

Slowing deforestation in Indonesia follows declining oil palm expansion and lower oil prices

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Abstract

Much concern about tropical deforestation focuses on oil palm plantations, but their impacts remain poorly quantified. Using satellites, we estimated annual expansion of large-scale (industrial) and smallholder oil palm plantations and their overlap with forest loss from 2001 to 2019 in Indonesia, the world's largest palm oil producer.

Over nineteen years, the area under oil palm doubled, reaching 16.24 million hectares (Mha) in 2019 (64% industrial; 36% smallholder), more than official estimates of 14.72 Mha. This expansion was responsible for nearly one-third (2.85 Mha) of Indonesia's loss of old-growth forests (9.79 Mha). Industrial plantations were associated with three times as much forest conversion as smallholder plantings (2.13 Mha vs 0.72 Mha). New plantations peaked in 2009 and 2012 and declined thereafter. Deforestation peaked in 2016 and fell below pre-2004 levels in 2017-2019. Expansion of industrial plantations and forest loss were correlated with palm oil prices. A price decline of 1% was associated with a 1.08% decrease in new industrial plantations and with a 0.68% decrease of forest loss. This slow-down provides an opportunity for the Indonesian government to focus on details of sustainable oil palm management. If prices rise, effective regulations will remain key to minimising deforestation.

Introduction

Concern for Indonesia's remarkable rain forests and their species-rich communities, including charismatic animals such as orangutans, tigers, and elephants is nothing new¹ but in recent decades this has increasingly focused on the palm oil industry². This multi-billion dollar industry is based on cultivation of the African oil palm (*Elaeis guineensis* Jacq.) and conversion to oil palm plantations has been highlighted as a major cause of deforestation and biodiversity loss³. In Indonesia, where half of global palm oil production occurs⁴, expansion of oil palm plantations has often replaced forests. Indonesia is a focus of conservation efforts because it has some of the world's richest forests with the most rapid deforestation⁵.

A growing number of consumers are demanding palm oil-based products that are not associated with forest loss. The European Union has also become increasingly concerned about avoiding deforestation-tainted imports, especially for biofuel⁶. Other nations, in tandem with environmental NGOs, have also made efforts to eliminate either all palm oil or deforestation-linked palm oil from consumer goods and other imports. Many of the world's largest traders and producers of palm oil have made "No Deforestation" commitments in which they guarantee to eliminate deforestation from their supply chain by a stated date⁷. Furthermore, in 2011, the Indonesian Government instituted a nationwide moratorium on developing new concessions on peatlands and "primary" forests, e.g. excluding natural forests impacted by selective timber harvesting, and reclassified as "secondary" forest by the Indonesian Ministry of Environment and Forestry⁸. This moratorium was extended indefinitely in 2019.

While many have blamed oil palm expansion for Indonesia's deforestation, this is contested by other scholars and by the industry and the government⁹. One analysis estimated that between 2001 and 2016 industrial oil palm plantations (i.e. large-scale intensively managed plantations owned and managed by companies) accounted for 23% of total Indonesia-wide deforestation¹⁰. Taken over a longer period, 1972-2015, a regional study found that in Kalimantan (Indonesian Borneo), industrial oil palm accounted for just 15% of total deforestation because most new plantations made use of land cleared decades before¹¹. However, from 2001 to 2017 conversion increased, accounting for 36% of total deforestation in Kalimantan¹². These studies demonstrate that the impacts of oil palm on forests clearly vary by region and period¹³. Several recent studies have demonstrated that industrial plantation expansion and associated forest conversion had slowed^{10,12} though not everyone agrees¹⁴. One reason for the slow-down might be, as indicated in a previous study from Kalimantan, that expansion of plantations is linked to the price of palm oil which has declined in recent years¹². There are also concerns that even if expansion of industrial plantations slows this may be replaced by less readily observed growth among smallholders¹⁵. Due to problems of detection previous studies omitted smallholder plantings. The Indonesian government estimates that these constitute 40% of the total area under oil palm¹⁶.

This article describes recent trends in Indonesia's oil palm expansion and links with forest loss. For the first time, we present an annual time-series showing the expansion for industrial and smallholder plantations, forest loss, and their overlap, from 2001 to 2019. These data derive from complete annual maps created by interpretation of annual cloud-free LANDSAT composites, SPOT-6 and UAV imagery¹⁷, combined with previously published sources of forest cover⁵ and tree loss¹⁸. We separate results by regions (Sumatra, Kalimantan, Papua, Sulawesi, Java and Maluku) to allow for different contexts. We compare our results against two previously published studies^{10,19} and against statistics from the Government of Indonesia¹⁶ to determine similarities and differences. We also examine the links with annual prices of crude palm oil and discuss the implications.

Results

Summary 2001-2019

We estimated that 82.59 Mha, or 44% of Indonesia's landmass was forest in 2019. Lowland forests (<500 asl), among the richest in the world²⁰ extended 55.59 Mha. These "forests" comprise old-growth natural forests, including those impacted by selective timber harvesting (reclassified as "secondary" forest by the Indonesian Ministry of Forestry and Environment). By comparison, the Ministry reported 82.5 Mha of "primary and secondary" forest in 2017²¹. The area of forest declined by 9.79 Mha (11%) from 2001 to 2019, representing an average annual deforestation rate of 0.51 Mha yr⁻¹. Sumatra and Kalimantan lost more forest than other regions with 4.08 Mha (25%) and 4.02 Mha (14%), respectively. A quarter (12.06 Mha) of Sumatra, and nearly half (25.74 Mha) of Kalimantan were forest in 2019. Papua (Indonesian New Guinea) lost the least amount of forest (0.75 Mha; 2%) and retained the largest area (34.29 Mha, 83% of its landmass, or 41% of Indonesia's remaining forests). Sulawesi experienced similar losses to

Papua (0.72 Mha; 7%) but retained less forest (9.11 Mha; 49% of its landmass). See Table 1 for a breakdown by regions considered.

Table 1. Oil palm plantation, forest loss, and share of forest loss caused by oil palm 2001-2019

Areas (in Ha)	Indonesia	Sumatra	Kalimantan	Papua	Sulawesi	Java Maluku
Landmass	189,130,128	47,467,842	53,498,290	41,227,232	18,627,593	21,135,660
2019 Forest area	82,590,327 (44%)	12,063,230 (25%)	25,742,162 (48%)	34,289,462 (83%)	9,114,005 (49%)	5,658,137 (27%)*
2019 forest area (<500 asl)	55,724,906	5,961,949	17,266,990	25,165,882	3,130,233	3,920,071
Forest loss 2001-2019	9,789,448 (11%)	4,075,312 (25%)	4,023,971 (14%)	748,640 (2%)	715,737 (7%)	213,487 (4%)
Forest converted to Oil Palm [¶]	3,094,882 (32%)	1,242,345 (31%)	1,593,260 (40%)	200,161 (27%)	46,782 (7%)	12,629 (6%)
Rapid conversion [§]	2,849,796 (29%)	1,166,806 (29%)	1,434,493 (36%)	194,996 (26%)	43,319 (6%)	10,181 (5%)
Rapid conversion to industrial	2,129,301 (22%)	553,480 (14%)	1,341,610 (33%)	194,671 (26%)	29,807 (4%)	9,733 (4.5%)
Rapid conversion to smallholder	720,495 (7%)	613,326 (15%)	92,884 (3%)	325 (0.0004%)	13,512 (2%)	448 (0.002%)

We used a sinusoidal projection to calculate areas.

(%) of landmass.

(%) of 2000 forest area.

(%) of forest loss.

¶ The area of forest that existed in year 2000 and became converted to oil palm plantation in 2019. Here, we cannot assume that all 3.09 Mha forest cleared were all caused by oil palm. The forest may have been cleared for other reasons well before being planted with oil palm.

§ The area of forest that was cleared and converted to oil palm in the same year. We can assert that all 2.85 Mha were cleared for oil palm.

* Maluku lost 201,081 ha of forest between 2001 to 2019. It had 5,167,788 ha forest left in 2019, or 66% of its landmass (7,876,562 ha). Java lost 12,406 ha. It had 703,836 ha forest left, or 5% of its landmass (13,259,098 ha)

The provinces of Bali and East and West Nusa Tenggara (landmass=7,173,511 ha) lost 12,301 ha of forest between 2001 and 2019, representing 2% loss. In 2019, there were 677,631 ha of forest and no oil palm in these three provinces.

From 2001 to 2019 Indonesia gained 8.48 Mha of oil palm plantations (6.19 Mha industrial; 2.28 Mha smallholder) reaching a total of 16.24 Mha in 2019, with 64% industrial and 36% smallholder. The estimated overall accuracy of the 2019 oil palm extent is 96% (see Supplementary Table S1 for full accuracy report). In this assessment, smallholder plantations developed in patterns that look like industrial plantations in satellite images (e.g., plasma schemes²²) were counted as “industrial”. We note that our total estimate includes immature, damaged, and failed plantations and thus surpasses estimates that include only closed-canopy mature plantations¹⁹ (e.g., 11.5 Mha). The Government of Indonesia’s estimates based on company reports and interview with smallholders (14.72 Mha), include mature and damaged plantations¹⁶, but likely omit some illegal plantations that go unreported. We estimate that oil palm plantations in the State Forest Zone (*Kawasan Hutan*), where oil palm is prohibited, covered 3.13

Mha in 2019, i.e., 19% of total oil palm area. See Table 2 for a comparison of datasets, and breakdown by regions considered.

Table 2. Oil palm expansion 2001-2019, and planted area based on three different sources: this study, a global study¹⁸ and Government statistics¹⁶

Areas (in Ha)	Indonesia	Sumatra	Kalimantan	Papua	Sulawesi	Java Maluku
Oil palm expansion (2001-2019)	8,477,253	3,457,500	4,598,415	221,117	164,471	35,749
Oil palm area, 2019 (This study)	16,237,047	9,486,516	6,044,517	272,808	374,686	58,520
Industrial	10,316,986 (64%)	4,684,385 (49%)	5,105,427 (84%)	271,486 (99.5%)	207,165 (55%)	48,522 (83%)
Smallholder	5,920,061 (36%)	4,802,130 (51%)	939,091 (16%)	1,322 (0.5%)	167,520 (45%)	9,998 (17%)
Oil palm area, 2019 (Descals et al. 2020) ^{18*}	11,531,006	6,770,223	4,259,152	175,803	304,442	36,379
Industrial	7,706,254 (67%)	3,692,628 (55%)	3,682,299 (86%)	169,880 (97%)	144,787 (48%)	27,556 (76%)
Smallholder	3,828,849 (33%)	3,077,595 (45%)	576,853 (14%)	5,923 (3%)	159,655 (52%)	8,823 (24%)
Oil palm area, 2019 (Ministry of Agriculture 2020) ^{16†}	14,724,420	8,299,729	5,713,504	213,359	450,499	47,328
Industrial	8,688,678 (59%)	3,560,687 (43%)	4,670,281 (82%)	180,685 (85%)	238,498 (53%)	38,527 (81%)
Smallholder	6,035,742 (41%)	4,739,042 (57%)	1,043,223 (18%)	32,674 (15%)	212,001 (47%)	8,801 (19%)

*Area of plantations extracted from a global oil palm map derived by based on radar data¹⁸. This dataset only includes mature (closed-canopy) plantations

†Area of plantation extracted from 2019 statistics of the Directorate General of Plantation Estates Crops of the Indonesian Ministry of Agriculture¹⁶. This dataset includes immature (open-canopy), mature (closed-canopy) and damaged plantations.

The area that was forest in 2000 and oil palm in 2019 is 3.09 Mha (32% of total forest loss: 9.79 Mha), with 2.85 Mha (29%) cleared and converted in the same year (termed “rapid conversion” in Table 1): 2.13 Mha (22%) by industry and 0.72 Mha (7%) by smallholders. In general, more plantations were established in areas cleared of forest before 2000 (5.39 Mha; black and white bars in Figure 1). Only in Papua did most new plantations replace forests (Figure 2).

Comparing regions shows that Kalimantan experienced the highest share of both total and rapid (same year) forest conversion to oil palm (40% and 36% respectively), followed by Sumatra (31% and 29%), Papua (27% and 26%) and Sulawesi (6% and 5%). In Sumatra and Sulawesi, industrial and smallholder driven conversion were similar in magnitude while industrial conversion dominated in Kalimantan and Papua (Table 1).

Annual trends

Industrial and smallholder plantations followed similar trends: expansion (black and white bars; Figure 1a,b,c) and rapid forest conversion to oil palm (white bars only) increased during the 2000s, peaked in 2009 (0.84Mha added; 0.28 Mha forest converted) and 2012 (0.80 Mha added; 0.31 Mha forest converted) and steadily declined thereafter. In 2019, overall plantation expansion had dropped to pre-2004 levels (0.16 Mha added; 0.059 Mha forest converted). The expansion of new oil palm plantings has slowed in all regions (Figure 2, and Supplementary Figures S1, S2), though this occurred later than elsewhere in Papua where expansion peaked in 2015 rather than 2012. The market price of crude palm oil (CPO) has also risen and then declined over the period of our study with peaks in 2008 and 2011 (Figure 1e). We note a positive correlation between annual CPO prices²³ and expansion of oil palm plantations (also industrial plantations, but not significant for smallholders) as well as with forest loss (Figure 1f). A decrease/increase in CPO prices by 1% was associated with a decrease/increase of new industrial plantations by 1.08% and with a 0.68% decrease/increase of forest loss (Figure 1g). Annual forest loss climbed in 2004, followed by variable but high rates that reached a maximum in 2016 (0.90 Mha cleared) before falling to pre-2004 levels (<0.34 Mha cleared) for three consecutive years (Figure 1d). This 2016 maximum is evident in Kalimantan and Sulawesi (Figure 3), but not in Sumatra where forest loss peaked in 2012. In Papua, forest loss peaked in 2015.

Discussion

We estimated the annual expansion of industrial and smallholder oil palm plantations and their overlap with forest loss from 2001 to 2019. Industrial plantations expanded faster than smallholder plantations (6.19 Mha added vs 2.28 Mha) and caused almost three times as much rapid forest conversion (2.13 Mha vs 0.72 Mha). We find an increase in plantations expansion and rapid forest conversion during the 2000s, followed by a decline after 2012 (Figure 1a,b,c). This decline was gradual for industrial plantations, and more abrupt for smallholders (Figure 1b,c). The industrial trend is consistent with other evaluations¹⁰ (Supplementary Figure S3), though Xu et al. (2020)¹⁴ reported a 2016 peak in expansion but discussions with those authors suggested an artefact caused by different data sources (Xu et al. pers. com.). We also observed an abrupt decrease of deforestation in 2017, 2018 and 2019. Our data show that expansion of plantations directly explained 29%-32% of total forest loss observed between 2001 and 2019. We conclude that oil palm was responsible for one-third of Indonesia's loss of old-growth forests over the last two decades. If we include impacts of industrial pulp and paper plantations (most commonly *Acacia mangium* Willd., and *Acacia crassicarpa* A.Cunn ex Benth), the direct conversion due to expansion of plantations directly explained 39%-42% of total forest loss observed between 2001 and 2019 (Supplementary Table S2). We underline that these estimates are conservative because they omit the indirect effects of plantations on forest loss through associated road expansion and resulting in-migration and associated forest conversion. They also exclude conversion of young forest re-growth, agroforests, and other mixed gardens. For evaluations of impacts of oil palm on regrowth forests more complex remote sensing assessments and field measurements will be necessary. Nevertheless, our results confirm oil palm's major role as a direct driver of old-growth forest loss, but also reveal that recent expansion and associated forest conversion have declined. Our data also shows that industrial

plantations caused more deforestation than smallholders and contrary to expectations¹⁵, smallholder plantations have followed a similar, and somewhat more abrupt, recent decline indicating that similar factors were at play, although this might change because smallholder oil palm is expected to grow from 40% (we find 36%) of the total national planted area to over 60% by 2030¹⁵.

Past warnings regarding the fate of Indonesia's lowland forests were justified^{1,20}. In Western Indonesia, and Sumatra in particular, but also Kalimantan to a lesser extent, remaining lowland forests are fragmented and scarce (see Figure 3). These forests have high conservation value but remain vulnerable to various threats including fire, conversion to plantations, hydropower dams and road developments²⁴⁻²⁷. Many also occur in a matrix of degraded forest and regrowth that has a potentially higher conservation value than is often acknowledged and should be included in conservation planning²⁸. In Western Indonesia strong conservation action is needed to manage and restore connectivity among forest areas. In contrast to Western Indonesia, Eastern Indonesia, and Maluku and Papua in particular, retain large unbroken tracts of relatively pristine forests offering development trajectories that should include forest protection as a core value. Given the profitability of the crop the oversight of further oil palm plantings is likely to remain contentious, though efforts to increase transparency over sourcing have increased.

Why did plantation expansion slow after 2012? The positive correlation with Crude Palm Oil (CPO) prices suggests that these were influential. The economies of China and India flourished from 2000 and 2011 and the price of CPO quadrupled (annual mean from USD 261 to USD 1077). This accelerated investment in new plantings. Around 2011-12, as the economies of China and India slowed, the market could not absorb the high increases in supply and prices began to decline. Subsequently, between 2011 and 2019, the annual price of CPO halved (USD 523 by 2019). Another reason for this price decline may be the influence of the crude oil price (i.e., "mineral oil") on the palm oil price²⁹, with the former reducing by nearly half from 2012 to 2019³⁰. Palm oil planting remains a risky investment due to the upfront expenses and the substantial time required to recoup costs. New investments became less attractive when the Indonesian government introduced the deforestation moratoria in 2011 (extended in 2019) and the government and others emphasising the need for regulations, including certification⁸.

Why has forest loss peaked in 2016 and slowed from 2017 to 2019? One factor is clearly the growth and decline in plantations already described. Another is fire. The 2016 peak (Figure 1d) reflects the El Niño-induced drought of 2015, when fire burned large areas of forest in Central Kalimantan³¹. Much of these losses were recorded only the following year by the tree loss dataset¹⁷ that we used in this study to calculate forest loss (see Methods). One study estimated that forest conversion to grasslands due to fire explained 20% of total forest loss in Indonesia between 2001 and 2016¹⁰. 2017 and 2018 were generally wetter resulting in less flammable landscapes. In contrast, 2019 was again a dry fire-prone year, though less forest was burned than in 2015³².

Might Indonesia have already reached the slowdown in forest loss expected for a forest transition? Despite the positive trends we believe that the common drivers described for forest transitions have not played any major role in the observed rise-and-fall patterns i.e., forest scarcity and economic development³³. The area of forest remains abundant overall (43% of Indonesia's landmass) and the impact of economic development in slowing forest loss would not be expected to emerge over such a short period³⁴.

Various other factors have likely influenced the declining trends. For example, in many regions remaining forests are often inaccessible or formally protected, and the improved legal basis for community-based land claims have likely further curtailed companies' access to land³⁵. Furthermore, an increasing number of consumers seek products that they consider ethical. This has generated various initiatives aimed at distinguishing and certifying products that avoid deforestation, and companies seeking to be associated with pledging to avoid forest clearing with "no-deforestation commitments"¹³. This interest has led to wide scrutiny of the palm oil industry using data that now include publicly available satellite imagery in near-real time³⁶. Taken over a longer period, we note that the average rate of deforestation experienced during the period considered (2001-2019), when Indonesia became a democracy was three times slower than during the dictatorship of the Suharto regime in 1980s and 1990s (0.51 Mha against 1.67 Mha)¹, also explaining why so many plantations were able to expand without replacing forests.

While the slowing in deforestation and the many commitments from industrial commodity producers to avoid forest loss justify cautious optimism, forest loss has not ceased and there is no guarantee that the low levels of conversion seen in 2017-2019 will remain. CPO prices might rise, increasing profitability of palm oil again, potentially driving further expansion. Demand driven by Indonesia's biodiesel program could stimulate expansion, particularly at the expense of forests that are excluded from the Moratorium (i.e., old growth forests impacted by selective timber harvesting, and reclassified as "secondary"). Palm oil buyers regularly breach their "*No Deforestation*" commitments because of incomplete transparency³⁷. Political changes may reverse forest policies with dramatic implications, as seen in Brazil. In response to the covid-19 pandemic the Indonesian government has relaxed or removed several forest regulations. These include removing licenses certifying that the wood comes from legal sources for timber export³⁸, allowing cleared lands within "protection forest" zones to be converted to food estates³⁹. The Indonesian government also amended a host of other environmental and labour regulations in the so-called "Omnibus Bill" of October 2020, which affects 79 existing laws⁴⁰.

On the positive side, deforestation has declined dramatically over the last half decade, the REDD+ agreements with Norway and with the Green Climate Fund are now rewarding the country for reduced emissions from the forest sector. Steps have also been taken to protect forests, including through increased community management⁴¹ and are gaining support and momentum. Transparency has improved, partly because of the growing availability of real-time deforestation monitoring tools³⁷, and independently verified certification criteria¹³. The slow-down in expansion (now at pre-2004 levels) also provides an opportunity for the Indonesian government to focus more on details of sustainable oil palm

planning and management⁴². Nevertheless, the demand for palm oil is expected to increase in the future⁴, and drivers of expansion may reverse recent trends. In the meantime, we must collectively invest in encouraging the good practice and transparency that serves conservation as well as local and global needs.

Methods

Annual loss of forest

Annual forest loss represents the area of old-growth forest that has been cleared each calendar year from 2001 until 2019. This measurement is based on the most recent annual Tree Loss dataset (v1.7) developed at University of Maryland with Landsat time-series imagery¹⁸. This dataset measures the removal of tree (tree height >5m) if the canopy cover of a 30 m x 30 m land unit (one Landsat pixel) falls below 30%. The latest tree loss map (version 1.7) has an improved detection of tree loss since 2011. However, the years preceding 2011 have not yet been reprocessed, so there may be inconsistencies. We also corrected several *Tree Loss* commission and omission errors by scanning a sequence of twenty annual cloud-free LANDSAT composites developed in Google Earth Engine (see last paragraph)⁴³.

The tree loss dataset does not distinguish between removal of natural forests (tree cover >90%) and planted trees (where canopy cover can also be >90% and tree height > 5m). To reduce any error resulting from this ambiguity, we excluded *Tree Loss* pixels outside of the area occupied by natural forests in year 2000, to determine losses in natural forest area rather than losses in planted trees. We used a natural evergreen “primary” forest area mask for year 2000 developed previously⁵. These dense forests usually have closed canopies (>90% cover) and high carbon stock (Above Ground carbon: 150 - 310 Mg C/Ha). They consist of tall evergreen dipterocarps growing on drylands or swamps (including peat-swamps). Here, “Forests” include intact and selectively harvested forests. Intact forests have never been disturbed by humans, or disturbances were too localized to be detected by the satellites. Selectively harvested forests have been subjected to industrial scale mechanized selective timber cutting and extraction. Intact and selectively logged forests are like “primary” and “secondary” forests on the Indonesian Ministry of Forestry and Environment’s forest maps²¹. They exclude young forest regrowth, agro-forests, mixed gardens, scrublands, tree plantations, agricultural land, and non-vegetated areas.

Annual expansion of oil palm plantations

We define an oil palm plantation as an area of land planted with oil palm trees (*Elaeis guineensis* Jacq.). An industrial oil palm plantation is owned and managed by a company. It typically covers several thousand hectares of land. It is an area bounded by long straight lines, often forming rectangular boundaries. On level land, plantings and harvesting trails are usually developed in straight lines forming a rectilinear grid (Supplementary Figure S4a). In contrast, on steep terrain, plantings and trails follow a distinctive curved pattern that follows contours (Supplementary Figure S4b). Smallholder plantations are

smaller, less structured, and more heterogeneous than industrial plantations. Smallholder plantations often form a mosaic, with other types of landcover (Supplementary Figure S4c,d,e).

We used a government-sanctioned “oil palm” base map developed by interpreters from the NGO AURIGA covering the entire Indonesia-wide extent of all oil palm plantations (small and large) as our starting point to map the expansion of all plantations. This map was created by visual interpretation of high resolution (1.5 m) SPOT 6 satellite imagery acquired between 2014 and 2018, complemented by photography (0.2-0.5 m) taken from an Unmanned Aerial vehicle in 2018 and Landsat imagery (15-30 m)¹⁷. We made some corrections to this base map to improve its quality. We removed coconut plantations misclassified as oil palm in the coastal southeastern district of Indragili Hilir, Riau Province, where Indonesia’s largest coconut plantations are found, using a land cover map from the provincial government (Supplementary Figure S5). We updated the plantation dataset with a 2019 radar composite developed previously¹⁹ (Supplementary Figure S6).

To map the expansion of industrial plantations in time we scanned our sequence of annual cloud-free Landsat composites from 2000 to 2019. We declared an area “converted to industrial oil palm” the year an area that presented the characteristics of industrial oil palm plantations appeared on our sequence of imagery (Supplementary Figure S7) and was within the extent of the “oil palm” base map. We delineated the boundaries of plantations in 1:50,000 using a visual, expert-based interpretation method. We also mapped the expansion of industrial pulp&paper plantations, as planting patterns and spectral colors of these plantations are clearly discernible from industrial oil palm (Supplementary Figure S8). We also employed indicative maps of oil-palm and pulp&paper concessions, reviewed several online and press reports, and spoke to many experts to further identify the location plantations.

We declared “smallholder oil palm” those areas classified as “oil palm” on the base map but that were not included in our draft-industrial plantations expansion map, because they lacked the patterns characteristic of large plantations. To estimate the expansion of smallholder plantations over time, we used the annual Tree Loss Dataset described above¹⁷. We assumed that the timing of tree loss indicated the year areas were developed into smallholder oil palm. Areas detected as “oil palm” by the base map that did not experience any tree loss during the 2001-2019 period were automatically classified as smallholder oil palm plantations that existed in year 2000.

We determined the area of forest converted to oil palm in the same year by measuring the overlap between the annual plantation map and the annual forest loss map. We declared an area of forest rapidly converted to plantations, if it became a plantation in the same year that it lost forest cover.

Map Validation

We validated the 2019 oil palm map using checks of 3209 points (620 industrial oil palm, 386 smallholder oil palm; 2203 involved other land uses). We placed the points randomly in non-forest areas below 500 asl and interpreted them using very-high resolution (< 1m) imagery extracted from Google Earth where individual oil palm trees can be seen.

Developing composite images.

We generated annual cloud-free Landsat composites for each year from 2000 to 2019 with Google Earth Engine (Supplementary Figure S9). The cloud observations in the Landsat images were firstly masked with the quality band 'pixel_qa', which is generated from the CFMASK algorithm and included in the Surface Reflectance products⁴⁴. Then, for each year, we created the annual composites using two criterions: 1) the median pixel-wise value of the Red, Near Infrared (NIR), and Shortwave Infrared (SWIR) bands of the images acquired between 1 January and 31 December, and 2) the minimum pixel-wise normalized burned ratio (NBR) of the images taken in the same given year. The composite image based on the median produces clean cloud-free mosaics but tends to omit new plantations developed at the end of the year. The second approach, based on the minimum NBR, produces noisier composites (residual clouds and shadows may persist), but it presents the advantage to capture the plantations that were developed at the end of the year.

Declarations

Supplementary Information is available in the online version of the paper.

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Author Contributions D.L.A.G., D. S designed the study. D.L.A.G., H.Y., M.A.S. created and analysed the maps. D.L.A.G, B.L. M.A.S and A.A. analysed the oil-palm and deforestation datasets. T. M; E.M., and A. A contributed information. D.L.A.G., B.L. and D.S. wrote the manuscript and produced the figures, with feedback from all authors.

Additional Information The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper.

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Figures

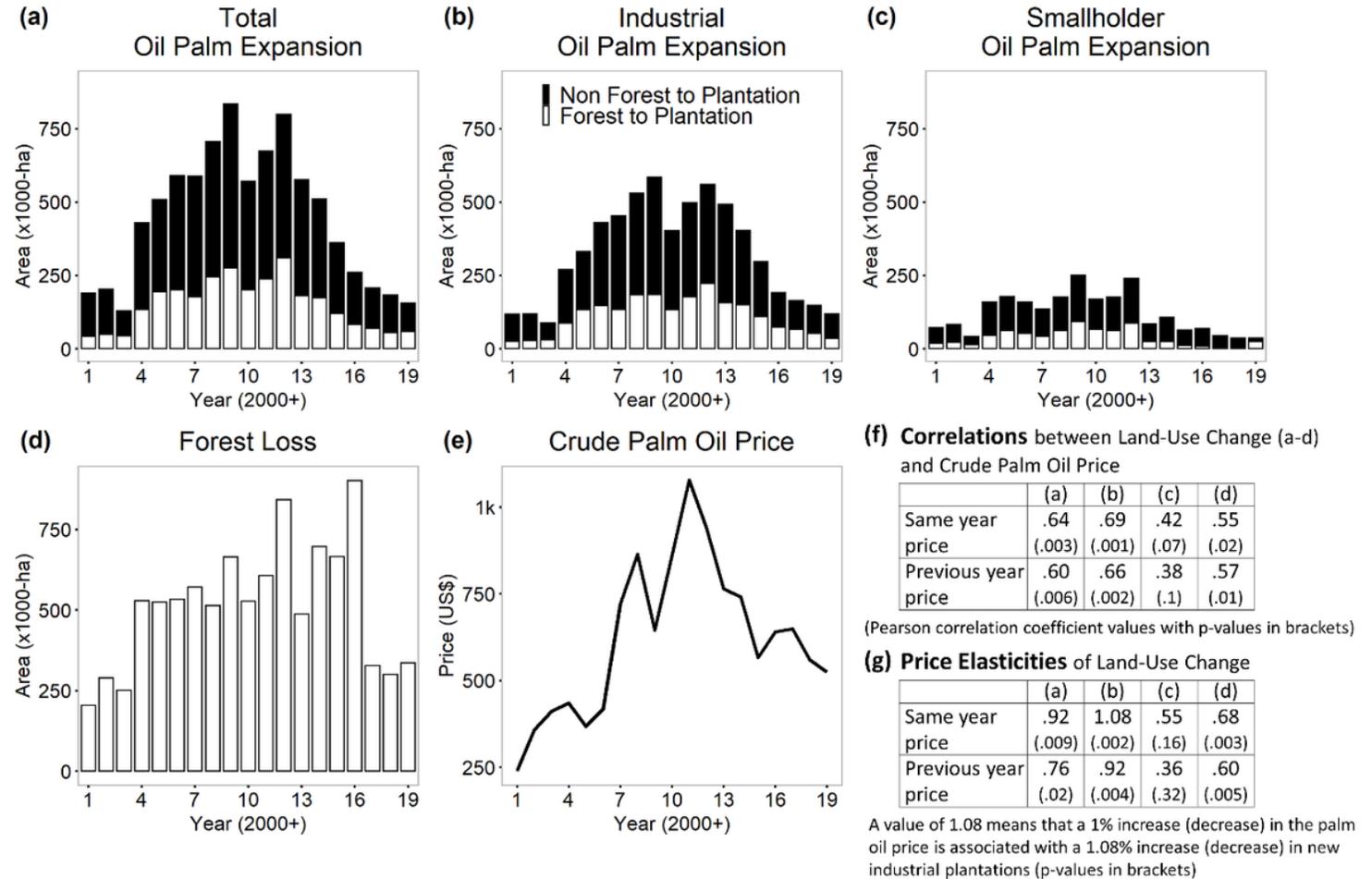


Figure 1

2001-2019 time-series of Indonesia's land-cover/use change interpreted from Landsat and Spot 6 imagery. Expansion of oil palm plantations by year (a), split between industrial and smallholder (b,c), and forest loss (d). Mean annual Crude Palm oil (CPO) price and correlations/elasticities with the previously shown land-cover change estimates (f,g). Price calculated from monthly prices in USD using IMF data (CPO prices 2020). In insets (a,b,c) white bars represent the areas of forest cleared and converted to plantations in the same year, and are comparable to annual forest loss (d). This rapid conversion constitutes 29% of all forest loss since 2000. The black bars represent areas of non-forest converted to oil palm. 96% (5.39 Mha) of those non-forest areas were non-forest in year 2000, 4% (0.24 Mha) were forest

cleared after 2000 and converted to plantations more slowly (after 2 to 18 years). These non-forest areas include conversion of young regrowth, mixed gardens agroforests and rubber plantations.

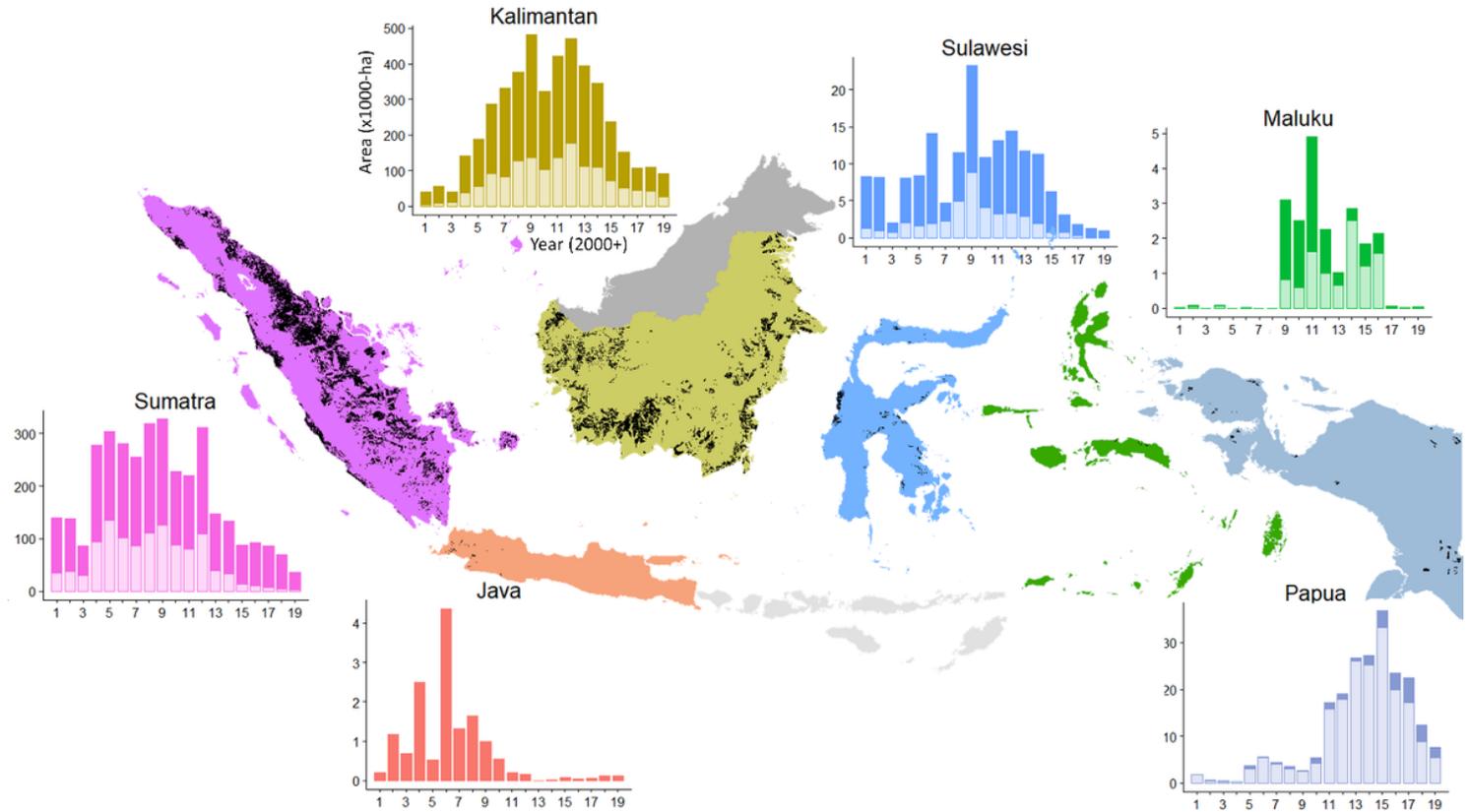


Figure 2

Oil palm expansion by region across Indonesia from 2001 to 2019. Y-axis represent areas (in 1000-ha, note different scales) of the total area of plantations (industrial and smallholder) added each year by rapidly clearing forests (light bars, below), or by using areas already cleared (dark bars, above). Black areas on the map represent the total 2019 oil palm area (industrial and smallholder combined).

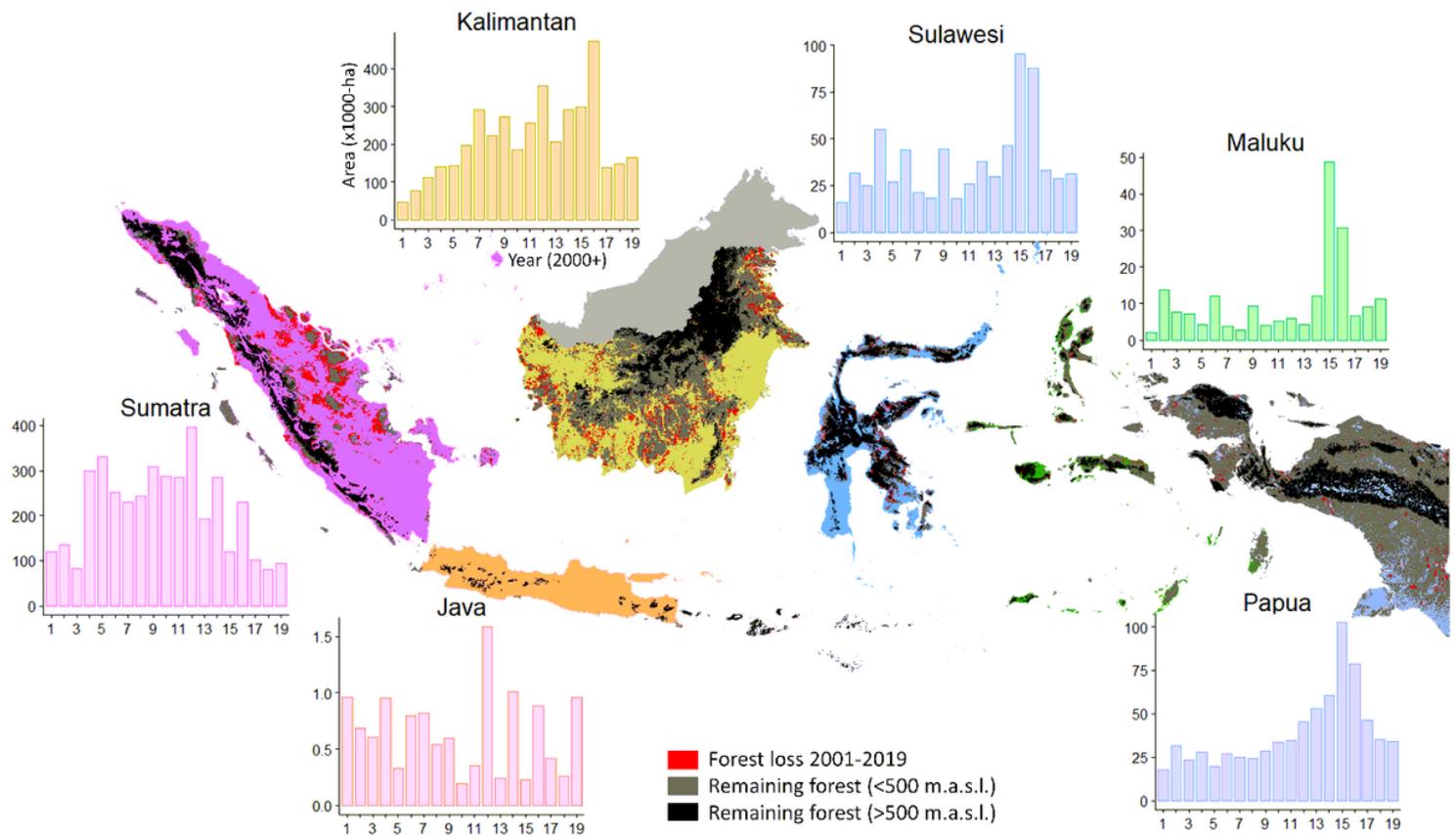


Figure 3

Remaining forest area in 2019 and annual forest loss by region from 2001 to 2019. Y-axis represent areas (in 1000-ha, note different scales) of forest cleared each year.

Supplementary Files

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