetation formations.

The 1990- and 2000-era products contained 57% and 62% data, respectively. Pixels containing data in both eras composed 41% of the study area. Although no-data regions potentially constrain analysis of transitions among land cover classes, our data set has ample coverage to evaluate land conversion to oil palm. Un-masked pixels in 1990 comprise 65% of planted oil palm in 2000, and un-masked pixels in 2000 compose 77% of 2010 planted oil palm and 71% of allocated leases.

Land cover validation. We validated the classified data set by randomly selecting 400 points from each of the 1990- and 2000-era mosaics ($n = 800$ points). Points were visually classified from raw Landsat data as belonging to one of the four land cover classes. If a point fell on an edge between two land covers, in a cloud or cloud shadow, or in an oil palm area, it was removed from the data set. We calculated overall accuracy (po), and the kappa coefficient (k) from a total of 582 validation points (1990: $n = 279$; 2000: $n = 303$). The comparison yielded a po of 0.77 and a k of 0.65.

Oil palm identification. Areas cleared for or planted with oil palm in 1990, 2000 and 2010 eras were manually digitized from Landsat satellite images. Multiple image dates before the target year often were required to detect and verify oil palm development. Clearing included roads through forest if these roads were arranged in distinctive gridded patterns indicating oil palm development. Where possible, oil palm detected in Landsat was confirmed using Quickbird, IKONOS or ALOS PALSAR imagery.

Land cover change projections. To assess potential future land cover sources for oil palm development in Kalimantan, we projected land cover in un-planted oil palm leases to 2010. Rates of land cover change from 1990 to 2000 were stratified by province and land type. We limited our calculations to un-masked pixels in both 1990- and 2000-era data sets. These gross rates of change were applied to 2000-era land cover within un-planted oil palm leases to predict 2010 land cover distribution within leased areas.

Land cover source analysis. We derived land cover sources for oil palm planted in 2000 from the 1990-era land cover product, for oil palm in 2010 from the 2000-era product, and for planned leases from projected 2010 land cover. Owing to the 10-year interval between the land cover product and oil palm coverage, our analysis may overestimate forest area conversion. Yet, the proportion of forested land cover (intact, logged and agroforest) converted to oil palm across Kalimantan (90%, 1990–2010) was surprisingly consistent with results from a detailed West Kalimantan case study (86%, 1989–2011; ref. 6).

Carbon bookkeeping model and sensitivity analysis. To estimate carbon flux from oil palm, a carbon bookkeeping model accounted for changes in AGB and peat soil organic carbon. A range of scenarios were evaluated by presenting mean, low, and high carbon flux estimates. To derive these values, we input mean AGB and peatland carbon emissions, as well as low and high values, calculated from 95% confidence intervals (oil palm growth equations) or ± 1 s.d. (all other carbon inputs). Our model is described in detail in the Supplementary Methods.

Avoided emissions and export tax revenues. Revenues from reduced emissions in REDD+ scenarios were calculated by coupling avoided emissions with realistic carbon credit prices. Export tax revenues from crude palm oil and crude palm kernel oil products were estimated for a typical 26-year plantation lifetime. We calculated export rates and prices from 2007 to 2009 annual domestic production, export quantity and export value (Supplementary Table S4). We coupled these estimates with plausible export tax rates as well as annual fresh fruit bunch yields and oil extraction rates developed from empirical data on Indonesian industrial-scale oil palm production to generate estimates of oil palm export tax revenue.

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Author contributions

L.M.C. conceived and designed the project; G.P.A. provided software and designed the land cover classification algorithm; A.M.P., S.N.T., K.M.C. and J.M.A. conducted spatial assessments; K.M.C., A.M.P. and L.M.C. compiled and analysed data; and K.M.C. and L.M.C. wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to K.M.C. or L.M.C.

Competing financial interests

The authors declare no competing financial interests.

CORRIGENDUM

Carbon emissions from forest conversion by Kalimantan oil palm plantations

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In the version of this Letter originally published online, there were several errors in calculations. The net 1990–2010 oil palm emissions given in the abstract should have been 61–73%. In the fire scenario, the increase in cumulative net carbon emissions above the non-fire scenario should have been 24%, and peatland emissions amounted to 35% of gross emissions from 1990–2010. Intact forests on mineral soils converted to oil palm plantations from 1990–2010 (12,072 km^2) account for < 1% of Indonesia's land area. These errors have now been corrected in all versions of the Letter.