Forest loss in Indonesian New Guinea (2001–2019): Trends, drivers and outlook

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ABSTRACT

The rich forests of Indonesian New Guinea are understudied and threatened. We used satellite data to examine annual forest loss, road development and plantation expansion from 2001 to 2019, then developed a model to predict future deforestation. No previous studies have attempted such a detailed assessment of past and future deforestation. In 2019, 34.29 million hectares (Mha), or 83% of Indonesian New Guinea, supported old-growth forest. Over nineteen years, 2% (0.75 Mha) were cleared: 45% (0.34 Mha) converted to industrial plantations, roads, mine tailings, or other uses near cities; 55% (0.41 Mha) cleared by transient processes including selective natural timber extraction, inland water bodies-related processes, fires, and shifting agriculture. Industrial plantations expanded by 0.23 Mha, with the majority (0.21 Mha; 28% of forest loss) replacing forests and reaching 0.28 Mha in 2019 (97% oil palm; 3% pulpwood). The Trans-Papua Highway, a ~4000 km national investment project, increased by 1554 km. Positive correlations between highway and plantations expansion indicate these are linked processes. Plantations and roads expanded rapidly after 2011, peaked in 2015/16, and declined thereafter. Indonesian government allocated 2.62 Mha of land for the development of industrial plantations (90% oil palm 10% pulpwood) of which 74% (1.95 Mha) remained forest in 2019. A spatial model predicts that an additional 4.5 Mha of forest could be cleared by 2036 if Indonesian New Guinea follows similar relationships to Indonesian Borneo. We highlight the opportunities for policy reform and the importance of working with indigenous communities, local leaders, and provincial government to protect the biological and cultural richness still embodied in this remarkable region.

1. Introduction

New Guinea, the world's largest tropical island, covers just 0.53% of the Earth's land (785,753 km^2), but is the most floristically diverse island in the world (Cámara-Leret et al., 2020). It hosts extensive old growth forests, including mangroves and peat swamps, in near pristine settings (Corlett and Primack, 2011; Sasmito et al., 2020). The region's

remarkable biota — such as the birds-of-paradise — have fascinated biologists for centuries, although much of the region's species remains "astoundingly little-known" (Beehler, 2007). A rapid botanical assessment in the foothills of the Foja Mountains in Indonesian New Guinea distinguished 487 plant morpho-species in 15 small plots and found that 156 (32%), could not be matched to herbarium specimens or published references suggesting a high proportion of undescribed species (Van

Heist et al., 2010). With such incomplete assessments, it is likely that many of the important locations for biodiversity conservation have not yet been identified. Similar richness and endemism are found among the fauna. The 748 bird species recorded in Indonesian New Guinea (see https://avibase.bsc-eoc.org/checklist.jsp?region=IDij checked by DS 6-5-2021), include 29 birds of paradise, and a similar number of kingfishers, parrots, raptors, and pigeons along with three cassowaries (Marshall and Beehler, 2007). Though some groups such as the birds are better known than the plants, much remains unknown about the fauna too: for example, even bird-of-paradise species are still being discovered (Scholes and Laman, 2018). The region's rich biological diversity is the result of a turbulent geological history and its variety of tropical habitats from sea level, climbing up to mountain ranges reaching 4884 m (Kooyman et al., 2019; Lohman et al., 2011; Morley, 2000; Toussaint et al., 2014).

Divided in half by its colonial history, the island comprises the nation of Papua New Guinea in the East with the remaining area of 411,387 km^2 (53%) in the West, being part of Indonesia. Indonesian New Guinea, also known as Western New Guinea, and *Tanah Papua* and formerly as *Irian Jaya* — comprises the provinces of Papua (312,806 km^2) and West Papua (98,581 km^2). These provinces suffered fewer human impacts than most tropical regions (Brooks et al., 2002; Supriatna et al., 1999) and remain relatively untouched compared with Western Indonesia (Java, Sumatra and Indonesian Borneo (Kalimantan)). They are home to diverse indigenous human cultures each with their own relationship to nature and natural resources (Boissiere and Purwanto, 2007; Kennedy, 2012), and until recent decades most human impacts appear to have been relatively localized (Bartlett et al., 2016; Johnson et al., 2016; O'Connell and Allen, 2015).

Since 2010, Indonesian New Guinea has become a focus for new plantations (Runtuboi et al., 2020). With diminishing available land elsewhere in the country, plantation companies (oil palm and pulpwood) are increasingly investing in the development of plantations in Papua and West Papua provinces, while the Indonesian government has invested in ambitious road construction programs to facilitate land development (Franky and Moragan, 2015; Sloan et al., 2019a). Road developments are also aimed at delivering healthcare, education, and sustainable economic opportunities to remote areas, but many observers are concerned that such developments will accelerate forest conversion as it did in Sumatra and Indonesian Borneo (Kalimantan) (Austin et al., 2019). Construction of the planned ~4000 km Trans-Papua Highway, a road started in 1979 to link all the major urban centres of Papua and West Papua provinces (Kirksey and Bilsen, 2002), has accelerated after 2000. Construction of another major highway intended to ease the development of a food estate project, the Merauke Food Estate and Energy Project, in the south of the island began in 2012. The Indonesian government degazetted 1.2 million hectares (Mha) of State Forest (*Kawasan Hutan*) in 2012 to facilitate these planned roads, oil palm and food estate developments (Mutia Dewi, 2020). In 2016, the president of Indonesia is reported to have allocated 85.7 trillion rupiah (~USD6.4 billion) to fund such development projects (including other infrastructure projects like sea ports) (Gokkon, 2017).

The provincial governments of Papua and West Papua provinces recognize the risks of the business-as-usual plantation and road-led development strategy pursued previously in Sumatra and Indonesian Borneo. These development models have driven deforestation and negatively impacted indigenous communities (Margono et al., 2014; Santika et al., 2019). In 2018, the Governors of Papua and West Papua provinces signed the Manokwari Declaration that commits them to conserve at least 70% of the region, ensure infrastructure developments are "environmentally appropriate" and based on principles of sustainable development while also protecting the rights and roles of indigenous communities (Cámara-Leret et al., 2019a). Other goals included developing the information management and monitoring systems needed to support and oversee sound conservation planning and implementation.

While various studies have examined conservation concerns and land cover change in Papua New Guinea (Alamgir et al., 2019; Filer et al., 2009; Laurance et al., 2011; Shearman and Bryan, 2011; Shearman and Bryan, 2015), Indonesian New Guinea is, by comparison, neglected. When it is considered it is typically part of a broader regional overview without concern for local details (Austin et al., 2019; Carlson et al., 2018; Miettinen et al., 2011). Exceptions include a recent study highlighting regional road developments, and associated threats to ecosystems and species through the potential of new infrastructure to promote land cover change (Sloan et al., 2019a). Another highlighted how new roads increase hunting of endangered species (Pattiselanno and Krockenberger, 2021). Despite sparse data, there have also been studies which identify areas of particular conservation value or concern (e.g. Supriatna et al., 1999; Hoover et al., 2017; Cámara-Leret et al., 2019b). None of these studies have made a detailed study of past and potential future land cover changes to better evaluate the impact and implied threat of new roads and associated developments.

Here, we use Landsat imagery (spatial resolution: 30 m × 30 m) to estimate annual forest loss, and road and plantation expansion from 2001 to 2019. First, we identify the distribution and nature of recent forest cover loss and land developments across the region. Second, we examine temporal correlations between these variables and discuss their patterns. Third, we assess other drivers of loss, such as impacts of logging, mining, and other processes. Finally, we overlay these data with detailed concession and protected area maps and develop a spatially explicit model to generate a deforestation risk map and assess possible future scenarios.

2. Methods

2.1. Forest area

Here we focus on old-growth forests (here abbreviated to "forests"). These relatively intact dense forests (typically canopy cover >80%; Tang et al., 2019) have high carbon stocks (Above Ground carbon: 150–310 Mg C/Ha). They grow and regenerate naturally, on dry mineral soils and in swamps. Our definition includes intact as well as selectively logged forests. Intact forests have not been severely disturbed by humans in recent decades, or disturbances were too old to be detected by the satellites. Selectively logged forests include old-growth forests that have been impacted by both artisanal tree cutting as well as by more extensive mechanized timber cutting and extraction. Selectively logged forests may have canopy cover <80%, depending on the intensity of, and recovery from, harvest. There is variation among all these forests. For example, on peat domes, forests may naturally be thinner, low carbon stock pole forests. In coastal regions, forests include mangroves as well as natural stands of Sago palm (*Metroxylon sagu* Rottb.) (Karim et al., 2008). In the drier regions of southern Papua province, on the island of Pulau Dolok in Merauke regency, forests include a unique tall mixed seasonally inundated savanna forest, with trees reaching up to 40 m in height, and 50–60% canopy cover and usually dominated by trees of the Myrtaceae family, such as *Melaleuca cajeputi* Powell and *Lophostemon suaveolens* (Sol. ex Gaertn.) Peter G.Wilson & J.T.Waterh. (widely known by its older synonym *Tristania suaveolens* Sm.) (Marshall and Beehler, 2007). Young forest regrowth, scrublands, tree plantations, agricultural land, and grasslands and non-vegetated areas are excluded. Intact and selectively logged or generally disturbed forests are synonymous with "Primary" and "Secondary" forests on the Indonesian Ministry of Forestry and Environment's maps (MoEF, 2018).

We mapped the extent of old-growth forests circa 2000 using cloud-free Landsat composite imagery (see Section 2.6). The old-growth forest map was created by supervised classification in a Random Forest classifier into 'Forest' and 'Non-Forest' classes. We trained the model to recognize mangrove forests along the coast using 'training pixels', being point coordinates labelled as either 'mangrove' or as 'other' because these forests have a distinct spectral response and location (coastal)

compared with other forest (Simard et al., 2019). We also used a peat-land map from Indonesia's Ministry of Agriculture to identify peat-swamp forests (Ritung et al., 2011). We called remaining forests, 'other forests', mainly forests on mineral soils, and in non-peat swamp locations.

2.2. Forest loss

We estimated 'annual forest loss' as the area of forest (as defined above) cleared by conversion or heavy degradation each calendar year from 2001 to 2019. This measurement is based on the annual Tree Loss dataset (version 1.7) developed at the University of Maryland with Landsat time-series imagery (Hansen et al., 2013). The Tree Loss dataset measures the removal of trees (tree height >5 m) if the canopy cover of a 30 m × 30 m land unit (one Landsat pixel) falls below 30%. It does not distinguish between removal of natural forests (canopy cover >80%, tall trees) and planted trees (where canopy cover can also be >80%). To reduce any error resulting from this ambiguity, we only included *Tree Loss* pixels inside of areas that our analysis identified as forests.

The measurement of forest loss detects conversion to industrial and smallholder plantations (e.g. oil palm, acacia, coffee, rubber, cacao, nutmeg), other types of agriculture (e.g. paddy fields), urban expansion (including transmigration sites), roads, and mining activity (e.g. digging for gold, or mine tailings). It can also include clearings in the forest caused by natural timber extraction, forest fires and other transient processes (e.g. movement of surface water). Forest loss in the forest canopy caused by the movement of surface water (canopy damage and death of trees caused by meandering rivers, expanding lakes, river overflow and surface run-offs) is usually temporary but forest regrowth will depend on damage inflicted and rivers changing course. Forest fires (canopy damage, death of trees, burnt understorey) will cause lasting forest loss if fires are sufficiently frequent. A forest that burns multiple times over just a few years is typically replaced by fire-tolerant vegetation, often dominated by grasses and ferns. If the forest is impacted by fire once, the larger trees survive and the forest regenerates quickly, except on peatlands, where one fire event may kill all emergent trees if it burns through the roots. Forest loss caused by cutting and extraction of timber (logging roads and clearings where trees are harvested) is usually temporary, as disused tracks and clearings in the forest interior recover after harvesting. In those cases where forest loss is temporary, the term forest degradation rather than forest loss is commonly used.

2.3. Expansion of industrial plantations

We define a "plantation" as an area of land planted with oil palm trees (*Elaeis guineensis* Jacq.), or with a single species of fast-growing trees, most commonly acacia (*Acacia mangium* Willd., and *Acacia crassicarpa* A.Cunn ex Benth.). An industrial plantation typically covers several thousand hectares of land. It is an area bounded by long straight lines, often forming rectangular boundaries. Harvesting trails are usually developed in straight lines forming a rectilinear grid. Annual expansion of industrial plantations represents the area of land (whether forest or non-forest) that has been converted to industrial plantation of oil palm or acacia each year. To map plantations, we scanned a sequence of annual cloud-free Landsat composites forward in time from 2000 to 2019 (see Section 2.6). We declared an area 'industrial plantation' the moment an area that presented the characteristics of industrial plantations (area bounded by several straight lines; spectral colours changing from green to bare land, dense network of trails forming a rectilinear grid) appeared on our sequence of imagery (Fig. A1). We delineated the boundaries of plantations at a scale of 1:50,000 using a visual interpretation method. This method has been used effectively previously (Gaveau et al., 2019; Sloan et al., 2019b). We performed this task in the GIS software ArcMap (10.4.1). We also employed maps of oil-palm and pulpwood (*Acacia*) concessions (see Section 2.7) to further identify the location of plantations. We determined the area of forest (and non-

forest) converted every year into industrial plantations. This was ascertained by measuring the overlap between the annual plantation map and the annual forest loss map.

2.4. Expansion of roads

Public roads are built and maintained by the government to facilitate the transport of goods and people from one settlement or city to another. The government of Indonesia defines its main public roads as national roads, provincial roads, and 'strategic roads' (intended to boost economic activity and development). The Trans-Papua Highway and the Merauke Integrated Food and Energy Estate (MIFEE) highway are strategic roads made up of several national and provincial road segments, some still under construction, across Papua and West Papua, totalling >4000 km.

The annual expansion of main roads represents the length of road segment created each year. To map the expansion of main roads, we scanned available maps from local and national governments to identify their approximate routes. Next, we scanned the sequence of annual cloud-free images forward in time from 2000 to 2019 to detect road segments added each year along those approximate routes. We delineated road segments in a 1:50,000 scale using a visual, expert-based interpretation method. We used a professional Cintiq 22HD Wacom tablet with definition display and pressure-sensitive pen for the digitizing process. We did not distinguish paved versus unpaved road segments.

2.5. Other drivers of forest loss

We estimated forest loss caused by industrial-scale mechanized logging by mapping the annual expansion of all primary logging roads (large enough to be detected on Landsat images). We delineated logging road segments inside logging concessions using a similar digitizing procedure as we did for public roads. Next, we recoded forest areas underneath as 'forest loss' because the original Tree Loss dataset (version 1.7) is known to undercount losses caused by logging roads prior to 2011 (Hansen et al., 2013). Next, we defined a 700 m distance from logging roads beyond which timber extraction typically ends in Indonesia (Gaveau et al., 2014). We buffered logging roads by this distance and declared any forest loss within this buffer as forest loss caused by timber extraction. Inside known active mangrove logging concessions (Sillanpää et al., 2017) where clear-cutting (keyhole) timber extraction techniques are used instead of the typical logging road network, we recorded any loss of mangrove forest as natural timber extraction.

Inland water body-related forest loss represents the area of forest that results from the expansion or shift of rivers and lakes between 2001 and 2019. To map these losses, we first created a detailed base map of inland water bodies (rivers and lakes) in 2000. We digitized small river lines at a 1:50,000 scale. We applied a supervised classification over the 2000 cloud-free Landsat composite to map larger rivers and lakes. Next, we combined our 2000 inland water bodies base map with a published map for changing water surface (Pekel et al., 2016), also developed with Landsat to measure the area where water expanded through surface run offs, expanding lakes, and changing river courses through to 2019. Within this area, we reclassified the annual cloud free composites (see Section 2.6) using a supervised classification to extract areas of forest converted to water instead of using the Tree Loss dataset (v.17) because we found that this latter dataset missed many of these events.

A burned forest is an area of forest characterized by deposits of charcoal and ash, removal of vegetation, and alteration of the vegetation structure. We estimated the areas of forest loss by fires by combining the forest loss map with active fire hotspots (NASA-FIRMS, 2020). If an area of forest loss coincided with a cluster of fire hotspots, this area was recoded as: forest loss by fires. This delineation was determined using a flexible and inclusive visual search and interpretation since the actual area detected 'burned' by the Landsat-derived forest loss map does not

always coincide exactly with the hotspot's coordinates.

We estimated the extent of forest loss caused by expanding population centres by measuring forest loss within 5 km of transmigration sites, regency and provincial capital cities and that did not qualify as any category of loss described earlier. We mapped transmigration sites using the 2000 cloud-free Landsat composite and government maps indicating their locations. We obtained the location of cities from government spatial data repository websites.

2.6. Annual cloud-free composites

We generated annual cloud-free Landsat composites for each year from 2000 to 2019 with Google Earth Engine (Gorelick et al., 2017). We masked cloud observations with the quality band 'pixel_qa', which is generated from the CFMASK algorithm and included in the Surface Reflectance products (Foga et al., 2017). Then, for each year, we created the annual composites using two criteria: 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 and new roads 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 captures plantations and roads that were developed near the end of the year.

2.7. Concession and protected area maps

Concessions are areas of land leased out to companies for the establishment and management of large monoculture plantations of oil palm or pulpwood (Acacia), for mining activities, or for the extraction of natural timber. Pulpwood and logging (for natural timber extraction) concessions are regulated and issued only by the Ministry of Environment and Forestry. We downloaded pulpwood and logging concession datasets from government data repositories (MOEF, 2020). We downloaded the protected area dataset from the same data repository. Assembling the oil palm concession dataset was more difficult due to a range of ascending permits that are required by Indonesian law to earn the right to clear forest, plant and then manage oil palm plantations (Paoli et al., 2013). We assembled maps of oil palm concessions based on various datasets compiled by various Indonesian NGOs. Details are provided in supplementary methods in Appendix A.

2.8. Predictive modelling

We developed a spatially explicit model of deforestation (forest loss) using the principles of land-rent theory (Angelsen, 1999). In general, plantation companies and farmers act to maximize profits by allocating any parcel of land to the use that earns the highest rent. Topography (slope and elevation), roads, restricted zones (protected areas), and lands allocated for the development of plantations (concessions) determine the spatial distribution of land rent. Roads improve accessibility into remote forest areas and reduce transportation costs of agricultural commodities, which tends to promote deforestation. Steep slopes and high elevations limit accessibility, which tends to reduce deforestation. Accordingly, we built a set of six spatial predictors at a spatial resolution of 100 m × 100 m including slope and elevation, distance to main public roads expressed as a cost map, the presence of logging roads, protected areas and active concessions of oil palm, pulpwood and mining sites. We defined active concessions as those where we observed industrial activity between 2000 and 2019. We modelled distance to public roads (including the Trans-Papua and MIFEE Highway) as a cost distance to simulate the propensity of people to travel along the path of least resistance. We calculated the cost distance as a function of slope as derived from the SRTM digital elevation model (Rabus et al., 2003).

We used weights of evidence and logistic regressions to generate deforestation-risk maps depicting the areas that are most at risk of deforestation. The risk maps have values ranging from 0 to 1, with higher values indicating greater vulnerability of deforestation. Weights coefficients were estimated for the categorical predictors (presence of active concessions, protected areas, and logging roads). Logistic regression coefficients were estimated for the continuous predictors (slope, elevation, and cost distance to public roads). The weights and logistic regression coefficients indicate the effect of predictors on forest loss. Positive weights/coefficients promote forest loss, negative ones reduce it, and close to zero values do not exert an effect. Since weights of evidence and logistic regressions assume that variables are spatially independent, correlation analysis between the predictor variables were performed. We tested several correlation methods. All tests highlighted no high correlation between paired variables. We performed the modelling using Dinamica Ego software (Soares-Filho et al., 2009).

We calibrated six models (each with different predictors) using the forest loss observed during the period 2010–2018 as the response variable. We chose this time frame because it captured most of variations in deforestation observed in the region. For each model, we generated yearly deforestation-risk maps, with probability values ranging from 0 to 1. To validate the model, we first simulated the spatial occurrence of forest loss from 2010 to 2018 using the average rate observed during this time frame. Simulation was performed via a cellular automata, in which the state of a cell at a subsequent timestep is based on its current state and the states of the neighbour cells. Deforestation allocation and expansion are controlled by *Patcher* and *Expander* functions in Dinamica EGO. The *Patcher* function operates by a seeding mechanism that generates new deforested patches (Soares-Filho et al., 2009). The *Expander* function operates by expanding or contracting patches. The size of new patches and expansion fringes assumes a lognormal distribution defined by the mean and variance of the patch sizes to be formed (Soares-Filho et al., 2009). Next, we validated the simulated forest loss map against the map of forest loss observed during the same time frame (2010–2018) based on a vicinity-based comparison method implemented in Dinamica EGO. This method quantified the number of matching 'deforested' cells (one cell = 10,000 m²) between the observed and simulated maps and produced a similarity measure ranging from 0% to 100%. We selected the simulation with the highest similarity adjusted for the number of parameters.

The selected model was used to predict forest loss over an 18-year time frame, i.e. to 2036. We developed two scenarios based on two hypothetical future speeds. In the first scenario, the speed of forest loss was estimated as the percentage of forest loss observed during 2010–2018 in Indonesian New Guinea relative to the total amount of forest left. In the second scenario, it was estimated as the percentage of forest loss observed in Indonesian Borneo during 2001–2018 (Gaveau et al., 2019).

3. Results

3.1. Situation in 2019

We estimate that 34.29 Million hectares (Mha), or 83% of Indonesian New Guinea was forest in 2019 (Fig. 1). This 'forest' comprises old-growth forests, including those impacted by selective timber harvesting (reclassified as 'secondary' forest by the Indonesian Ministry of Forestry and Environment). This area of forest includes 30.30 Mha on drylands, and non-peat swamp habitats ('other forests'), 2.82 Mha of peat-swamp forest and 1.17 Mha of mangrove forest. By comparison, the Ministry reported slightly less: 33.74 Mha of 'primary and secondary' forest in 2017 (MOEF, 2018). About one third of the non-forest area (6.86 Mha) was a savanna ecosystem, the Trans-Fly eco-region dominated by grasslands at the southern tip of the island in the Merauke Regency. Legally gazetted conservation areas, including reserves and national parks, protected 8.68 Mha, or 21% of the total land area.
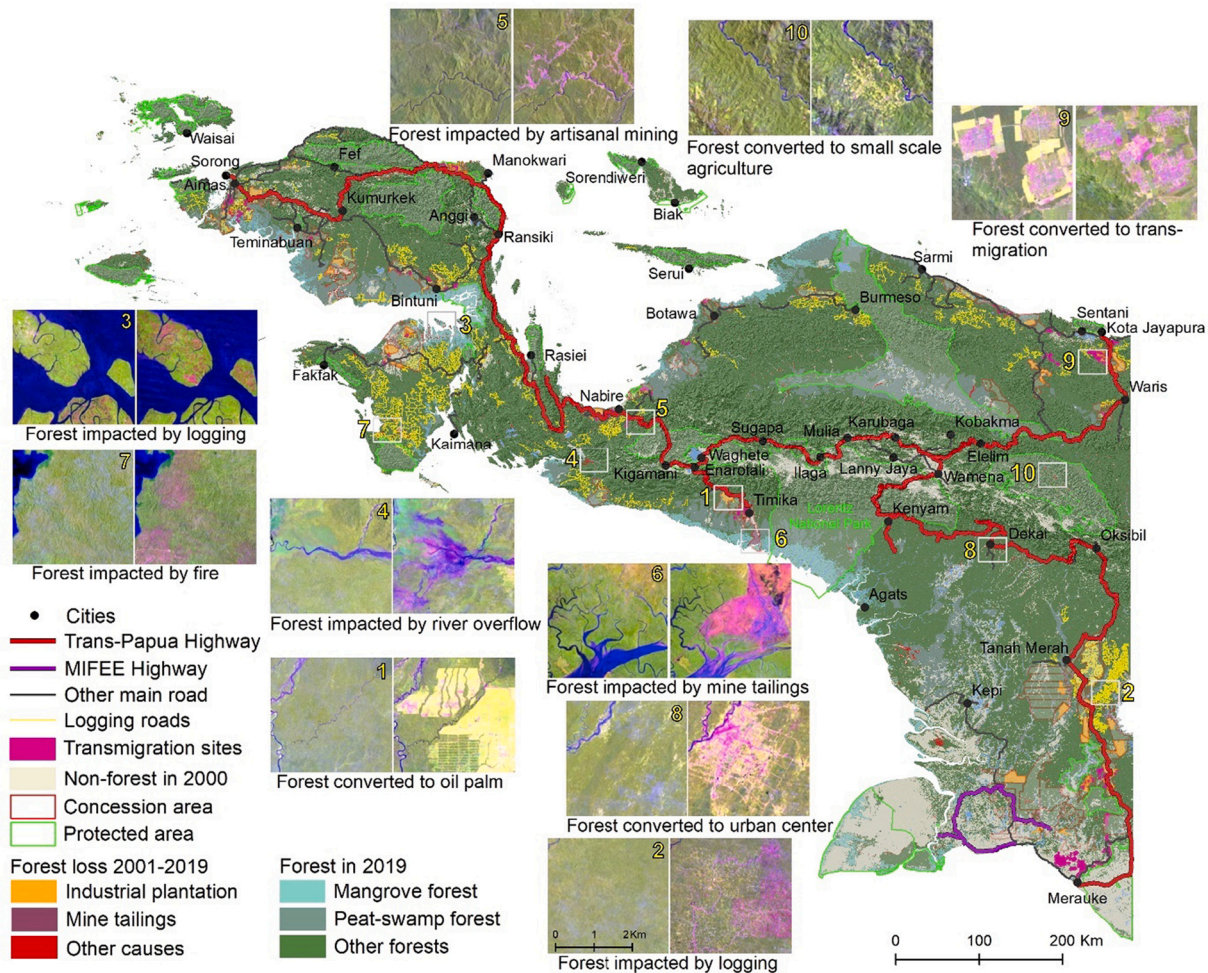
Fig. 1. Land use and land cover change 2000 to 2019. The insets show two image pairs taken before and after forest disturbance at 10 specific locations. All insets have the same scale. This map can be viewed interactively at: https://nusantara-atlas.org/#en.

We mapped 8434 km (km) of main public roads in 2019, including 3887 km of Trans-Papua Highway (red line; Fig. 1), and 336 km of highway built specifically to develop the Merauke Integrated Food and Energy Estate project in the south of the island (purple line; Fig. 1). We mapped 22,035 km of wide (>15 m) temporary trails built in the forest interior to extract natural timber (logging roads, Fig. 1), translating into a density of logging trails of 0.064 km km^{-2} across the whole of Indonesian New Guinea. In addition, we mapped 21,293 km of local roads, and 10,855 km of harvesting trails inside industrial plantations. The full set of roads and trails mapped in this study is shown in Fig. A2.

We mapped 136 distinct industrial plantations (min = 85 ha; max = 16,882 ha; mean = 2068 ha), covering a total planted area of 281,223 ha in 2019 (271,486 ha oil palm; 9737 pulpwood). We found these plantations in 87 'active' concessions from a total of 177 concessions given out by the government (1.81 Mha oil palm; 813,000 ha pulpwood). We also found one 'active' mining concession (198,000 ha) where mining company Freeport extracts gold and copper and where it dumps its wastes (tailings). Seventy four percent (2.10 Mha) of this total concession area (2.83 Mha) was still forest in 2019 (1.37 Mha oil palm; 577,000 ha pulpwood; 149,000 ha mining). Our planted area includes immature, damaged, and failed plantations and thus surpasses estimates that include only closed-canopy mature plantations (e.g., 175,803 ha, Descals et al., 2021). The Government of Indonesia's estimates based on company reports (213,359 Mha) include mature and damaged plantations (DGOEC, 2020).

3.2. Forest loss and drivers (2001 to 2019)

About 2% of old-growth forest, that is 748,640 ha, was lost between 2001 and 2019: 511,882 ha (1.9%) in Papua, 236,758 ha (2.6%) in West Papua. We estimate that 45% (336,877 Mha) have become converted to plantations, mining, roads, and population centres, while 55% (411,763 Mha) have been impacted by transient processes such as selective natural timber extraction, inland water bodies-related processes, fires, and other drivers (shifting agriculture, cryptic timber harvesting and mining, tornadoes and landslides) (Table 1). We break down these numbers by drivers below (see also Table 1).

We estimate that 208,223 ha of forest have been permanently

Table 1
Summary of drivers of forest loss.

Drivers of forest loss	Forest loss (ha)	Forest loss (%)
Industrial plantations (oil palm +pulpwood)	208,223	28
Selective natural timber extraction	120,500	16
Inland water bodies	83,800	11
Roads + population centres	115,366	15
Fire	39,347	5
Mining	13,288	2
Other drivers[a]	168,116	23
Total forest loss (2001–2019)	748,640 ha	100

[a] Includes shifting cultivation and other processes, such as landslides, tornadoes, undetected understory fires, cryptic logging and artisanal mining activities.

converted to industrial oil palm and pulpwood plantations (97% oil palm; 3% pulpwood) since 2000, of which 97% were cleared and converted within the same year (203,202 ha; sum of all white bars in Fig. 2). This conversion explains 28% of total forest loss. Oil palm and pulpwood concessionaires converted large rectangular blocks of old-growth forest to large oil palm and acacia estates (mean size = 2068 ha) inside concessions. An example of this conversion is shown in inset 1 of Fig. 1.

We estimate that 120,500 ha (16% of total forest loss) were cleared by selective natural timber extraction. This estimate combines the loss of forest directly replaced by the 22,035 km network of extraction (logging) roads, by clearings near these roads (within 700 m) and by 'keyhole logging' extraction patterns in the world's largest mangrove concession (Sillanpää et al., 2017). This clearance is temporary, as the forest usually regenerates along extraction sites within a few years (Gaveau et al., 2013; Sillanpää et al., 2017). Typical examples of natural timber extraction with logging roads and in mangrove forests seen by satellites are shown in insets 2 and 3 of Fig. 1.

We estimate that 83,800 ha (11%) of forest lost due to inland water bodies-related processes including the expansion or shift of rivers and lakes. An example of this transient process is shown in inset 4 of Fig. 1.

We identified 13,288 ha of forest cleared by mining activities (2%), including 1000 ha of forest cleared by artisanal gold mining along the Trans-Papua Highway near the city of Nabire (see inset 5, Fig. 1), and 11,372 ha cleared by tailings dumped in the Aikwa Delta system by Freeport's Grasberg gold and copper mine located in the Sudirman Mountains in Mimika Regency (see inset 6, Fig. 1). These observations are corroborated by Alonzo et al. (2016).

We estimate, from fire hotspots and Landsat imagery, that fires impacted 39,347 ha (5%) of forest, including three large forest fires in October 2015 in West Papua (see inset 7, Fig. 1). This clearance is likely temporary, as forest fires usually only burn the understory, and the vegetation regenerates after fire.

We determined that 115,336 ha (15%) were cleared by road expansion and population centres. This included forest directly cleared by the expanding route of public roads, and forest cleared within 5 km of transmigration sites, regency, and provincial cities. See for example, the rapidly expanding city of Dekai (inset 8, Fig. 1) and expanding transmigration sites near the Jayapura city (inset 9).

Shifting cultivation and other processes, such as landslides, tornadoes, undetected understory fires, cryptic logging and artisanal mining activities are presumed to account for the remaining 166,920 ha (22%) that we have not characterized. An example of forest impacted shifting agriculture inside Pegunungan Jayawijaya Wildlife Reserve is shown in Inset 10 of Fig. 1.

3.3. Deforestation trends

From 2001 to 2010 annual forest losses were relatively consistent, averaging 26,000 ha, before rising to 103,000 ha in 2015 and declining back reaching 35,000 ha in 2018 and finally 34,000 ha again in 2019 (Fig. 2, panel a). These trends largely reflect Papua province, where forest loss peaked in 2016 (59,000 ha) and then reduced by more than half by 2019 (20,000 ha). In West Papua, trends were less pronounced, but also with a peak in 2015 (44,000 ha) when several large forest fires occurred in Fakfak Regency (see inset 7 in Fig. 1).

3.4. Plantation expansion

By the end of 2000, there were 50,842 ha of industrial plantations (all oil palm). Between 2001 and 2019 the total area of plantations increased by 230,381 ha (220,644 ha oil palm; 9737 ha pulpwood), with the majority (208,842 ha; or 28% of forest loss) replacing forests. Much of this expansion occurred in Papua Province (168,361 ha; 73%), and in the two southern regencies of Boven Digul and Merauke (109,585 ha; 48%), which contain just 15% of Indonesian New Guinea's landmass. There appears to be three distinct periods for expansion. First, from 2001 to 2010 expansion averaged 2843 ha each year. Then, in 2011, this expansion accelerated until it peaked in 2015 (38,000 ha added, Fig. 2d). In the third phase, expansion declined again though it remained higher than the average pre-2010 level. Plantations expansion from
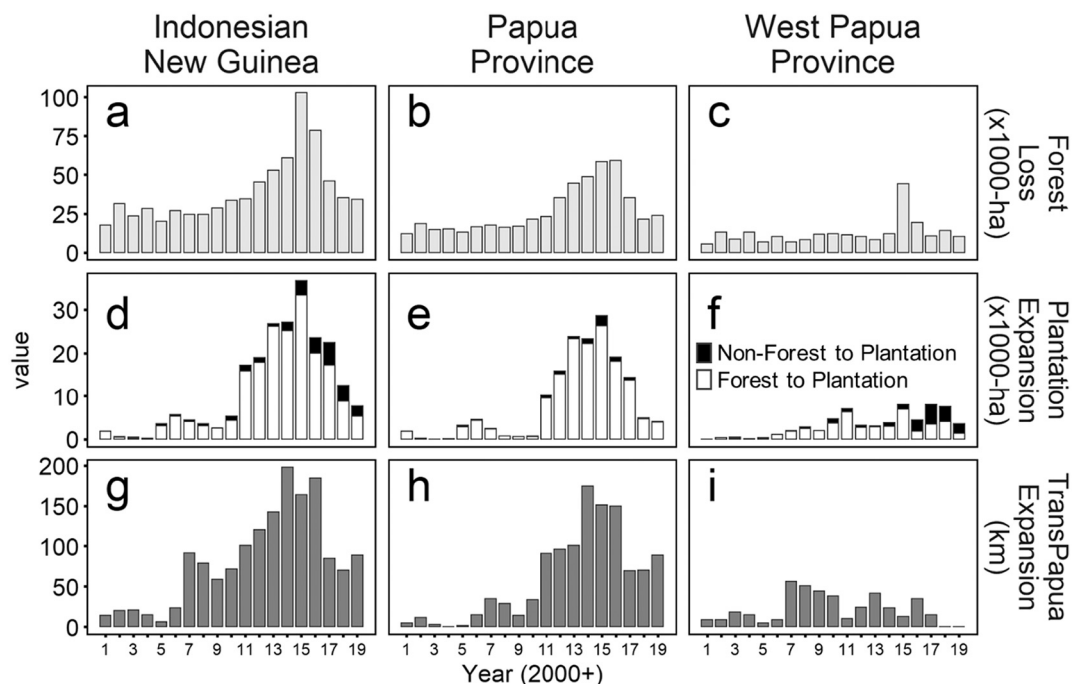

Fig. 2. Indonesian New Guinea's land-use change and its two provinces Papua and West Papua from interpretation of Landsat imagery year-by-year (2001–2009). Here we present the annual loss of forest area (a, b, c), the concomitant annual expansion of industrial plantations of oil palm and pulpwood (97% oil palm; 3% pulpwood) (d, e, f) and the expansion of the Trans-Papua Highway. The white bars in (d, e, f) represent the area of forest cleared and converted to industrial plantations in the same year.

2001 to 2019 focused on Papua Province and appears associated with the Merauke Integrated Food and Energy Estate (73%, 168,000 ha, Fig. 2e). Forests converted to plantations within one year of forest clearance exhibit similar trends (white bars in panels d, e, f).

3.5. Highway construction

By the end of 2000, 2333 km of Trans-Papua Highway had already been built (construction started in 1979). Between 2001 and 2019 the Highway increased by 1554 km, reaching 3887 km in 2019. This included a 202 km road section built through Lorentz National Park (a World Heritage site), followed by 575 km added to link the remote cities of Kenyam, Dekai and Oksibil (Fig. 1). In 2019, the Trans-Papua Highway was nearly complete though 51 km remained unopened. The construction of the Trans-Papua Highway generally increased from 2001 to 2016 (Fig. 2g), from 14 km of road added in 2001 to 185 km in 2016, with a peak in 2014 (198 km added). In Papua Province (Fig. 2h), there were two distinct periods: an average of 16 km added each year from 2001 to 2010 and then increasing to a maximum of 175 km in 2014. We see less variation in West Papua (Fig. 2i). Roads expansion declined in 2017 (85 km) and 2018 (70 km), with little increase in 2019 (89 km). This drop reflects changes in Papua Province. In Papua's southern Merauke district, construction of the highway built for the Merauke Integrated Food and Energy Estate (MIFEE) began in 2012, totalling 336 km in 2019 (purple line; Fig. 1). Transmigration population centres (totalling 129,427 ha, 90% established before 2000; Fig. 1) and industrial plantations are all located within 35 km of these Highways.

3.6. Correlations

Variation in annual forest loss is positively correlated with the annual expansion of industrial plantations ($r^2 = 0.80$, $p < 0.01$; Fig. 3a). This is clearer in Papua ($r^2 = 0.88$, $p < 0.01$) than in West Papua ($r^2 = 0.27$, $p = 0.021$) (Fig. 3b & c). The annual expansion of the Trans-Papua Highway and plantations are positively correlated ($r^2 = 0.75$, $p < 0.01$; Fig. 3). This relationship is strong in Papua but not in West Papua ($r^2 = 0.79$, $p \leq 0.01$ versus $r^2 = 0.0088$, $p = 0.70$, Fig. 3e, f). Similar patterns arise between annual highway expansion and forest loss ($r^2 = 0.67$, $p < 0.01$, $r^2 = 0.84$, $p < 0.01$, $r^2 = 0.19$, $p = 0.57$ for Indonesian New Guinea, Papua, and West Papua respectively) (Fig. A2).

3.7. Predictive model

We calibrated six spatially explicit models of deforestation with the observed 2010–2018 forest loss (Table 2). We retained the model that included active concessions, protected areas, and slope-based road cost because it had the highest similarity (39% of observed forest loss were properly simulated) with the fewest parameters (Model 3 in Table 2). The model performed well in regions where forests have been converted to industrial plantations, roads, and population centres, representing 45% (336,877 Mha) of total forest loss. It was not successful in simulating actual outcomes where forests were impacted by other more dynamic processes including timber extraction, shifting agriculture, understorey fires, artisanal mining, floods and landslides, which account for 55% (411,763 Mha) of total observed forest loss but often transient processes and appear less dependent on road access.
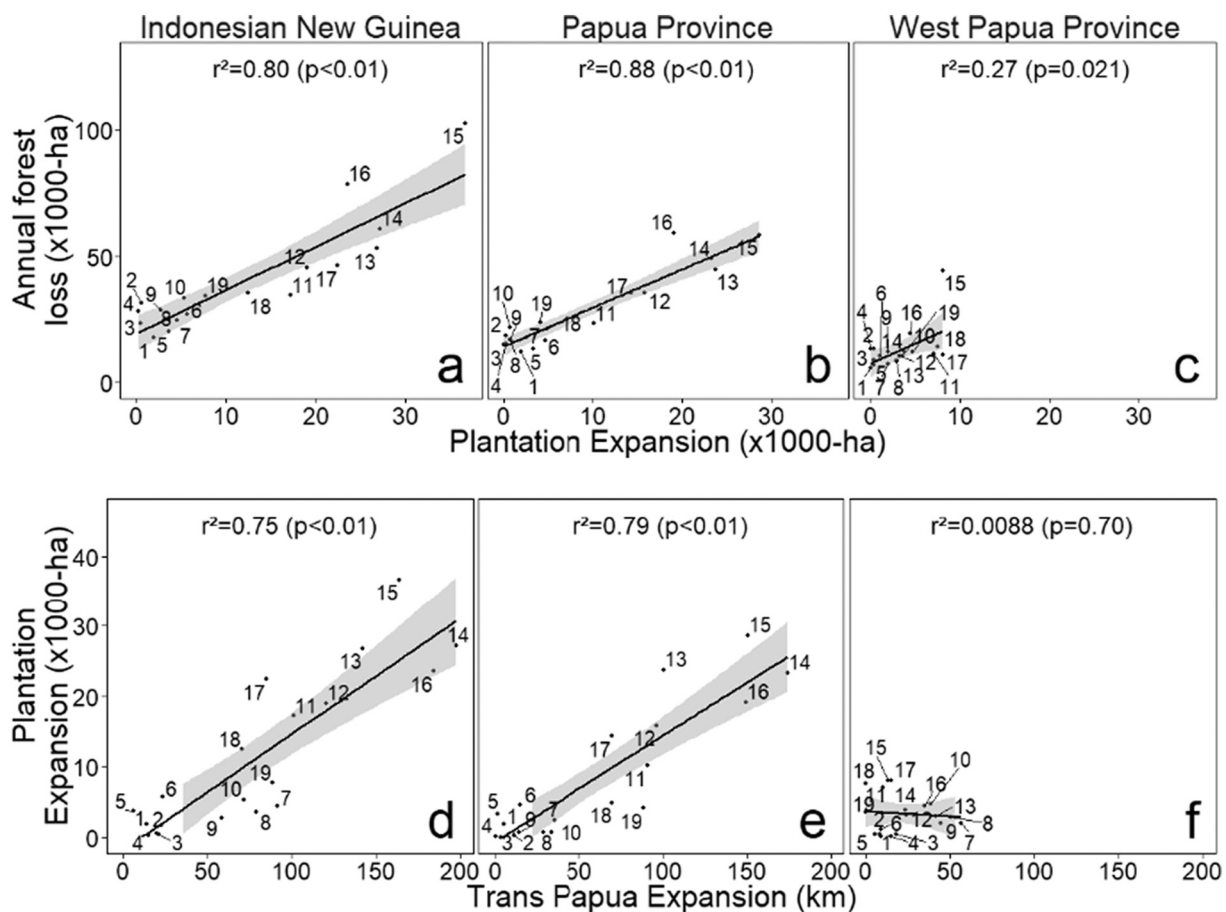

Fig. 3. Scatter plots and associated correlation line and Pearson's correlation coefficient (r^2) between the annual expansion of plantations and the annual loss of forest (a, b, c) and between the annual expansion of the Trans-Papua road and the annual expansion of plantations (d, e, f) in Indonesian New Guinea (a, d) and its two provinces, Papua (b, e) and West Papua (c, f). The shaded areas show the 95% confidence interval for predictions from the linear model.

Table 2
Spatially explicit models describing forest loss across Indonesian New Guinea.

Model		Similarity
6	*Response* ~ Active Concessions + Road[a] + PA + Elevation + Slope + Logging Road	36%
5	*Response* ~ Active Concessions + Road[a] + PA + Elevation + Slope	34%
4	*Response* ~ Active Concessions + Road[a] + PA + Elevation	36%
3	*Response* ~ Active Concessions + Road[a] + PA	39%
2	*Response* ~ Active Concessions + Road[a]	36%
1	*Response* ~ Active Concessions	31%

Response denotes presence versus absence of forest loss (also termed deforestation).
PA denotes protected areas.
[a] Denotes a cost distance to main roads.

We assessed the augmented threat posed by the observed expansion of roads by comparing the resulting deforestation-risk map against a hypothetical deforestation-risk map if roads had remained at their 2000 level. The construction of new roads increased the area of forest at risk of deforestation (probability >0.66) by 30% compared to the hypothetical scenario of halting such developments. Lowland forests near the cities of Dekai and Kenyam in Papua Province experienced the highest augmented threat (Fig. 4). The forests near the cities of Tanah Merah Merauke, and Timika remained overall the most threatened. The threshold of 0.66 is the lowest probability value in which a forest pixel was seen converted to non-forest in our projections (Fig. 5).

We projected future deforestation for 18 years, to 2036, for two scenarios using two empirically derived historic deforestation rates, one low and one high (Fig. 5). In the first scenario, forest loss was estimated at around 55,843 ha yr^{-1} although we note that this rate varied slightly year on year since it was estimated as the percentage of forest loss during 2010–2018 in Indonesian New Guinea relative to the total amount of forest left in the preceding year. This is the 'Limited Expansion Scenario' despite new roads. In the second scenario, using the speed of forest loss experienced by Indonesian Borneo during 2001–2018, we estimated forest loss at 253,907 ha yr^{-1}. This is the 'Business-as-usual Scenario' of rapid expansion seen in Indonesian Borneo following roads construction, and strong government support for plantation expansion.

In the limited expansion scenario, a total of 932,119 ha of forest would be lost by 2036, with 701,335 ha alone in active concessions (596,715 ha oil palm; 93,974 ha pulpwood; 10,646 ha mine tailings), 35,636 ha in inactive concessions, and 195,148 ha along roads. In the business-as-usual scenario a total of 4.50 Mha would be lost by 2036, with 720,353 ha in active concessions, 430,147 ha in inactive concessions, and 3.2 Mha along roads. The forest between the cities of Kenyam and Dekai, and between Tanah Merah and Merauke, would be the most severely impacted (Fig. 5).

4. Discussion

We have mapped and described trends in forest loss, industrial plantation development and road expansion, and their overlap in Indonesian New Guinea each calendar year from 2001 to 2019. We showed that the presence of concessions, roads and protected areas influenced the spatial distribution of forest loss and used them to predict future losses under different scenarios. These data are presented interactively in the Nusantara Atlas (Nusantara Atlas, 2021), a platform developed to monitor the impacts of expanding roads, mines and industrial plantations on forests, and thus assist the provinces oversee their commitments under the Manokwari Declaration (Cámara-Leret et al., 2019a). Overall, our results provide information for planning across this important, yet understudied region.

About 34.29 million hectares (Mha) of forest remained in Indonesian New Guinea in 2019, representing 42% of Indonesia's forests and the Asia Pacific region's largest area of intact old-growth forest. Furthermore, we find that Indonesian New Guinea has 8.5% (1.17 Mha) of the world's mangrove forests (13.58 Mha), with Papua's Mimika coast and West Papua's Bintuni Bay home to Indonesia's largest contiguous mangrove blocks (340,000 ha and 222,000 ha), only second to the Sundarbans in Bangladesh (Bunting et al., 2018; Global Mangrove Watch, 2021). We found a good agreement (5% difference) between the 2000 mangrove extent of 1,132,447 ha reported by Simard et al. (2019) and this study (1,191,690 ha). Given their importance to fisheries and role in carbon sequestration, conserving these mangroves is crucial (Murdiyarso et al., 2015). Furthermore, we find that with 2.82 Mha of intact forest occurring on 'officially recognised' peat, Papua and West Papua provinces have Indonesia's largest remaining intact peat forests. There are large uncertainties in these estimates (Warren et al., 2017) and
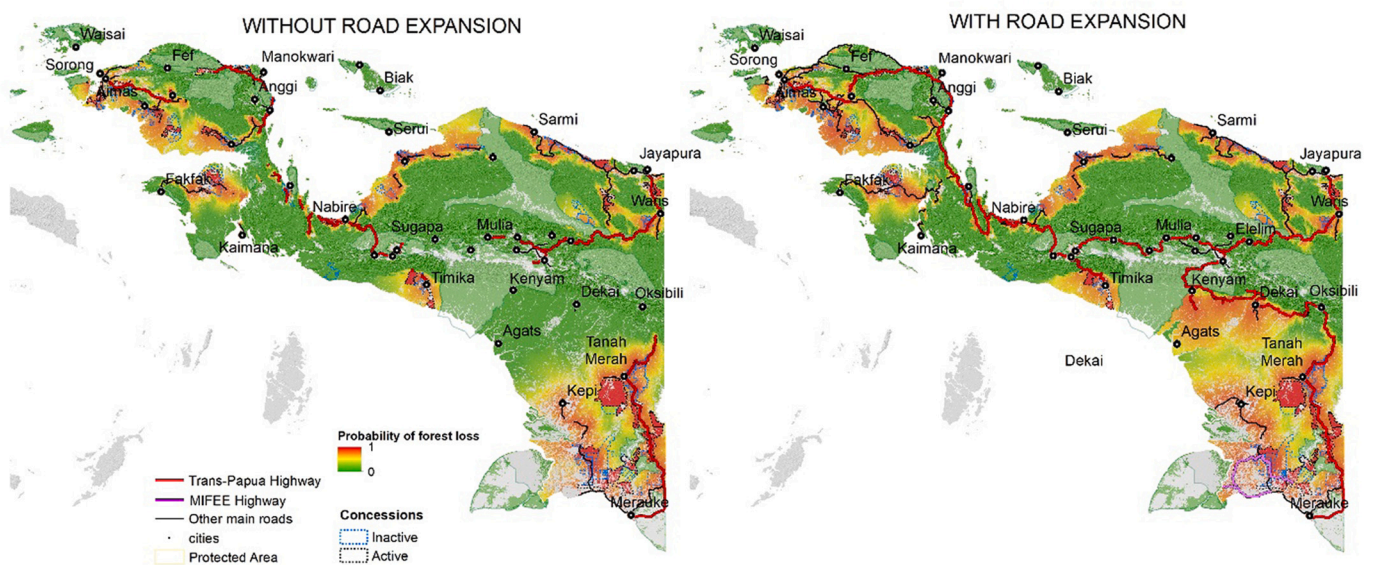

Fig. 4. Map of Indonesian New Guinea showing a hypothetical deforestation-risk map without road expansion, i.e. as roads were in 2000 (Left Panel), and with the observed expansion of roads between 2001 and 2019 (Right Panel). Trans-Papua and MIFEE Highways (red and purple lines) and other main roads (black). Areas of forest at high risk of deforestation are in red while low risk areas are green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
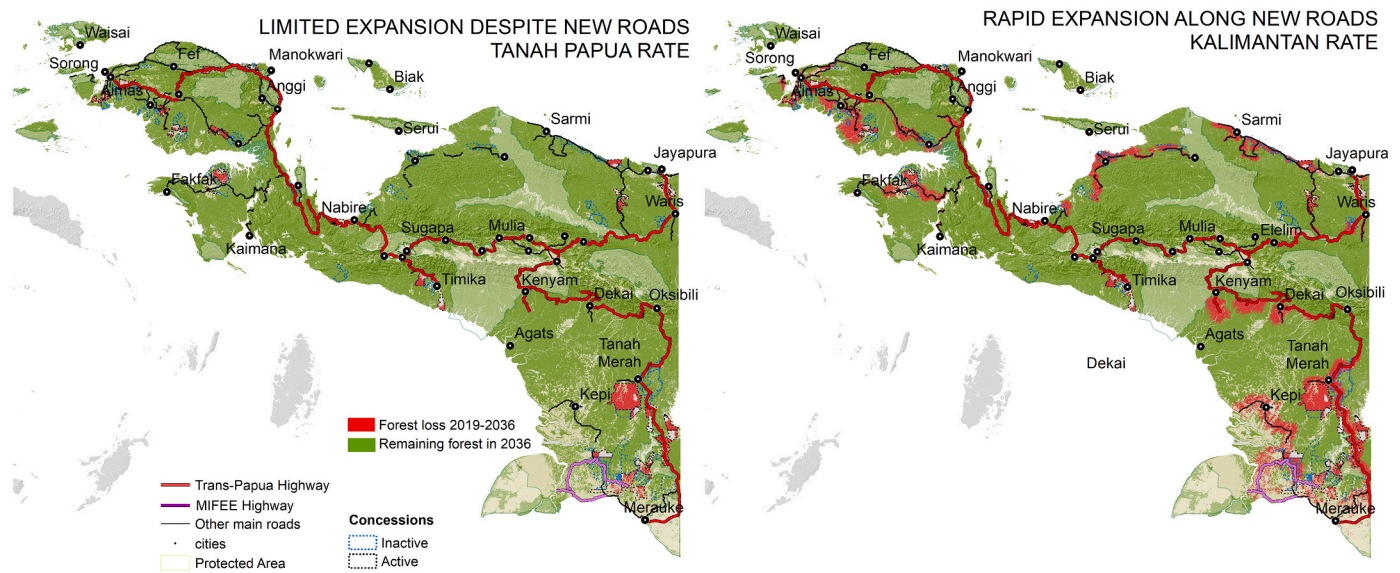
Fig. 5. Forest conversion outlook to 2036 under two scenarios.

recent ground truthing by Bappenas have highlighted a need to revise the current peat maps for Indonesian New Guinea (Imam Basuki pers. comm. to DS 2021).

What are the conservation implications of the changes we observed? Our knowledge of the region's biodiversity is sufficient to underline that many unique taxa will be at increased risk of loss as old growth forests are converted. In line with patterns seen elsewhere these risks will be further compounded by forest fragmentation, degradation, and increased accessibility (Maxwell et al., 2016). Nonetheless, our spatial knowledge of these sometimes local and vulnerable species remains limited (Cámara-Leret et al., 2020; Marshall and Beehler, 2007; Van Heist et al., 2010). We have not attempted any formal spatial priority setting here, though this is much needed and would be a valuable complement to our analysis. Such an exercise would reflect the new information generated over the last two decades (e.g., Vollering et al., 2016; Cámara-Leret et al., 2020) but will also be vital to highlight the many remaining unknowns (see e.g., Supriatna et al., 1999). Nonetheless, we note that areas we have identified as being at high risk of deforestation by 2036, overlap the priorities for increased protection according to one recent assessment of 2353 endemic plants and the threat posed by climate change: e.g., north of Tanah Merah, southwest of Jayapura, near Sarmi, Timika, and Sorong (Cámara-Leret et al., 2019b).

While our study has focused on land-cover change, we underline that this is only one aspect of the threats facing the region's remarkable biodiversity. Evidence from the tropics in general, and the region specifically, show that new roads do not merely increase the risk of forest loss but, unless effective controls are implemented, also increase access for harvesting and hunting. For example, roads tend to increase overall hunting pressures and also favour commercialisation as livelihoods, and associated practices, shift from subsistence to markets (Pattiselanno and Krockenberger, 2021). Such increased hunting modifies wildlife communities with profound long-term impacts on the ecology and values of the remaining forests. We note that in 2009 conservation responsibilities across the whole of Indonesian New Guinea, with 7.8 million hectares of protected areas, employed just 143 staff (Sheil et al., 2015). Few protected areas are regularly visited let alone actively protected by these staff (Sheil et al., 2015). As roads expand and access improves, the need for active protection, and associated costs, will increase.

Overall, Indonesian New Guinea has suffered less forest loss and degradation than the rest Indonesia. Just 2% of old growth forests were cleared from 2001 to 2019 and we estimate that more than half (55%; 411,763 Mha) associated with ephemeral events such as selective timber

extraction, fires, shifting agriculture, artisanal mining and landslides can recover if it is not further impacted or subsequently converted. The specific pixels impacted by these processes proved difficult to simulate from the variables we assessed. Our simulations proved more effective (39% similarity) in simulating the other, arguably more concerning 45% (or 336,877 Mha) where forests were more likely to be permanently lost due to common processes associated with road infrastructure: the development of new industrial plantations, mines, population centres, and the roads themselves. It is this road associated forest loss that is our concern here. We have not quantified what proportion of road associated changes are ephemeral. Precision is not our goal here: we rather wish to use a simple transparent method to indicate likely future deforestation hotspots if recent trends continue.

The density of primary logging roads (0.064 km/km^2) was lower, around one seventh, than what we had seen previously in Borneo (using similar techniques, Gaveau et al. (2014), found 0.48 km/km^2) and comparable to the densities observed in Central Africa during the 1980s and 1990s (Laporte et al., 2007). Nonetheless, extensive forest cover means that most developments impact these unique ecosystems. We showed that 88% of new industrial plantations (oil palm and pulpwood) replaced forests and accounted for 28% of observed deforestation. Mining remains a concern too. Notably, for over three decades the Grasberg Mine, the world's largest goldmine and second largest copper mine, has been releasing approximately 230,000 tons/day of tailings into rivers that flow into the Aikwa Delta in Mimika Regency (Taberima et al., 2020). While we show that the total forest loss (11,372 ha) resulting from this process contributes just 2% of total forest loss across Indonesian New Guinea, nonetheless the ecological and human impacts are considerable (Perlez and Bonner, 2005).

Roads have played a fundamental role in determining the pace and distribution of forest loss. The national government has invested heavily in roads, with the Trans-Papua Highway and the Merauke Food and Energy Estate Road intended to boost expansion of plantations and food estates. Our analysis clarifies these developments. Annual growth of the Trans-Papua Highway is correlated with the area of industrial plantations added, indicating the synergy between road and plantations expansion. We observed a surge in activity after 2010, peaking at 2014–2016 while in other regions of Indonesia the expansion of plantations had slowed several years earlier as prices of crude palm oil declined and the global economy slowed (Gaveau et al. under review). This recent peak is particularly marked in Papua Province, which attracted new plantations for several years longer than in other

provinces likely due to the opportunities and incentives provided by the Merauke Integrated Food and Energy Estate. We note that the observed correlation between roads and plantations need not be inevitable. While plantation developments require access, with sufficient controls in place new roads need not imply new plantations—though it is unclear if sufficient controls can be mustered in Indonesian New Guinea to permit such developments. Here we will not attempt a comprehensive review of the possible costs and benefits of roads as these have been reviewed many times (Laurance et al., 2014; Laurance and Arrea, 2017). Nonetheless we note that the financial costs are often greater than anticipated. Projects such as the Trans-Papuan Highway that cross rugged rain-soaked terrain are challenging to develop and maintain due to landslides (Garwood et al., 1979), collapse and floods (Alamgir et al., 2017). Whatever their engineering requirements, new roads bring developments that may be viewed differently depending on perspectives. UNESCO has noted that the threats posed by new roads to the globally recognised values of the Lorentz National Park, a World Heritage Site, may require it to be designated as a World Heritage Site 'in danger' (Sloan et al., 2019a). In addition to such recognised high-profile concerns, we see many other less known issues. For example, our observations show that the Trans-Papua Highway has already attracted artisanal gold mining in Nabire Regency, massive expansion of industrial plantations in Merauke and Boven Digul, and the rapid growth of Kenyam and Dekai Towns since they have been linked by 575 km of Trans-Papua Highway opening these areas to external market forces.

While roads and associated development can bring welcome benefits to previously remote and neglected communities, this requires detailed planning and is often debateable in practice. At least one recent study contends that the road infrastructures being developed in West Papua Province's Tambrauw regency will primarily benefit companies rather than local communities (FWI, 2020). According to the study, neither past nor planned road construction in the regency was designed to help people access health care or other services or opportunities. Instead, they facilitate access by concession owners to their oil concessions and benefit their subsequent extractive industries with consequent harm to forests, to indigenous peoples and to biodiversity (FWI, 2020). Concern that commercial interests dominate over local needs remain common across the region (Boissière et al., 2013; Ariutama and Fahmi, 2019). We note that the Merauke Integrated Food and Energy Estate (MIFEE) launched in 2011 to develop over 1.2 million ha of rice, soya, sugar, cassava and oil palm, and triggered the construction of the MIFEE Highway described in this study have displaced numerous indigenous Marind-Anim communities (Chao, 2019).

The Minister of Environment and Forestry issued a regulation in 2020 that fast tracks permits for previously protected forest (*Hutan Lindung*) to be converted for food production (Jong, 2020). Such policy changes favour plantation developments at the expense of forests and the careful planning needed to account for the needs and concerns of indigenous communities. In the latter part of 2020, partly in response to COVID 19, the Indonesian national government already announced an expansion of the food estate model to include Merauke Mappi and Boven Digul Regencies, ostensibly to reduce dependence on food imports. Cheaper transport will reduce the cost of basic commodities including cement and other construction materials, bringing developments and new opportunities for plantations, mining, and other developments in many forest rich areas. Our model indicates the likely nature, magnitude, and location of future threats to the region's forest. If development follows a top-down "business-as-usual" model like what has already occurred in Indonesian Borneo, our model suggests that an estimated 4.54 Mha of additional old growth forest could be lost by 2036. The relatively pristine forest regions surrounding Kenyam and Dekai, and in Boven Digul, Mappi and Merauke regencies comprising many important ancestral lands of indigenous groups are likely to experience significant deforestation if new roads bring the anticipated plantations, mining, food estates and associated influx of labour. Is there an alternative development scenario that will preserve the rich forest and cultural heritage of Indonesian New Guinea? First it is helpful to look briefly at the regulatory context.

The history of Indonesia's state interventions concerning forests is complex but key aspects provide context. Indonesia's constitution recognizes traditional ownership (*hak asal-usul*, Article 18) over forest but also declares, in an apparent conflict with traditional rights, that it is the state that has responsibility for controlling the use of the nation's natural resources (*menguasai*, Article 33) (Lynch and Harwell, 2002; Wrangham, 2002). This contradictory message permitted post-independence governments to assert ever greater control over forests through a series of laws and regulations (Wrangham, 2002). However, the constitution remained unchanged, and Indonesia's Constitutional Court has ruled that customary forest lands (*hutan adat*) cannot also be State Forest land and that the government's past claims to vast areas of forests were and are invalid (Butt, 2014). Thus this ruling (No. 35 of 2012) and various subsequent laws have recognised customary claims to ancestral territories (Larson et al., 2016). The central government's response has been high-profile commitments to improve the legal rights of Indonesia's indigenous people and to return many forests to local communities. This process has raised various concerns, and there have been various efforts to re-impose government controls and oversight.

Within this history of contested claims several initiatives to reconcile forest protection and local needs have been developed around government led "Social Forestry" programs. Within these initiatives the government maintains overall authority and the emphasis is on communities being granted rights to manage and draw value from forest under a set of rules, rights, and obligations. It is in the context of such efforts combined with increased recognition of customary lands that many authors propose and promote some form of "social forestry" (for example, sago, candlenut and nutmeg production) as an alternative to industrial-scale oil palm, pulpwood and food estates (e.g., Fatem, 2019; Ungirwalu et al., 2019). Nonetheless, such government controlled social forestry programs have had mixed success (Fisher et al., 2019); different land use contexts required different investment strategies to ensure social and environmental benefits (Meijaard et al., 2020). Whatever the outcome, social forestry appears to be the model of choice by the provincial governments of Papua and West Papua (see Manokwari Declaration) for engaging with customary communities on their terms (Fatem, 2019). However, the status of customary forests remains unclear due to limited political will and incomplete procedures for recognition (Myers et al., 2017). As a result, the recognition of customary forests and awarding of social forestry permits by government authorities, have been slow (Meijaard et al., 2020).

There are more radical approaches to land-use planning and implementation that recognize the primacy of indigenous rights and attempt to reconcile multiple, sometimes competing, demands (Wollenberg et al., 2009; Boissiere et al., 2010; Sarkar et al., 2017). Given the long history of local control over their own territories along with the identification oversight and protection of their natural resources, these approaches appear well suited to Indonesian New Guinea. There is a need to integrate development and environmental constraints, with local preferences in a manner that indigenous people can benefit from and thus favour and support, and that can also include explicit conservation goals to the degree that these are acceptable to stakeholders (Wollenberg et al., 2009; Boissiere et al., 2010; Padmanaba et al., 2012). Relevant evidence that such approaches have value for both conservation and people is available from local examples from within Indonesian New Guinea showing that—at least in remote regions where government oversight has been largely absent—community-based oversight has been effective in protecting large areas of land and forest in a near pristine state (Sheil et al., 2015). In addition, there is often strong support from traditional communities in Indonesian New Guinea for land-use planning, with official recognition, that designates large areas, as identified by the communities themselves, to be protected in perpetuity (Sheil and Boissière, 2006; Boissiere et al., 2010; Padmanaba et al., 2012; Sheil et al., 2015; Van Heist et al., 2015).

In any case, we favour approaches that recognize that indigenous communities have clear rights to their lands and resources that do not depend on anyone else's permission. Ensuring such rights appears consistent with Indonesia's constitution and would be particularly valuable in Indonesian New Guinea. Land-use planning in Papua needs to be based on a solid understanding of the benefits of economic development versus its social and environmental costs (Boissiere et al., 2010; Padmanaba et al., 2012). Papuans revere their customary practices and institutions making these a strong basis for building conservation and development opportunities around what local people themselves find important and desirable (Sheil and Boissière, 2006; Sheil and Lawrence, 2004; Van Heist et al., 2015). These local practices, though often labelled 'traditional', remain flexible and will adapt to changing requirements but can nonetheless benefit from external recognition and support when addressing novel threats, especially those that arise externally (Sheil et al., 2015). Strengthening this bottom-up decision-making process requires avoiding outdated top-down approaches. Effective, consensual, and frequent engagement between local representation and all layers of government is key to ensure alignment of local, regional and national development planning.

5. Conclusion

Indonesian New Guinea is opening to large-scale development. While overall forest losses remain limited, there are significant local impacts and a high likelihood of more. Our models show how ongoing road development may lead to more extensive deforestation. Future land use decisions should carefully weigh the positive and negative impacts of developments within this ethnically and biologically diverse region. Listening to, and seeking guidance from, the people impacted by these decisions is crucial for avoiding harmful developments. This is a global concern, and we call on the international community to support the Indonesian and Papuan people and their elected governments in making the best decisions.

CRediT authorship contribution statement

David Gaveau: Conceptualization, Methodology, Formal Analysis, Writing Original Draft, Reviewing and editing, Supervision. **Lucas Rodrigues**: Software (Dinamica Ego). **Bruno Locatelli**: Formal Analysis, Visualisation. **Mohammad Salim**: Resources, Data Curation, Visualisation. **Husnayaen Husnayaen**: Resources, Data curation, Visualisation. **Erik Meijaard**: Writing Original Draft, Reviewing and Editing. **Charlie Heatubun**: Reviewing and Editing. **Douglas Sheil**: Conceptualization, Writing Original Draft, Reviewing and Editing.

Declaration of competing interest

David Gaveau is a member of the IUCN Oil Palm Task Force, a group tasked by the IUCN to investigate the sustainability of palm oil and he has done oil palm related work for this task force, and for Greenpeace. Erik Meijaard chairs and has received funding from the IUCN Oil Palm Task Force and he has done work paid by palm oil companies and the Roundtable on Sustainable Palm Oil. Douglas Sheil is a member of the IUCN Oil Palm Task Force and he has facilitated student research in an oil palm concession (ANJ-Agri).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2021.109225.

References

Alamgir, M., Campbell, M.J., Sloan, S., Goosem, M., Clements, G.R., Mahmoud, M.I., Laurance, W.F., 2017. Economic, socio-political and environmental risks of road development in the tropics. Curr. Biol. 27, R1130–R1140.

Alamgir, M., Sloan, S., Campbell, M.J., Engert, J., Kiele, R., Porolak, G., Mutton, T., Brenier, A., Ibisch, P.L., Laurance, W.F., 2019. Infrastructure expansion challenges sustainable development in Papua New Guinea. PLoS One 14, e0219408.

Alonzo, M., Van Den Hoek, J., Ahmed, N., 2016. Capturing coupled riparian and coastal disturbance from industrial mining using cloud-resilient satellite time series analysis. Sci. Rep. 6, 35129.

Angelsen, A., 1999. Agricultural expansion and deforestation: modelling the impact of population, market forces and property rights. J. Dev. Econ. 58, 185–218.

Ariutama, I.G.A., Fahmi, A., 2019. Inclusive growth, educational attainment and morbidity rate in Papua Province. Econ Dev. Anal. J. 8, 54–64.

Austin, K.G., Schwantes, A., Gu, Y., Kasibhatla, P.S., 2019. What causes deforestation in Indonesia? Environ. Res. Lett. 14, 024007.

Bartlett, L.J., Williams, D.R., Prescott, G.W., Balmford, A., Green, R.E., Eriksson, A., Valdes, P.J., Singarayer, J.S., Manica, A., 2016. Robustness despite uncertainty: regional climate data reveal the dominant role of humans in explaining global extinctions of Late Quaternary megafauna. Ecography 39, 152–161.

Beehler, B., 2007. Papuan terrestrial biogeography, with special reference to birds. In: Marshall, A., Beehler, B. (Eds.), The Ecology of Papua. Periplus, Singapore, pp. 196–206.

Boissiere, M., Purwanto, Y., 2007. The agricultural systems of Papua. In: Marshall, A., Beehler, B. (Eds.), Ecology of Papua. Periplus, Singapore, pp. 1125–1158.

Boissiere, M., Sassen, M., Sheil, D., Heist, M., Jong, W., Cunliffe, R., Wan, M., Padmanaba, M., Liswanti, N., Basuki, I., 2010. Researching local perspectives on biodiversity in tropical landscapes: lessons from ten case studies. Participatory Biodiversity Assessment for Policy, Planning and Practice. Cambridge University Press, Cambridge, Taking Stock of Nature, pp. 113–141.

Boissière, M., Locatelli, B., Sheil, D., Padmanaba, M., Sadjudin, E., 2013. Local perceptions of climate variability and change in tropical forests of Papua, Indonesia. Ecol. Soc. 18.

Brooks, T.M., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A., Rylands, A.B., Konstant, W.R., Flick, P., Pilgrim, J., Oldfield, S., Magin, G., 2002. Habitat loss and extinction in the hotspots of biodiversity. Conserv. Biol. 16, 909–923.

Bunting, P., Rosenqvist, A., Lucas, R.M., Rebelo, L.-M., Hilarides, L., Thomas, N., Hardy, A., Itoh, T., Shimada, M., Finlayson, C.M., 2018. The global mangrove watch—a new 2010 global baseline of mangrove extent. Remote Sens. 10, 1669.

Butt, S., 2014. Traditional land rights before the Indonesian constitutional court. Law Environ. Dev. J. 10, 1.

Cámara-Leret, R., Schuiteman, A., Utteridge, T., Bramley, G., Deverell, R., Fisher, L.A., McLeod, J., Hannah, L., Roehrdanz, P., Laman, T.G., E, S., Y, d.-F., C, H., 2019a. The Manokwari declaration: challenges ahead in conserving 70% of Tanah Papua's forests. For. Soc. 3, 148–151.

Cámara-Leret, R., Raes, N., Roehrdanz, P., De Fretes, Y., Heatubun, C., Roeble, L., Schuiteman, A., van Welzen, P., Hannah, L., 2019b. Climate change threatens New Guinea's biocultural heritage. Sci. Adv. 5, eaaz1455.

Cámara-Leret, R., Frodin, D.G., Adema, F., Anderson, C., Appelhans, M.S., Argent, G., Arias Guerrero, S., Ashton, P., Baker, W.J., Barfod, A.S., Barrington, D., Borosova, R., Bramley, G.L.C., Briggs, M., Buerki, S., Cahen, D., Callmander, M.W., Cheek, M., Chen, C.-W., Conn, B.J., Coode, M.J.E., Darbyshire, I., Dawson, S., Dransfield, J., Drinkell, C., Duyfjes, B., Ebihara, A., Ezedin, Z., Fu, L.-F., Gideon, O., Girmansyah, D., Govaerts, R., Fortune-Hopkins, H., Hassemer, G., Hay, A., Heatubun, C.D., Hind, D.J.N., Hoch, P., Homot, P., Hovenkamp, P., Hughes, M., Jebb, M., Jennings, L., Jimbo, T., Kessler, M., Kiew, R., Knapp, S., Lamei, P., Lehnert, M., Lewis, G.P., Linder, H.P., Lindsay, S., Low, Y.W., Lucas, E., Mancera, J. P., Monro, A.K., Moore, A., Middleton, D.J., Nagamasu, H., Newman, M.F., Nic Lughadha, E., Melo, P.H.A., Ohlsen, D.J., Pannell, C.M., Parris, B., Pearce, L., Penneys, D.S., Perrie, L.R., Petoe, P., Poulsen, A.D., Prance, G.T., Quakenbush, J.P., Raes, N., Rodda, M., Rogers, Z.S., Schuiteman, A., Schwartsburd, P., Scotland, R.W., Simmons, M.P., Simpson, D.A., Stevens, P., Sundue, M., Testo, W., Trias-Blasi, A., Turner, I., Utteridge, T., Walsingham, L., Webber, B.L., Wei, R., Weiblen, G.D., Weigend, M., Weston, P., de Wilde, W., Wilkie, P., Wilmot-Dear, C.M., Wilson, H.P., Wood, J.R.I., Zhang, L.-B., van Welzen, P.C., 2020. New Guinea has the world's richest island flora. Nature 584, 579–583.

Carlson, K.M., Heilmayr, R., Gibbs, H.K., Noojipady, P., Burns, D.N., Morton, D.C., Walker, N.F., Paoli, G.D., Kremen, C., 2018. Effect of oil palm sustainability certification on deforestation and fire in Indonesia. Proc. Natl. Acad. Sci. 115, 121–126.

Chao, S.M.H.l.n., 2019. In the Shadow of the Palms: Plant-Human Relations Among Marind-Anim, West Papua.

Corlett, R.T., Primack, R.B., 2011. Tropical Rain Forests: An Ecological and Biogeographical Comparison. John Wiley & Sons.

Descals, A., Wich, S., Meijaard, E., Gaveau, D.L., Peedell, S., Szantoi, Z., 2021. High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. Earth Syst. Sci. Data 13, 1211–1231.

DGOEC, 2020. Tree Crop Estate Statistics of Indonesia/Statistik Perkebunan Indonesia 2018–2020. Directorate General of Estate Crops, Ministry of Agriculture, Indoonesian Government.

Fatem, S.M., 2019. Connecting social forestry to conservation policies in Tanah Papua. For. Soc. 3, 141–147.

Filer, C., Keenan, R.J., Allen, B.J., Mcalpine, J.R., 2009. Deforestation and forest degradation in Papua New Guinea. Ann. For. Sci. 66, 813.

Fisher, M.R., Dhiaulhaq, A., Sahide, M.A.K., 2019. The politics, economies, and ecologies of Indonesia's third generation of social forestry: an introduction to the special section. For. Soc. 3, 152–170.

Foga, S., Scaramuzza, P.L., Guo, S., Zhu, Z., Dilley Jr., R.D., Beckmann, T., Schmidt, G.L., Dwyer, J.L., Hughes, M.J., Laue, B., 2017. Cloud detection algorithm comparison and validation for operational Landsat data products. Remote Sens. Environ. 194, 379–390.

Franky, Y., Moragan, S., 2015. West Papua Oil Palm Atlas: The Companies behind the Plantation Explosion. Awas MIFEE, Jakarta. https://awasmifee.potager.org/?p=1205. (Accessed November 2020).

FWI, 2020. Infrastruktur di Papua untuk siapa? Forest Watch Indonesia, Jakarta. <https://fwi.or.id/wp-content/uploads/2020/05/final-Factsheet-Infrastruktur-Papua-2.pdf> (accessed October 2020).

Garwood, N.C., Janos, D.P., Brokaw, N., 1979. Earthquake-caused landslides: a major disturbance to tropical forests. Science 205, 997–999.

Gaveau, D.L., Kshatriya, M., Sheil, D., Sloan, S., Molidena, E., Wijaya, A., Wich, S., Ancrenaz, M., Hansen, M., Broich, M., 2013. Reconciling forest conservation and logging in Indonesian Borneo. PLoS One 8, e69887.

Gaveau, D.L., Sloan, S., Molidena, E., Yaen, H., Sheil, D., Abram, N.K., Ancrenaz, M., Nasi, R., Quinones, M., Wielaard, N., 2014. Four decades of forest persistence, clearance and logging on Borneo. PLoS One 9, e101654.

Gaveau, D.L., Locatelli, B., Salim, M.A., Yaen, H., Pacheco, P., Sheil, D., 2019. Rise and fall of forest loss and industrial plantations in Borneo (2000–2017). Conserv. Lett. 12, e12622.

Gaveau, D.L.A., Locatelli, B., Salim, M.A., Husnayaen, H., Manurung, T., Descals, A., Angelsen, A., Meijaard, E., Sheil, D., 2021. Slowing deforestation in Indonesia follows declining oil palm expansion and lower oil prices. Commun. Earth Environ. https://doi.org/10.21203/rs.3.rs-143515/v1 (under review).

Global Mangrove Watch, 2021. <https://www.globalmangrovewatch.org/> (accessed February 2021).

Gokkon, B., 2017. Indonesia's big development push in Papua: Q&A with program overseer Judith J. In: Dipodiputro, In Mongabay News. Jakarta, Mongabay.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27.

Hansen, M., Potapov, P., Moore, R., Hancher, M., Turubanova, S., Tyukavina, A., Thau, D., Stehman, S., Goetz, S., and Loveland, T., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.

Hoover, J.D., Kumar, S., James, S.A., Leisz, S.J., Laituri, M., 2017. Modeling hotspots of plant diversity in New Guinea. Trop. Ecol. 58, 623–640.

Johnson, C.N., Alroy, J., Beeton, N.J., Bird, M.I., Brook, B.W., Cooper, A., Gillespie, R., Herrando-Pérez, S., Jacobs, Z., Miller, G.H., 2016. What caused extinction of the Pleistocene megafauna of Sahul? Proc. R. Soc. B Biol. Sci. 283, 20152399.

Jong, H., 2020. New rule puts Indonesia's protected forests up for grabs for agribusiness, In Mongabay News. Mongabay, Jakarta. https://news.mongabay.com/2020/11/indonesia-protected-forest-agribusiness-food-estate-regulation/. (Accessed February 2021).

Karim, A., Tie, A.P.L., Manan, D., Zaidul, I., 2008. Starch from the sago (Metroxylon sagu) palm tree—properties, prospects, and challenges as a new industrial source for food and other uses. Compr. Rev. Food Sci. Food Saf. 7, 215–228.

Kennedy, J., 2012. Agricultural systems in the tropical forest: a critique framed by tree crops of Papua New Guinea. Quat. Int. 249, 140–150.

Kirksey, S.E., Bilsen, K., 2002. A road to freedom; Mee articulations and the Trans-Papua Highway. Bijdragen tot de taal-, land-en volkenkunde/J. Hum. Soc. Sci. SE Asia 158, 837–854.

Kooyman, R.M., Morley, R.J., Crayn, D.M., Joyce, E.M., Rossetto, M., Slik, J.F., Strijk, J. S., Su, T., Yap, J.-Y.S., Wilf, P., 2019. Origins and assembly of Malesian rainforests. Annu. Rev. Ecol. Evol. Syst. 50, 5.1–5.25.

Laporte, N.T., Stabach, J.A., Grosch, R., Lin, T.S., Goetz, S.J., 2007. Expansion of industrial logging in Central Africa. Science 316, 1451.

Larson, A.M., Monterroso, I., Banjade, M.R., Mwangi, E., 2016. Community rights to forests in the tropics: progress and retreat on tenure reforms. Global Perspectives. Edward Elgar Publishing, Cheltenham, UK, In Comparative Property Law.

Laurance, W.F., Arrea, I.B., 2017. Roads to riches or ruin? Science 358, 442–444.

Laurance, W.F., Kakul, T., Keenan, R.J., Sayer, J., Passingan, S., Clements, G.R., Villegas, F., Sodhi, N.S., 2011. Predatory corporations, failing governance, and the fate of forests in Papua New Guinea. Conserv. Lett. 4, 95–100.

Laurance, W.F., Clements, G.R., Sloan, S., O'connell, C.S., Mueller, N.D., Goosem, M., Venter, O., Edwards, D.P., Phalan, B., Balmford, A., 2014. A global strategy for road building. Nature 513, 229–232.

Lohman, D.J., de Bruyn, M., Page, T., von Rintelen, K., Hall, R., Ng, P.K., Shih, H.-T., Carvalho, G.R., von Rintelen, T., 2011. Biogeography of the Indo-Australian archipelago. Annu. Rev. Ecol. Evol. Syst. 42, 205–226.

Lynch, O.J., Harwell, E., 2002. Whose natural resources? Whose common good. Towards a Paradigm of Environmental Justice and the National Interest in Indonesia, Centre for International Environmental Law (CIEL), Washington, DC, US, and Jakarta, Indonesia 86.

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F., Hansen, M.C., 2014. Primary forest cover loss in Indonesia over 2000-2012. Nat. Clim. Chang. 4, 730–735.

Marshall, A. J., and Beehler, B. M., eds., 2007. "The Ecology of Papua", pp. 1-749 & 768. Periplus Editions, Singapore.

Maxwell, S.L., Fuller, R.A., Brooks, T.M., Watson, J.E., 2016. Biodiversity: the ravages of guns, nets and bulldozers. Nat. News 536, 143.

Meijaard, E., Santika, T., Wilson, K.A., Budiharta, S., Kusworo, A., Law, E.A., Friedman, R., Hutabarat, J.A., Indrawan, T.P., Sherman, J., 2020. Toward improved impact evaluation of community forest management in Indonesia. Conserv. Sci. Pract. 3, 1–14. https://doi.org/10.1111/csp2.189 e189.

Miettinen, J., Shi, C., and Liew, S. C. J. G. C. B., 2011. Deforestation Rates in Insular Southeast Asia Between 2000 and 2010. 17, 2261–2270.

MOEF, 2018. The State of Indonesia's Forests 2018. Ministry of Environment and Forestry. Republic of Indonesia, Jakarta.

MOEF, 2020. Online portal of Indonesia's Ministry of Environment and Forestry. <https://dbgis.menlhk.go.id/portal/home/> (accessed May 2020).

Morley, R.J., 2000. Origin and Evolution of Tropical Rain Forests. John Wiley & Sons, Ltd., Chichester, UK.

Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D.C., Manuri, S., Krisnawati, H., Taberima, S., Kurnianto, S., 2015. The potential of Indonesian mangrove forests for global climate change mitigation. Nat. Clim. Chang. 5, 1089–1092.

Mutia Dewi, V, 2020. Historical evidence of palm oil expansion in Papua. Vol. 2020. Foresthints, Jakarta. <https://foresthints.news/opinion-historical-evidence-of-palm-oil-expansion-in-papua/#:~:text=The%20results%20of%20a%20study,years%20(2000%20%2D%202019)> (accessed June 2020).

Myers, R., Intarini, D., Sirait, M.T., Maryudi, A., 2017. Claiming the forest: inclusions and exclusions under Indonesia's 'new' forest policies on customary forests. Land Use Policy 66, 205–213.

NASA-FIRMS, 2020. MODIS Active Fire/Hotspot Data. Fire Information for Resource Management (FIRMS). <https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms/active-fire-data> (accessed July 2020).

Nusantara Atlas, 2021. Nusantara Atlas. http://nusantara-atlas.org/. (Accessed May 2021).

O'Connell, J.F., Allen, J., 2015. The process, biotic impact, and global implications of the human colonization of Sahul about 47,000 years ago. J. Archaeol. Sci. 56, 73–84.

Padmanaba, M., Boissière, M., Ermayanti, Sumantri, H., and Achdiawan, R., 2012. "Perspectives on Collaborative Land Use Planning in Mamberamo Raya Regency, Papua, Indonesia: Case Studies From Burmeso, Kwerba, Metaweja, Papasena, and Yoke. (Project Report).". CIFOR, Bogor, Indonesia.

Paoli, G.D., Gillespie, P., Wells, P.L., Hovani, L., Sileuw, A., Franklin, N., Schweithelm, J., 2013. Oil Palm in Indonesia: Governance, Decision Making and Implications for Sustainable Development. The Nature Conservancy, Jakarta, Indonesia.

Pattiselanno, F., Krockenberger, A., 2021. Road development and Indigenous hunting in Tanah Papua: connecting the facts for future wildlife conservation agendas. For. Soc. 181–189.

Pekel, J.-F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. Nature 540, 418–422.

Perlez, J., and Bonner, R., 2005. Below a Mountain of Wealth, a River of Waste. New York Times 27.

Rabus, B., Eineder, M., Roth, A., Balmer, R., 2003. The shuttle radar topography mission-a new class of digital elevation models acquired by spaceborne radar. Photogramm. Remote Sens. 57, 241–262.

Ritung, S., Wahyunto, Nugroho, K., Sukarman, Hikmatullah, Suparto, C, T., 2011. Peatland Map of Indonesia. Department of Research and Development of Agricultural Land Resources, Ministry of Agriculture.

Runtuboi, Y.Y., Permadi, D.B., Sahide, M.A.K., Maryudi, A., 2020. Oil palm plantations, forest conservation and indigenous peoples in West Papua Province: what lies ahead? For. Soc. 23–31.

Santika, T., Wilson, K.A., Budiharta, S., Law, E.A., Poh, T.M., Ancrenaz, M., Struebig, M. J., Meijaard, E., 2019. Does oil palm agriculture help alleviate poverty? A multidimensional counterfactual assessment of oil palm development in Indonesia. World Dev. 120, 105–117.

Sarkar, S., Dyer, J.S., Margules, C., Ciarleglio, M., Kemp, N., Wong, G., Juhn, D., Supriatna, J., 2017. Developing an objectives hierarchy for multicriteria decisions on land use options, with a case study of biodiversity conservation and forestry production from Papua, Indonesia. Environ. Plan. B Urban Anal. City Sci. 44, 464–485.

Sasmito, S.D., Sillanpää, M., Hayes, M.A., Bachri, S., Saragi-Sasmito, M.F., Sidik, F., Hanggara, B.B., Mofu, W.Y., Rumbiak, V.I., Taberima, S., 2020. Mangrove blue carbon stocks and dynamics are controlled by hydrogeomorphic settings and land-use change. Glob. Chang. Biol. 26, 3028–3039.

Scholes, E., Laman, T.G., 2018. Distinctive courtship phenotype of the Vogelkop Superb Bird-of-Paradise Lophorina niedda Mayr, 1930 confirms new species status. PeerJ 6, e4621.

Shearman, P., Bryan, J., 2011. A bioregional analysis of the distribution of rainforest cover, deforestation and degradation in Papua New Guinea. Austral Ecol. 36, 9–24.

Shearman, P., Bryan, J.E., 2015. The State of the Forests of Papua New Guinea 2014: Measuring Change Over the Period 2002–2014. University of Papua New Guinea.

Sheil, D., Boissière, M., 2006. Local people may be the best allies in conservation. Nature 440, 868.

Sheil, D., Lawrence, A., 2004. Tropical biologists, local people and conservation: new opportunities for collaboration. Trends Ecol. Evol. 19, 634–638.

Sheil, D., Boissière, M., Beaudoin, G., 2015. Unseen sentinels: local monitoring and control in conservation's blind spots. Ecol. Soc. 20.

Sillanpää, M., Vantellingen, J., Friess, D.A., 2017. Vegetation regeneration in a sustainably harvested mangrove forest in West Papua, Indonesia. For. Ecol. Manag. 390, 137–146.

Simard, M., T. Fatoyinbo, C. Smetanka, V.H. Rivera-monroy, E. Castaneda, N. Thomas, and T. Van der stocken., 2019. Global Mangrove Distribution, Aboveground Biomass, and Canopy Height. ORNL DAAC, Oak Ridge, Tennessee, USA. <https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1665> (accessed April 2021).

Sloan, S., Campbell, M.J., Alamgir, M., Engert, J., Ishida, F.Y., Senn, N., Huther, J., Laurance, W.F., 2019a. Hidden challenges for conservation and development along the Trans-Papuan economic corridor. Environ. Sci. Pol. 92, 98–106.

Sloan, S., Meyfroidt, P., Rudel, T.K., Bongers, F., Chazdon, R., 2019b. The forest transformation: planted tree cover and regional dynamics of tree gains and losses. Glob. Environ. Chang. 59, 101988.

Soares-Filho, B. S., Rodrigues, H. O., and Costa, W., 2009. Modeling Environmental Dynamics With Dinamica EGO. Centro de Sensoriamento Remoto. Universidade Federal de Minas Gerais. Belo Horizonte, Minas Gerais 115.

Supriatna, J., De Fretes, Y., Mack, A., Yeager, C., Olivieri, S., Burnett, J., Wijayanto, I., Suryadi, S., Suhandi, A., 1999. The Irian Jaya Biodiversity Conservation Priority-setting Workshop (Final Report). Conservation International, Washington, DC, USA.

Taberima, S., Junaedi, E., Sarwom, R., Lindongi, L.E., Mulyanto, B., 2020. The acid mine drainage (AMD) impact of tailings and non-tailings on the ecosystem changes in the ModADA sedimentation area, Timika. J. Degraded Min. Lands Manag. 7, 2085.

Tang, H., Armston, J., Hancock, S., Marselis, S., Goetz, S., Dubayah, R., 2019. Characterizing global forest canopy cover distribution using spaceborne lidar. Remote Sens. Environ. 231, 111262.

Toussaint, E.F., Hall, R., Monaghan, M.T., Sagata, K., Ibalim, S., Shaverdo, H.V., Vogler, A.P., Pons, J., Balke, M., 2014. The towering orogeny of New Guinea as a trigger for arthropod megadiversity. Nat. Commun. 5, 1–10.

Ungirwalu, A., Awang, S., Maryudi, A., Priyono, S., 2019. Small scale ecology and society: forest-culture of Papua nutmeg (Myristica argantea Warb.). http://repository.unipa.ac.id:8080/xmlui/handle/123456789/375. (Accessed January 2021).

Van Heist, M., Sheil, D., Rachman, I., Gusbager, P., Raweyai, C., Yoteni, H., 2010. The forests and related vegetation of Kwerba, on the Foja Foothills, Mamberamo, Papua (Indonesian New Guinea). Blumea Biodivers. Evol. Biogeogr. Plants 55, 153–161.

Van Heist, M., Liswanti, N., Boissière, M., Padmanaba, M., Basuki, I., Sheil, D., 2015. Exploring local perspectives for conservation planning: a case study from a remote forest community in Indonesian Papua. Forests 6, 3278–3303.

Vollering, J., Schuiteman, A., de Vogel, E., van Vugt, R., and Raes, N., 2016. Phytogeography of New Guinean Orchids: Patterns of Species Richness and Turnover. 43, 204–214.

Warren, M., Hergoualc'h, K., Kauffman, J.B., Murdiyarso, D., Kolka, R., 2017. An appraisal of Indonesia's immense peat carbon stock using national peatland maps: uncertainties and potential losses from conversion. Carbon Balance Manag. 12, 1–12.

Wollenberg, E., Campbell, B., Dounias, E., Gunarso, P., Moeliono, M., Sheil, D., 2009. Interactive land-use planning in Indonesian rain-forest landscapes: reconnecting plans to practice. Ecol. Soc. 14.

Wrangham, R., 2002. Changing policy discourses and traditional communities, In Which Way Forward?: People, Forests, and Policymaking in Indonesia. eds C. Colfer, d.A.P. Resosudarmo, pp. 20–35. CIFOR, Bogor.