

# Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia

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Industrial agricultural plantations are a rapidly increasing yet largely unmeasured source of tropical land cover change. Here, we evaluate impacts of oil palm plantation development on land cover, carbon flux, and agrarian community lands in West Kalimantan, Indonesian Borneo. With a spatially explicit land change/carbon bookkeeping model, parameterized using high-resolution satellite time series and informed by socioeconomic surveys, we assess previous and project future plantation expansion under five scenarios. Although fire was the primary proximate cause of 1989–2008 deforestation (93%) and net carbon emissions (69%), by 2007–2008, oil palm directly caused 27% of total and 40% of peatland deforestation. Plantation land sources exhibited distinctive temporal dynamics, comprising 81% forests on mineral soils (1994–2001), shifting to 69% peatlands (2008–2011). Plantation leases reveal vast development potential. In 2008, leases spanned ~65% of the region, including 62% on peatlands and 59% of community-managed lands, yet <10% of lease area was planted. Projecting business as usual (BAU), by 2020 ~40% of regional and 35% of community lands are cleared for oil palm, generating 26% of net carbon emissions. Intact forest cover declines to 4%, and the proportion of emissions sourced from peatlands increases 38%. Prohibiting intact and logged forest and peatland conversion to oil palm reduces emissions only 4% below BAU, because of continued uncontrolled fire. Protecting logged forests achieves greater carbon emissions reductions (21%) than protecting intact forests alone (9%) and is critical for mitigating carbon emissions. Extensive allocated leases constrain land management options, requiring trade-offs among oil palm production, carbon emissions mitigation, and maintaining community landholdings.

greenhouse gas emissions | agribusiness | *Elaeis guineensis* | moratorium | REDD+

Global demand for food, biofuels, and natural resources drives capitalized agricultural development, especially for tropical plantations (1–4). Forest and peatland conversion to plantation agriculture may be a substantial source of greenhouse gas (GHG) emissions from land cover change (5, 6), which generates 10–20% of net global GHG emissions (7). By acquiring extensive arable lands, plantations also affect land availability for smallholder farmers and communities, potentially altering local livelihood options (8, 9). Whereas environmental degradation from tropical agribusiness may overwhelm benefits of high-yield plantations for world food security (6, 10), impacts on carbon (C) flux and livelihoods are highly uncertain because locations and land sources for plantations remain largely undocumented.

Complex processes of land acquisition and plantation development unfold across heterogeneous biophysical and socio-political landscapes in both time and space. Land cover histories constrain present land use and potential outcomes from agribusiness expansion (11). Discerning the land cover trajectories that precede agribusiness development requires documenting historical land use by various agents, as well as land jurisdiction (12, 13).

Longitudinal, regionally informed land cover assessments at high temporal and spatial resolution are essential to capture the land cover sources and dynamic, often-punctuated changes brought about by plantation expansion (14, 15).

Such refined evaluations are critically needed in tropical countries, especially Indonesia. Since 1990, Indonesia has experienced one of the most rapid plantation expansions worldwide. The Agricultural Ministry's records indicate that from 1990 to 2010, oil palm (*Elaeis guineensis*) area increased 600% to 7.8 Mha (16). Over 90% of this development occurred in Sumatra and Indonesian Borneo (Kalimantan) (17), regions that lost ~40% of lowland forests from 1990 to 2005 (18). As a result of this extensive deforestation, annual GHG emissions in Indonesia—currently among the top 10 national emitters—are sourced predominantly from land cover/land use change (19). However, the locations, patterns, and land cover sources for oil palm plantation expansion; the extent and distribution of undeveloped oil palm leases pending near-term development; and carbon emissions from oil palm agriculture remain largely undocumented (20–22).

To acquire such datasets for tropical regions requires integrating remote sensing products with interdisciplinary methods and analyses (15). Although optical remote sensing satellites such as Landsat have sufficient temporal (~20 d) and spatial (<30 m) resolution to detect small land cover patches and punctuated land cover change, they are hampered by cloud cover and cannot be used to map carbon stocks (23, 24). Technologies such as light detection and ranging (LiDAR) and radar are effective for mapping aboveground live biomass (AGB) [metric tons (t) C·ha<sup>-1</sup>] in tropical forests (e.g., refs. 25 and 26), and even belowground carbon in peatlands (27), yet are not available to capture historical (i.e., pre-2000) conditions. As a result of these limitations, carbon flux estimates from land cover change typically rely on multiplying forest area lost by forest AGB (28). However, such measures contain considerable uncertainties because they treat AGB as a discrete rather than a continuous variable, cannot account for carbon flux from land cover change pre- and postdeforestation, and may group multiple land covers into a few broad classes (29). Until carbon flux from land cover change can be directly assessed, a transition-based framework—where emissions and sequestration are estimated for multiple land cover transitions over time and space—is the most robust method to evaluate carbon emissions from agribusiness-related land change (30).

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Quantifying carbon stocks for major tropical land covers, including logged forests and existing agricultural lands, presents several major challenges. Since the 1980s, Kalimantan's intact forests experienced massive degradation from logging in federal timber concessions, with related declines in AGB, and subsequent regrowth (12, 14, 31). However, forest degradation from logging is difficult to detect due to its spatial and temporal heterogeneity, and timber volume removed and biomass accumulation from forest regeneration are variable (15, 32). Moreover, rural agrarian communities in Kalimantan maintain considerable landholdings associated with swidden agriculture (9, 33). These managed agricultural lands, common throughout the humid tropics, are characterized by fallow-cropping cycles of land clearing and regrowth that generate substantial, yet heterogeneous and dynamic, carbon stocks (34, 35). Because Kalimantan contains one-third of Indonesia's peatlands, which harbor the most tropical peat carbon worldwide, belowground carbon is also critical (36, 37). Clearing and draining these peatlands produce considerable carbon emissions from peat oxidation and burning (38, 39).

Although oil palm plantations continue to expand (40), the Government of Indonesia (GOI) has pledged to reduce 26% of their projected business-as-usual 2020 GHG emissions (2.5–3 Gt CO<sub>2</sub> equivalent) (41). Diverse international initiatives—including Reducing Emissions from Deforestation and Forest Degradation (REDD+), industry roundtables (e.g., Roundtable on Sustainable Palm Oil), and multinational donor agreements—seek to reduce carbon emissions or mitigate impacts of tropical agribusiness. Spatially explicit land change models are useful heuristic tools to evaluate the potential of these proposed policies to achieve their intended outcomes (11, 42). Such models facilitate comparisons among future scenarios that may incorporate economic conditions, natural phenomena, company practices, and smallholder decision making. Ideally, scenario modeling identifies unforeseen relationships and outcomes to provide critical insights for evaluating trade-offs among policies and practices.

Given the importance of Indonesia's land-based carbon emissions, and uncertainties surrounding historical and future oil palm development, we developed a longitudinal study of oil palm plantation development (1989–2020) in Ketapang District, West Kalimantan (Fig. 1). This district comprises the full range of land covers found in Kalimantan, has experienced rapid and extensive land cover change from diverse processes and agents (e.g., wildfires, logging, and plantations), and was among the earliest districts to receive private sector oil palm development (~1994). Using this representative region, we (i) evaluate how allocated and planted oil palm, including land cover types converted, vary across both space and time; (ii) assess the relative contribution of oil palm expansion to deforestation and carbon flux; and (iii) model future scenarios of oil palm expansion and forest conservation policies to

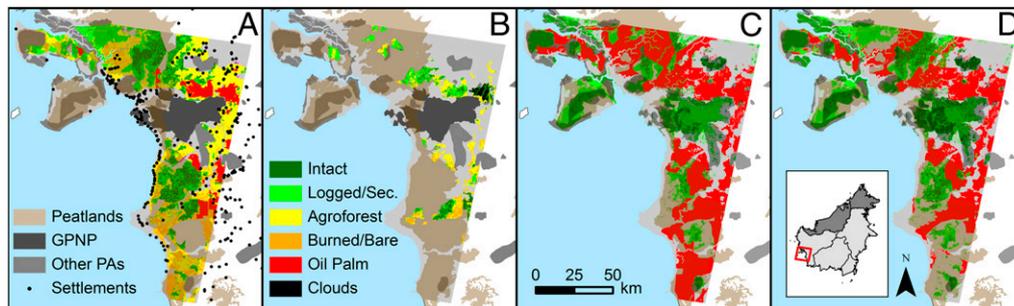
examine potential effects on land cover, carbon flux, and agrarian community landholdings.

To assess land cover change, we evaluated transitions among land cover classes (Fig. 2) derived from classified Landsat images acquired from 1989 to 2008, supplemented by a 2011 Landsat image with recent oil palm expansion delineated. Then, we modeled the potential effects of future oil palm expansion and forest conservation policies on land cover, carbon flux, and rural agrarian communities from 2008 to 2020. We contrasted five locally informed scenarios of oil palm development: business as usual (BAU), moratoria (M) on oil palm expansion into peatlands and intact (MInt) and previously logged forests (MSec), and forest protection (FP) for intact (FPInt) and previously logged (FPSec) forested lands exempt from oil palm expansion under the moratorium.

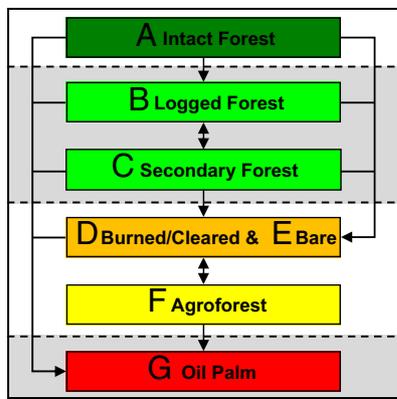
## Results

**Oil Palm Development.** In this Ketapang study region, oil palm plantation land clearing was first observed in the 1994 Landsat image. By 2008, plantation area ( $n = 16$  leases) had expanded to occupy 6% of land outside protected areas (PAs) (Fig. 1A). Analysis of regional governmental records indicates that median initial oil palm lease clearing occurred 3 y (range 1–6) after the first record of lease application. Because oil palm development is controlled by lease allocation and influenced by market and political conditions, expansion rates were highly punctuated. From 1994 to 1997, all planted oil palm (0.60% of non-PA land area·y<sup>-1</sup>) occurred in leases awarded from 1990 to 1994 ( $n = 6$ ), predominantly in former logging concessions (14). From 1997 to 2005, a period characterized by political and financial volatility, we observed reduced expansion in active leases (0.04%·y<sup>-1</sup>), and no new leases began clearing. Elevated 2005–2008 clearing rates (1.33%·y<sup>-1</sup>) were facilitated by clearing in 10 new leases distributed since 2003, coupled with relatively high export commodity prices (6). In 2008, 65% of non-PA lands were allocated to oil palm leases ( $n = 45$  leases). However, 91% of these leased lands ( $n = 29$  leases) had yet to begin land preparation and clearing. From 2008 to 2011, 11 leases initiated clearing, driving high conversion rates (2.60%·y<sup>-1</sup>), and oil palm expanded to occupy 14% of non-PA lands (Fig. 1B). Eighty percent of allocated lease area remains unplanted, with 61% on peatlands.

**Land Cover Sources for Oil Palm.** From 1989 to 2008, forests were the primary land cover source (49%) for oil palm plantations. Intact forests composed the majority of this conversion (21%), followed by secondary (21%) and logged (7%) forests. In addition, 37% of oil palm replaced agroforests and agricultural fallows. Only 14% of oil palm was sourced from burned/cleared and bare lands. Across the time series, land and soil types sourced for oil palm expansion were dynamic (Fig. 3). From 1994 to 2001, 81% of



**Fig. 1.** Study region in Ketapang District, West Kalimantan, Indonesia. This coastal region (12,000 km<sup>2</sup>, Landsat path/row 121/061) contains ~50% peatlands and surrounds Gunung Palung National Park (GPNP, 1,000 km<sup>2</sup>) and other protected areas (PAs, 1,800 km<sup>2</sup>). (A) 2008 land cover in oil palm leases. Whereas 6% of non-PA lands were cleared for or planted with oil palm, 91% of plantation leases (6,037 km<sup>2</sup>,  $n = 45$ ) sited mainly (62%) on peatlands remained undeveloped. (B) Land cover sources for oil palm, 1994–2011. Forests (intact, logged, and secondary) were the primary land cover source (49%) for oil palm. By 2011, oil palm spanned 14% of non-PA lands. (C) Business-as-usual (BAU) scenario, 2020. Forests cover only 24% of the region, and oil palm occupies 41% of non-PA lands. (D) FPsSec scenario, 2020. Protection against deforestation and degradation of intact and logged forests in PAs and undeveloped oil palm leases yields 36% greater forest fraction (32% of the region) and 28% lower oil palm area (~30% of non-PA lands) compared with BAU. Future land cover maps (C and D) were chosen from 60 model runs per scenario.

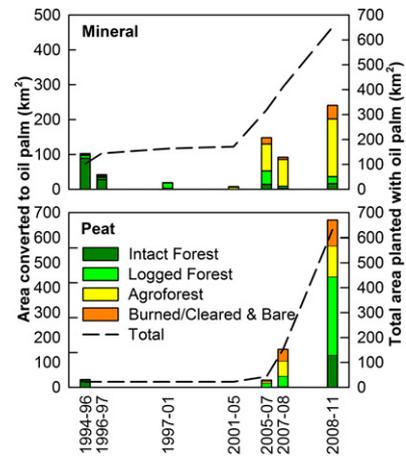


**Fig. 2.** Land cover transitions. Our land cover change simulation, implemented in Dinamica environment for geoprocessing objects (EGO) (51), incorporated dynamic forest degradation (logging), deforestation, and regrowth transitions among seven major land cover classes derived from Landsat satellite data: (A) intact forests, closed-canopy natural forests without detectable evidence of disturbance; (B) logged forests, natural forests with detectable canopy disturbance; (C) secondary forests, recovering logged forests (i.e., not burned, cleared, or relogged after the initial logging event); (D) burned and cleared lands, nonforests characterized by recent clearing or burning, including fields burned or cleared for swidden rice production; (E) bare lands, including roads, rivers, human settlements, and open mines; (F) agroforests and agricultural fallows, swidden agricultural production systems including rice fields, rice fallows, rubber, fruit gardens, and coconut groves, with regrowth on previously burned, cleared, and bare soil areas; (G) oil palm, areas cleared for or planted with oil palm. Unidirectional land cover transitions are indicated by dashed lines. For example, although intact forests can be logged, these logged forests cannot return to their previous intact state within the modeled 32-y time series.

plantations were converted from forests on mineral soils. Conversely, from 2001 to 2008, agroforests and nonforests were cleared at the highest rates (72%). Since 2008, forested peatlands composed the largest fraction (44%) of conversion. Through 2007, 73% of oil palm expansion occurred on mineral soils with 27% on peatlands. However, from 2007 to 2008, peatlands composed 54% of conversion, reaching 69% from 2008 to 2011. By 2011, planted oil palm spanned 51% mineral soils and 49% peatlands.

**Forest Cover Loss.** Deforestation—conversion of intact, logged, and secondary forest—averaged  $2.9\% \cdot y^{-1}$  from 1989 to 2008 (Table S1). Forest cover outside PAs decreased from 59% to 22%, with especially steep declines in intact forest area (51–6%, Fig. S1). Forest loss peaked at  $9.0\% \cdot y^{-1}$  during extensive fires associated with the 1997–1998 El Niño Southern Oscillation (ENSO) (12). Wildfires escaping from oil palm plantations likely contributed to this deforestation; ~8% of total area burned in 1997 occurred <5 km from oil palm. The major proximate causes of forest cover loss were fire related (93%), including transitions to agroforests and agricultural fallows and direct conversion by fire. Whereas only 6% of regional 1994–2008 forest loss could be directly attributed to oil palm expansion, by 2007–2008, 27% of deforestation was ascribed to oil palm, including 40% of all peatland deforestation. Over 50% of forests converted to oil palm had been logged before forest clearing. Although we observed several locations where logging was conducted or contracted by oil palm companies, we did not attribute logging to oil palm development. Our analyses therefore underrepresent the proportion of intact forest loss and associated carbon emissions driven by plantation expansion.

**Land Cover Change Under Land Management Policy Scenarios.** Across oil palm expansion scenarios, by 2020, oil palm covered 29–41% of non-PA lands. Under BAU, 62% of oil palm was planted on peatlands (Fig. 1C). However, for all M and FP scenarios, only 46–49% of oil palm was converted from peatlands. Whereas oil palm extent did not differ significantly across M and FP scenarios ( $P \geq 0.05$ ), the FP scenarios conserved significantly higher forest

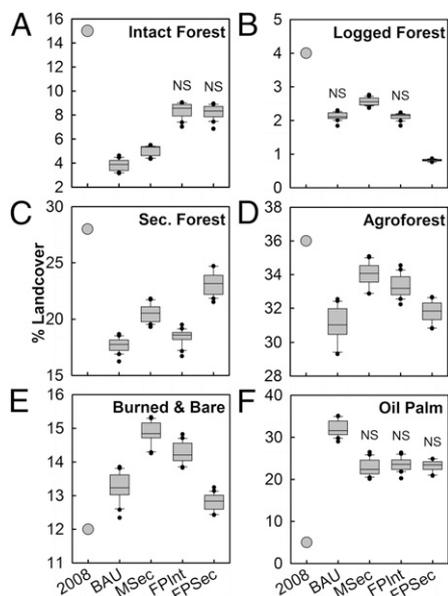


**Fig. 3.** Land cover sources for oil palm plantation establishment and total planted oil palm, from 1994 to 2011. Land cover sources across (Upper) mineral and (Lower) peat soils were identified by analyzing land cover transitions to oil palm pixels for each time step of the seven-image time series. Oil palm planting began in the Ketapang study region in 1994. Through 2007, oil palm plantations were concentrated on mineral soils. By 2011, 49% of oil palm was planted on peatlands.

fraction and generated significantly lower burned/cleared and bare fraction than the M scenarios (Fig. 4). The FPsec scenario (Fig. 1D) yielded significantly higher forest fraction coupled with significantly lower agroforest and burned/cleared and bare fraction than the FPint scenario. Land cover class fractions were not significantly different between the MInt and MSec scenarios.

**Carbon Flux.** From 1989 to 2008, total carbon committed to the atmosphere was estimated at  $11.4 \text{ MtC} \cdot y^{-1}$ , with  $12.3 \text{ MtC} \cdot y^{-1}$  gross emissions, and  $0.9 \text{ MtC} \cdot y^{-1}$  gross sequestration (Fig. S2). The 1997–1998 ENSO event with associated fires contributed the highest annual net carbon flux (19% of the 20-y total- $y^{-1}$ , Fig. 5). Peatlands were the source of 57% of net carbon emissions. The proportion of net carbon flux from peatlands increased from 50% in the 1990s to 68% in the 2000s. The AGB pool yielded 65% of net carbon emissions, whereas peat burning and draining contributed 21% and 14%, respectively. Whereas forest regrowth offset gross carbon emissions in the AGB pool by 2%, agroforest growth offset 9% of these emissions. Land cover transitions mediated by fire composed 69% of net carbon flux, followed by logging (27%). Oil palm emitted only 3% of net carbon from 1994 to 2008 or 4% excluding the 1996–1997 ENSO time step (Fig. S3). Over 75% of gross carbon emissions from oil palm were sourced from clearing AGB in intact, logged, and secondary forests on mineral soils. Peatland deforestation and draining for oil palm contributed relatively few gross emissions (10% and 11%, respectively).

**Carbon Flux Under Land Management Policy Scenarios.** From 2008 to 2020, modeled mean annual carbon flux in the BAU scenario was  $11.9 \text{ MtC} \cdot y^{-1}$ ,  $14.0 \text{ MtC} \cdot y^{-1}$  gross emissions, and  $2.1 \text{ MtC} \cdot y^{-1}$  gross sequestration (Fig. S2). Both M and FP scenarios showed reductions in net carbon emissions compared with BAU. Excluding oil palm from forests and peatlands under the M scenarios reduced net carbon emissions only 3–4% below BAU. Because so few intact forests remain, protecting secondary and logged forests (FPsec) achieved more than twofold greater carbon reductions (21%) than protecting intact forests alone (FPint, 9%). Across all scenarios, 86–92% of net carbon emissions originated from peatlands. The peat burning pool contributed 44–52% of carbon flux, with 30–36% attributed to peat draining. The AGB pool contributed only 13–24% of net carbon emissions. Whereas fire-related land cover transitions were the primary cause of carbon flux in all scenarios (67–74%), oil palm was the second leading source of carbon emissions (18–26%, Fig.



**Fig. 4.** Land cover distribution in 2008 with projections through 2020 for five oil palm expansion scenarios. Land cover is compared for (A) intact forests, (B) logged forests, (C) secondary forests, (D) agroforests and agricultural fallows, (E) burned/cleared and bare soils, and (F) oil palm. Shaded circles denote 2008 land cover. Line demarcates the median of 20 scenario runs; shaded upper and lower bounds indicate 25th/75th percentiles; whiskers represent 10th/90th percentiles. NS indicates nonsignificant ( $P \geq 0.05$ ) differences in land cover fraction between scenarios, measured with paired  $t$  tests. The MInt scenario (not displayed) did not differ significantly from the MSec scenario for all land cover classes.

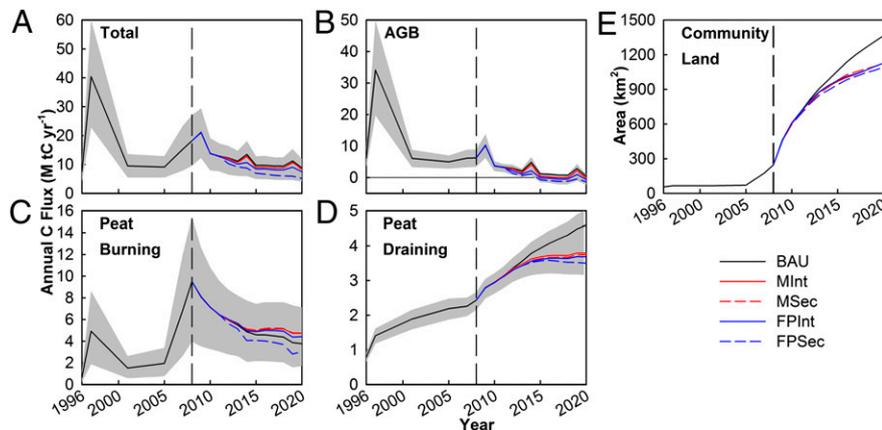
S3). Peat draining comprised the greatest source (54–59%) of gross emissions from oil palm, with 26–33% derived from conversion of AGB in intact, logged, and secondary forests on peatlands. Deforestation on mineral soils contributed only 8–12% of gross oil palm emissions. Carbon sequestration from oil palm growth offset only 15% of gross oil palm emissions for the 12-y period in the BAU scenario. Net annual carbon emissions decreased from 2008 to 2020 in all scenarios, driven by declining emissions from peat burning and AGB pools (Fig. 5 A–D). In all scenarios except BAU, the AGB pool became a net carbon sink by 2020. Drained peatlands became the primary carbon emissions source in 2020 for the BAU and FPSec scenarios. M and FP scenarios yielded stable levels of emissions from peat draining starting in ~2015, yet draining emissions continued to increase through 2020 under BAU.

**Agrarian Communities.** From our field-generated maps of 247 resident agrarian communities, we estimate that 3,928 km<sup>2</sup> of “community-managed lands” (<5 km from settlements, excluding PAs) span this region. Through the early 2000s, community land area converted to oil palm remained low, increasing from 1% in 1996 to 2% in 2005 (Fig. 5E). In 2008, community area planted with oil palm expanded to 6%, and 51 surveyed communities (21%) were <5 km from planted oil palm. Moreover, 59% of community-managed lands, representing 191 villages, overlapped oil palm leases. By 2011, community lands occupied by oil palm had more than doubled (13%). By 2020 under BAU, even including a 2-km buffer around settlements preventing oil palm conversion, planted oil palm spanned 35% of community-managed land area. In the best-case FPsec scenario, 28% of community-managed land area was controlled by oil palm plantations in 2020.

## Discussion

**Oil Palm Lease Allocation and Development.** Because oil palm development is characterized by lags between lease allocation—including requests, assessments, and permits—and the onset of landclearing, conversion of allocated oil palm leases alone will generate considerable near-term deforestation and carbon emissions. Although fires were the primary proximate cause (93%) of regional deforestation from 1989 to 2008, since 2007, plantation expansion directly contributed 27% of regional deforestation. Governmental lease records indicate that currently awarded or “committed” oil palm development will be concentrated in peatlands. Whereas ~50% of the Ketapang region spans peatlands, in 2011, 61% of undeveloped lease area was allocated on peatlands. These leases were allocated before the 2011 GOI moratorium on peatland conversion and remain available for oil palm development. BAU scenario results indicate that ~40% of peatlands will be planted with oil palm by 2020, with carbon emissions from peatlands projected to contribute 87% of total emissions under BAU. Existing regulations prohibiting using fire to prepare lands for plantation agriculture, if enforced, may mitigate peat burning emissions. However, oil palm cultivation on peatlands requires draining these soils, resulting in committed carbon emissions from peat oxidation that will continue beyond 2020. Such projections are dependent on the volume of peat losses related to peat drainage depth, characterized by pronounced temporal and spatial heterogeneity and thus considerable uncertainty (38).

**Forest Protection Critical for Carbon Emissions Mitigation.** Critically, outcomes from five policy scenarios indicate that mitigating carbon emissions requires not only prohibiting oil palm expansion into peatlands, but also actively protecting forests in oil palm leases and PAs from all causes of deforestation and degradation. Conservation-based M scenarios reduced 2008–2020 carbon emissions only 3–4% below BAU levels. Merely enforcing a moratorium on converting forests and peatlands to oil palm plantations is predicted to generate negligible carbon emissions



**Fig. 5.** Annual carbon flux and community land area planted with oil palm under five policy scenarios. (A) Total carbon emissions peaked in 1997–1998 when ENSO-associated fires burned (B) aboveground biomass (AGB) and (C) peatlands. (D) Carbon emissions from peat draining were a minor contributor to carbon flux pre-2009, but became a major source of emissions by 2020. (E) Community land area (<5 km from settlements, excluding PAs) converted to industrial oil palm plantations increased from 6% in 2008 to 28–35% in 2020 across all scenarios. Results from 1989 to 2008 were annualized and then plotted at the final year of each interval. Lines represent means of 20 model runs for each scenario. Gray areas indicate minimum and maximum annual estimated carbon flux derived by applying low and high carbon input values. Positive values indicate carbon emissions; negative values represent carbon sequestration.

reductions because other proximate causes (e.g., wildfires) continue to contribute to forest loss. Moreover, as agroforests are converted to oil palm plantations, smallholder agriculture may be displaced onto forested lands. Compared with BAU, the FP scenarios yielded 9–21% carbon emissions reductions while conserving 22–36% greater forest cover. FP and M scenarios maintained similar plantation area. Most importantly, results from the FPsec scenario reveal that protecting secondary and logged forests, not covered by the GOI moratorium (43), is the strategy that most effectively reduces carbon emissions and maintains forest cover extent. Contrasted with FPint, by 2020 FPsec yielded 11% greater forest cover with 13% lower net carbon emissions. Forest protection depends on effective prevention of wildfire, logging, and agriculture on forested lands within oil palm leases and PAs.

**Oil Palm Expansion onto Communities' Lands.** In contrast, the BAU trajectory, with ~40% of non-PA land area planted to oil palm by 2020 and only 24% residual forest cover, generates extreme concentration of palm oil agribusiness, with global markets and industry behavior affecting smallholder farmers, local ecosystems, and regional economies. Impacts of such teleconnections are amplified when community-managed lands are converted to plantations. Whereas forests were the primary land cover source (49%) for oil palm across our time series, from 2001 to 2008 agroforests and agricultural fallows comprised the majority (55%) of plantation land clearing. In all future scenarios, even when a 2-km buffer around settlements was enforced (a restriction not required by any current GOI regulations), 28–36% of non-PA lands <5 km from village centers were projected for conversion to oil palm by 2020.

Community-managed agricultural lands are often viewed as underused and treated as “degraded” by governments and companies (8, 9). Moreover, these lands have been recommended as targets for land swaps that aim to shift oil palm from forests (e.g., refs. 5, 44, and 45). However, the term degraded is inherently value laden: Degraded for whom, for how long, and relative to what? Moreover, land sparing worldwide has occurred only under a limited set of circumstances (46). Secondary effects of plantation expansion into established agricultural lands, including smallholder displacement and changes in land access, require long-term assessments of complex responses and impacts (2, 4, 47). Converting swidden agricultural systems disregards both the rights of smallholder farmers and the diverse services these lands provide and may not spare forested lands from deforestation.

**C Sequestration.** Our land change model contributes an advance in carbon accounting by incorporating dynamic forest and agricultural regrowth to estimate carbon emissions offsets. Results suggest that secondary forest, agroforest, and oil palm growth contributed relatively low carbon offsets through sequestration (8% through 2008 and 17% in the BAU scenario). Although carbon sequestered through forest regrowth could become increasingly important in systems experiencing forest transitions over extradecadal timescales (48), we find that reducing proximate carbon emissions requires considerable efforts to achieve continuous protection of existing forests within oil palm leases and PAs.

**Implications.** Protecting intact, logged, and secondary forests but especially peatlands is most critical for reducing carbon emissions from land cover change in Kalimantan. We caution that viable land management solutions—constrained by extensive allocated oil palm leases—may not simultaneously provide full carbon emissions mitigation benefits while protecting smallholder agriculture and maximizing palm oil production. Nevertheless, our analyses generate several insights for evaluating the relative impacts of oil palm plantation development. First, although multiple studies examine trade-offs among future land cover scenarios, rarely have local communities been considered in land policy evaluations (but see ref. 49). Including diverse agents (e.g., communities, governments, and companies) into locally informed and realistic policy simulations will best capture heterogeneous responses to and outcomes from projected conditions. Second, substantially enhanced

government and private sector transparency, especially surrounding lease allocation, is critical for understanding the lags and feedbacks that characterize industrial agricultural development (36). Most importantly, assessments of sustainable palm oil must consider land use histories and evaluate whether the process of land acquisition—especially from resident smallholder farmers and communities—not only meets criteria for free, prior, and informed consent or dissent, but also is equitably and transparently compensated. By incorporating diverse trade-offs for multiple agents, such research enhances our capacity to discern context-specific conditions, land use policies, and potential outcomes driven by land acquisition and conversion to plantation agriculture.

## Methods

**Satellite Image Processing.** Eleven Landsat images [thematic mapper (TM) and enhanced thematic mapper plus (ETM+), 30 m; path 121/row 61] were acquired from 1989 to 2008. All were somewhat cloudy (11–71%), so scenes from adjacent years (e.g., 1999 and 2001) were merged to create a time series of 7 images (1–7 y between time steps). Total land area assessed was 12,038 km<sup>2</sup>. PAs comprised 2,779 km<sup>2</sup> with the remaining 9,329 km<sup>2</sup> outside PAs. One module of Carnegie Landsat Analysis System–Lite (CLASlite) (50) was used to convert Landsat data to reflectance and to apply a probabilistic spectral unmixing model, yielding fractional cover per pixel consisting of photosynthetic vegetation, nonphotosynthetic vegetation, and soil (50).

**Land Cover Classification.** We developed a land cover classification system using CLASlite and ancillary (e.g., slope) data to identify dominant land covers in the region (Fig. 2 and *SI Methods*). Areas planted with or being cleared for oil palm were manually digitized from Landsat reflectance data, including an image acquired in July 2011. Clearing included roads laid out in gridded patterns indicating future oil palm development. Oil palm locations were confirmed with global positioning system (GPS) data collected from 2005 to 2011.

**Land Change Model.** With Dinamica EGO, we modeled spatially explicit land cover change from 2008 to 2020 (*SI Methods*). We developed a module to allocate oil palm expansion independent of other land cover change. To constrain plantation expansion, we obtained oil palm concession maps (“oil palm leases”) for 2008 (*SI Methods*). These leases represent plantations at all stages of the permitting and development process. Over 99% of 2008 planted oil palm fell within these leases, suggesting lease maps provide suitable boundaries for oil palm expansion. Oil palm expansion is a function of plantation establishment rate (i.e., number of leases initiating clearing per annum), annual lease clearing rate, and plantation location. To determine plantation location, plantations initiating clearing were selected randomly from 29 undeveloped oil palm leases. Within an active plantation lease, oil palm expanded until the entire lease area, constrained by specific scenario conditions, was converted. Oil palm could not expand into unsuitable regions (>45° slope, >500 m above sea level) or areas regulated as off-limits (<200 m from rivers, PAs). We collected settlement coordinates (247 villages with >100 households per village) from 2005 to 2010. Oil palm expansion was excluded from circular buffers (2-km radius) around villages.

**Scenarios.** With our model, we contrasted five scenarios of oil palm development. All scenarios were run for 12 y (2008–2020) with ENSO events occurring at 5-y intervals starting from the 2009 ENSO. BAU reflects Indonesia's national objective to double oil palm production by 2020 (40). BAU applies the 2005–2008 mean plantation establishment rate of two plantations initiating clearing per annum and assumes that the area cleared per plantation continues to proceed at the mean 1989–2008 rate (2,900 ha·y<sup>-1</sup>). M scenarios correspond to policies prohibiting forest and peatland conversion to oil palm. The Government of Norway has entered into a bilateral agreement to pay the GOI \$1 billion (US) to enforce a mid-2011–2013 moratorium on the allocation of new forestry and plantation permits on “primary natural” forests and peatlands (43). Under the MInt scenario, oil palm plantations initiating clearing from 2012 to 2020 are prohibited from expanding into peatlands and intact (approximately equivalent to primary natural) forests. Our scenario is considerably more restrictive and sustained than the GOI's moratorium; in MInt, expansion is prohibited even if the land was already leased for oil palm in 2008, and restrictions are implemented for 8 y (vs. 2 y under the GOI moratorium). In the MSec scenario, MInt restrictions are expanded to prevent conversion of logged and secondary forests to oil palm. Except for these constraints, the M scenarios are identical to BAU. FP scenarios simulate proposed REDD projects and industry initiatives by

protecting forested lands exempt from oil palm expansion in the M scenarios. Forests in PAs, undeveloped oil palm leases, and oil palm leases initiating clearing post-2011 receive full protection from degradation and deforestation, including fire, from 2012 to 2020. Forests outside oil palm leases and PAs remain unprotected. These protections are implemented in combination with the moratorium on oil palm expansion into intact forests and peatlands. Under the FPInt scenario, intact forests and peatlands are protected from deforestation and logging. The FPsec scenario extends protection to logged and secondary forests. Displaced land cover change or “leakage” may occur when forested lands are protected. In FP simulations, we prevented leakage by protecting forests after allocation of land cover changes for each modeled time step.

**Carbon Flux Quantification.** We designed a carbon bookkeeping model, parameterized with regional carbon data and coupled with the Dinamica EGO land cover change model, to track spatially explicit carbon stocks and flows (*SI Methods*). In the AGB pool (Table S2), we estimated carbon emissions from deforestation and logging of intact, secondary, and logged forests, as well as from agroforest clearing. We measured carbon sequestration from

growth of secondary forest, agroforest, and oil palm. In the belowground carbon pool (Tables S3 and S4) we assessed carbon emissions from peatland draining and burning. To estimate emissions from peat draining, land cover classes on peatlands including agroforests, oil palm, burned/cleared, and bare soil were treated as drained. We assumed that no burning occurs in peatlands planted with oil palm and we did not include peat emissions from draining post-2020. Thus, carbon emissions from oil palm on peatlands were underestimated (22).

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