ZURICH UNIVERSITY OF APPLIED SCIENCES
SCHOOL OF LIFE SCIENCES AND FACILITY MANAGEMENT
INSTITUTE OF NATURAL RESOURCE SCIENCES

Quantification of deforestation on Borneo in the last 20 years based on open source geodata

Bachelor Thesis

HS23

by

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BSc Environmental engineering

Submission date: 29.10.2023

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Imprint

Institute
Institute of Natural Resource Sciences

Form of citation
APA 7th edition

Keywords
deforestation, spatiotemporal analysis, open-source geodata, Borneo, palm oil

Abstract

The Borneon tropical forests and peatlands play an important ecological and climatic role, due to their vast biodiversity and climate regulation effects. However, they are threatened by forest loss due to land-use change and fires. The deforestation of tropical forests is related to far-reaching implications for water regulation and greenhouse gas emissions.

It is thus of imperative importance for policymakers to have recent quantitative information on the drivers of forest loss to monitor existing and plan future sustainable development initiatives. Thus, this thesis examines deforestation and its causes on Borneo over the past two decades. It addresses annual deforestation rates, land conversion to oil palm plantations and other crops, the impact of the Roundtable on Sustainable Palm Oil (RSPO) label and the impact of infrastructure on deforestation. The analysis is based on open-source geospatial data generated by modern remote sensing techniques which were processed with open-source solutions.

While 395,548km^2 of Borneo (54.3%) were covered by primary forest in 2001, deforestation has brought this number down to 334,269km^2 (45.9%) in 2021 with the peak forest loss of 5,881km^2 in 2016. Annual rates showed a declining trend thereafter to ~2,000km^2. However, forest degradation by selective logging was not considered. Forest fires peak in El Niño years and are the major forest loss driver within the otherwise well-preserved protected areas. Oil palm plantations were responsible for 21.4% of all primary forest logging (excluding forest fires) from 2001 - 2013. Primary forest loss in RSPO-certified concessions was almost inexistent, as they are predominantly located on previously cleared land. Other crops only play a minor role in deforestation. Infrastructure doubled over the study period from 10,332km^2 to 21,789km^2. 91.2% of primary forest loss is located within 2000m of newly built up areas underlining its role as a major driver of deforestation.

Boreno has continued to lose significant amounts of primary forest over the past two decades. With the planned relocation of Indonesia's capital to Kalimantan, as well as the El Niño phenomenon magnified by climate change, the challenges for forest conservation will continue to be immense, even as government regulations such as Indonesia's moratorium on primary forest clearing, introduced in 2011, begin to take effect.

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1 Introduction

Borneo, the third largest island in the world, is home to extensive tropical forests and peatlands. They have a vital ecological and climatic role on a global scale and are of great socioeconomic value on a national and regional level (Harrison et al., 2020). With an estimated 10,000 to 15,000 species of flowering plants, 37 endemic bird and 44 endemic mammal species (MacKinnon et al., 1997), Borneo is part of the Sundaland biodiversity hotspot (Myers et al., 2000). However, this vast flora and fauna is threatened by land use change, climate change and fire with the IUCN listing 415 species as threatened (Harrison et al., 2020). Among them is the humans' closest relative, the critically endangered Borneo Orangutan (*Pongo pygmaeus*, IUCN, 2016). In addition to biodiversity loss, these factors also have profound consequences at regional and global levels. Among them are restrained water quality and quantity regulation services and release of GHGs (Foley et al., 2011). Because of these far-reaching consequences, measures to halt, protect, or even reverse tropical deforestation have received increased attention. This, for example, through incorporating regulatory standards, corporate voluntary sustainability commitments, protected area networks, economic incentives, and demand-side interventions (Austin et al., 2019).

Vegetable oil producing crops such as canola, soybean, sunflower, and oil palm occupy ~7.5% of the world's agricultural land with a total annual production of 217 Mt (2020 - 2022, OECD, 2023). This demand is expected to increase to 310 Mt by mid-century (Byerlee et al., 2016), due to the increasing world population and as a renewable resource for biofuel (Abdul Majid et al., 2021). With a share of approximately one-third, palm oil is globally the most widely used vegetable oil (Kamyab, 2022; OECD, 2023). Borneo, which is split between the two largest palm oil producers in the world - Malaysia and Indonesia produce 85% of the world's palm oil - is a cultivation hotspot due to its tropical climate and high rainfalls (Kamyab, 2022). In addition to oil palm, other crops such as rice, groundnut, cassava, coffee, cocoa, maize, rubber, coconut, and pulpwood are also cultivated in Malaysia and Indonesia (FAO, 2023). However, their harvest areas are subject to much less expansion and therefore, apart from coconut (Meijaard et al., 2020), do not pose a major problem in landscape ecology in this region (Potapov et al., 2021).

Another driver closely linked to forest loss is expansion of infrastructure (Meijer et al., 2018; Sloan et al., 2019). Especially in Asia, large infrastructure expansions proceeded in the last two decades (Potapov et al., 2022). Besides forest loss, new infrastructure is also linked to increased hunting pressure and light pollution (Kamyab, 2022; Lewanzik & Voigt, 2014).

Over the past decade, open source GIS has steadily improved and gained relevance in academia and industry (Coetzee et al., 2020; Mobasheri, Mitasova, et al., 2020). Combined with open-source geospatial data, which became widely available since 2008 (Zhu et al., 2019), it promises to have the potential to accelerate the solution of global and interdisciplinary problems (Coetzee et al., 2020; Mobasheri, Pirotti, et al., 2020). Moreover, machine learning algorithms allowed classification into land use by recognition of repeating patterns (Crowley & Cardille, 2020). These advances have been widely applied for mapping of deforestation (Curtis et al., 2018; Hansen et al., 2013) and detection of oil plam (Danylo et al., 2021; Descals et al., 2021).

Although many recent global datasets provide the basis for analyzing the key drivers of deforestation, the most recent studies examining this for Borneo were conducted a few years ago ago, without focus on other drivers besides (industrial) oil palm (Gaveau et al., 2019, 2014). Building upon these modern open-source datasets, this thesis investigates deforestation and its drivers, within the spatial extent of Borneo, and a temporal scope spanning the past two decades. More precise, the following questions are addressed: (i) what is the yearly extent of deforestation, (ii) which influence did the introduction of the Roundtable for Sustainable Palm Oil (RSPO) have on deforestation rates, (iii) how much existing cropland was converted into oil palm plantations and (iv) how does proximity to infrastructure impact deforestation rates? Annex I provides a list of the in-depth questions that help to answer these guiding questions.

Considering the global importance of this region, providing answers to these questions is crucial to aid policy makers monitor global initiatives for sustainable development, climate change mitigation, and conservation of biodiversity and ecosystem functions at the regional level of Borneo. These initiatives include the United Nations Framework Convention on Climate Change, the Paris Agreement and COP26 Glasgow Declaration, the Convention on Biological Diversity and the UN Sustainable Development Goals (SDGs). Especially SDGs responsible consumption and production (SDG 12), cilmate action (SDG 13) and life on land (SDG 15), as well as to a smaller extent life under water (SDG 14) and clean water and sanitation (SDG 6). Furthermore, NGOs operating on Borneo (e.g. Borneo Orangutan Survival Foundation, Bruno Manser Fonds, etc.) can use these results for the selection of new projects as well as for communication to raise public awareness on deforestation and its drivers.

2 Literature review

2.1 Deforestation

Forests are among the most important terrestrial ecosystems and are fundamental to all life processes (Zafirah et al., 2017). Tropical forests play a more influential role in the climate cycle and various biodiversity processes in comparison to other terrestrial biomes (Zafirah et al., 2017). Their ecosystem services include regulation of the water cycle (quality and quantity), carbon storage, natural pest control, climate regulation, pollination and seed dispersal (Nasi et al., 2002). Undoubtedly, they possess the highest biological diversity, with estimates that consider the global share to be more than half (Jenkins et al., 2013). Additionally, tropical forests are also indispensable for social and cultural identity, livelihoods and climate change adaptation and mitigation (Ometto et al., 2022).

However, tropical forests are threatened. Reports estimate that almost half (Hansen et al., 2013), or even nine-tenths (FAO, 2020), of global deforestation is happening in the tropics, of which rainforests have the highest share (Hansen et al., 2013). In 2010 Gaveau et al. indicated that three-quarters of Borneo was covered with forest in the early 1970s, reducing to only 390,000 km^2 (52.8%) remaining forested of which 210,000 km^2 are considered intact (2014). Much of this deforestation is due to conversion to large-scale agricultural plantations (mainly soybeans, oil palm, corn, cotton, and livestock; see Section 2.2), which represents one of the main causes of the decline in species richness in flora and fauna (Jaureguiberry et al., 2022; Ometto et al., 2022). Forests also prevent nutrient runoff and erosion due to their vegetation cover (Sweeney & Newbold, 2014). Subsequently, deforestation can lead to enhanced sedimentation and thus shallower river networks. This in return can cause massive floods during monsoon season (Zafirah et al., 2017).

The protection of the forest is also important because it serves as CO_2 reservoir. These carbon stocks get released by deforestation and account for 10-15% of anthropogenic GHGs (Houghton, 2013). Even if cultivated trees are subsequently grown, they cannot retain the same amount of CO_2 (Waring et al., 2020). In 2011, as a reaction to the deforestation rates, Indonesia instituted a moratorium on new licenses for oil palm and timber plantations as well as logging on primary forests and peat lands (Busch et al., 2015). Busch et al. estimate that an additional 241 - 615 $MtCO_2$ equivalents could have been saved if the moratorium had already been implemented in 2000 (2015).

Another major problem is forest degradation. Matricardi et al. state that forest degradation in the tropics occurs over even larger areas than it is deforested (2020). However, this is much more difficult to measure because it occurs in the forest and leaves a closed canopy, making it challenging to use remote sensing methods.

2.2 Oil palm *(Elaeis guineensis)*

Originating from West Africa, the oil palm *(Elaeis guineensis)* is the most efficient and important oil-producing crop worldwide, with a lifespan of ~25 years (Kamyab, 2022). It has the highest yield in tropical climates with high rainfall (Kamyab, 2022). Hence it is successfully cultivated in Malaysia and Indonesia, with yields ranging from 10 to 35 tons of fresh fruit bunch (FFB) per hectare (Kamyab, 2022). These two countries produce 85% of the world's palm oil (Kamyab, 2022; Ritchie, 2021). Figure 1 shows that in less than 20 years global harvest area has almost quadrupled from 8 Mha in 1994 to 29 Mha in 2021 (FAO, 2023). Therefore, it was extensively mapped using the characteristic backscatter response of palm-like trees from remotely sensed data (Descals et al., 2021).

While the massive expansion of production capacities over the last decades is associated with economic growth and rapid development, the ecological impact of converting forest into giant oil palm monocultures and the environmental pollution caused by large quantities of by-products, mainly palm oil mill effluent (POME), during oil extraction pose major problems (Kamyab, 2022). The revenue from previous logging of old growth forest helps to subsidize the initial plantation costs (Fitzherbert et al., 2008). However, the conversion is estimated to lose up to 45% of species diversity, density and biomass of invertebrate communities (Barnes et al., 2014). Moreover, the drainage of peatlands for land preparation causes the release of large amounts of GHGs (Sheil, 2009). These expansions of harvested areas are also closely linked to changing market values (Gaveau et al., 2022).

Per ton of FFB, 600-700 kg of POME are produced (Kamyab, 2022). POME is effluent from the mills and has a high content of chemical oxygen demand (COD), biochemical oxygen demand (BOD) and heavy metals (Hadiyanto et al., 2013). It also carries large amounts of nutrients such as nitrogen or phosphorus (Jeong et al., 2014). This renders it highly toxic to aquatic life forms (Kamyab, 2022). Ultimately, this effluent, insufficiently treated in the majority of cases, leads to health risks for the population living along waters with oil palm mills upstream, eventually even affecting crops irrigated with this water (Kamyab, 2022).

Palm oil has been used mainly in the food (80%) and to a lesser extent in the non-food sector (20%) including biodiesel (Basiron & Weng, 2004). Today, 68% are used in foods, 27% in industrial applications and 5% is used for bioenergy (Ritchie, 2021). 87% of the European Union's (EU) palm oil imports in 2017 were processed into biodiesel (Abdul Majid et al., 2021). This demand is expected to increase even more as the EU has solid legislation around biofuel production (Abdul Majid et al., 2021). But global population growth and the simultaneous increase in demand for vegetable oil will also further increase demand in this area.

Thus, the market urgently requires solutions to reduce its environmental impact. One solution to meet the growing demand for palm oil without expanding cropland is to increase oil extraction rates. Nevertheless, despite research in this area, the OERs have stagnated at 19-21% over the past 40 years (Chang et al., 2003; Chew et al., 2021). Another option to reduce pressure on land conversion is genomic research to improve yields, with various approaches being taken (Murphy et al., 2021). A private producer claims that his research has the potential to increase yields by up to 20% (Sime Darby Plantation, 2020). However, after a remarkable 40% increase in yield from 1994 to 2011, it has since stagnated at 15 tons per hectare (see Figure 1) and such advances take time for implementation due to the ~25 year lifespan of plantations.

In summary, oil palm is an essential crop globally, known for its efficiency and high yields in tropical regions. While it has contributed significantly to economic growth, its expansion has come at the cost of deforestation and pollution, posing challenges to biodiversity and ecosystems. Nonetheless, markets will continue to thrive, requiring new solutions to reduce land use change and innovations in processing.

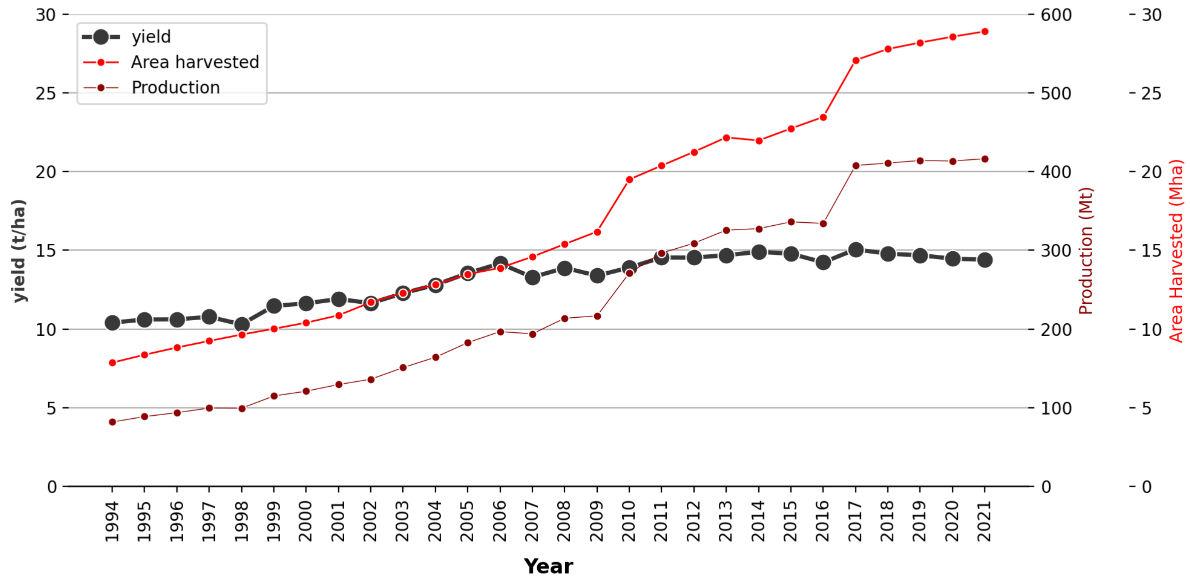


Figure 1: Global harvest area and production of oil palm evolve accordingly, with no yield improvement since 2011 (FAO, 2023).

2.3 Labels for sustainable palm oil

Growing concern about the significant forest loss and ecosystem degradation caused by deforestation has brought cultivation of palm oil to public attention. As a result, the Roundtable on Sustainable Palm Oil (RSPO) was established in 2004 to build a market for sustainable palm oil by establishing environmental and social standards for palm oil production (Abdul Majid et al., 2021; RSPO, 2023). The RSPO is formed by producers, retailers, investors and social and environmental NGOs, with currently over 5000 members (RSPO, 2023). With a share of 19% of the oil palm market (Ritchie, 2021), it is almost exclusively the only certification standard in global palm oil trade (Murphy et al., 2021). Other labels such as the Malaysian Sustainable Palm Oil (MSPO) and the Indonesian Sustainable Palm Oil (ISPO) have little to no share in international markets and focus mainly on smallholders (Murphy et al., 2021). RSPO states that compliance with its standards can mitigate the negative impacts of palm oil production on the environment and local communities (2023). Since 2005 RSPO demands that new plantations must not replace primary forest and a High Conservation Values (HCV) assessment is required for certification, which besides ecological factors, also considers a wide range of social stakeholders, including local communities (Murphy et al., 2021). Since 2018, a High Carbon Stock (HCS) report is additionally required, which prohibits clearing for oil palm on HCS classified lands (RSPO, 2018). Despite public discussion on oil palm, a study on Swiss consumers showed, that only 9% of the participants were aware of the RSPO label (Wassmann et al., 2023).

A major criticism, however, is that if forests are not classified as HCV or HCS RSPO certifications continue to allow logging (Cazzolla Gatti et al., 2019). In addition, significant tree losses were reported prior to and post-certification (Cazzolla Gatti et al., 2019). Furthermore, deforestation rates in certified areas are comparable to or even exceed those in uncertified areas, leading Cazzolla Gatti et al. to conclude that sustainable palm oil may not be sustainable (2019). The criticism from non-governmental organizations is even more staggering. They claim that RSPO auditors commit numerous violations in the licensing process, such as failing to identify indigenous land rights claims, faulty HCV assessments or serious labor abuses (EIA, 2015; Greenpeace International, 2013).

2.4 Infrastructure

Expansion of infrastructure is happening at a high rate across the globe. In the last two decades, the amount of built-up land area has increased by 47%, whereby this rate is even higher in Asia at 73% (Potapov et al., 2022). With an additional 25 million kilometers of paved roads and more than 300,000 kilometers of rail track, translating into a 60% expansion of land transportation infrastructure by 2050 compared to 2010, infrastructure development will continue at a rapid rate (IEA, 2013; Laurance et al., 2014). It is estimated that 90% of this growth will take place in developing countries projecting enormous consequences for Borneo (Laurance et al., 2014).

With deforestation and infrastructure development in remote areas, hunting pressure is intensifying (Kamyab, 2022), as well as poaching with improved accessibility (Moore et al., 2018). In addition, the expansion of habitation of humans stimulated by infrastructure developments is leading to an increase in human-wildlife conflicts (Kamyab, 2022).

Not only does new infrastructure increase settlement and thus human density but it is also associated with greater dispersal pressure of invasive species, leading to new corridors such as roads or rail tracks that facilitate their introduction (Dar et al., 2015; Mungi et al., 2021). Moreover, the resulting increase in light pollution affects the behavior of individual animal species, which in turn can influence their ecosystem services, eventually leading to effects of land erosion (Lewanzik & Voigt, 2014).

Since large parts of Borneo are covered with forest, new infrastructure projects cut through these areas, separating and isolating large interconnected habitats (Alamgir et al., 2019) and enhancing deforestation nearby (Meijer et al., 2018; Sloan et al., 2019). Although ecologists agree that habitat loss has far-reaching and detrimental consequences for biodiversity (see Section 2.1, Section 2.2), there is disagreement about the impact that fragmentation itself has (Didham et al., 2012; Fahrig, 2013; Haddad et al., 2015; Miller-Rushing et al., 2019). Observational studies often focused only on single aspects of fragmentation (e.g., edge, isolation, area) and failed to take in the full context of the complex interconnected structures of habitats (Haddad et al., 2015). However, a comprehensive experiment indicated, that biodiversity in fragmented habitats is reduced from 13% up to 75% (Haddad et al., 2015). More recently, Püttker et al. underlined that biodiversity of forest-dependent animal and, to an even greater extent, plant species are negatively affected by habitat fragmentation, especially through edge effects (2020). This also applies to Borneo, as many infrastructure projects, including the planned relocation of the Indonesian capital (Lyons, 2019), are estimated to have huge impacts on biodiversity (Alamgir et al., 2019).

To sum up, the expansion of infrastructure contributes not only to habitat loss, but also to increased habitat isolation due to fragmentation, increased introduction of invasive species, and light pollution, disturbing the fauna.

2.5 Other crops

While some studies say that besides oil palm, which accounts for 88% of industrial plantations, pulp wood is the only crop to cover the other 12% (Gaveau et al., 2019). However, other studies report that groundnut and coconut are also grown in Borneo, but not in the from of industrial plantations (Meijaard et al., 2020). Coconut plantations occur mainly in smallholder form (<4ha) and thus (Meijaard et al., 2020), make it challenging to map with remote sensing methods (Descals et al., 2021). However, it is thought to have almost a fivefold worse impact on biodiversity (Meijaard et al., 2020), These results, though, have caused a lot of controversy (Rochmyaningsih, 2020).

In Southeast Asia, the total cropland extent (excluding perennial woody crops) saw only moderate growth. While 172.9 Mha were permanently used as cropland between 2000 and 2003, 184.5 Mha were used between 2016 and 2019 (Potapov et al., 2021). A gain of 30.9 Mha offsetted a reduction of 19.3 Mha (Potapov et al., 2021). Nevertheless, due to public awareness and the rapid expansion of harvest area, oil palm has been extensively researched and mapped (Descals et al., 2021), while maps on other crops harvest area distribution are still sparse (Meijaard et al., 2020).

In summary, due to much smaller expansion of cropland and perennial woody crops, oil palm diminishes the importance of research on other crops in Southeast Asia and thus there are hardly any maps available making use of the advances in remotely sensed data processing (see Section 2.6).

2.6 Advances in remote sensing

Since the launch of the Landsat-1 MSS satellite in 1972, an increasingly comprehensive time series database has been built as newly launched satellites have been equipped with more advanced technology (Crowley & Cardille, 2020). However, it was not until 2008 that this data was made available through the free and open Landsat data policy (Zhu et al., 2019). Combined with the launch of the European Space Agency's open-access Copernicus mission, research from satellite data has exploded in recent years (Crowley & Cardille, 2020; Zhu et al., 2019). This development has also been facilitated by the availability of massive-throughput analysis platforms like the Google Earth Engine implemented in 2010 (Crowley & Cardille, 2020). Another crucial achievement was the development of machine learning algorithms that separates the remotely sensed data into meaningful classifications (Crowley & Cardille, 2020). Furthermore, machine learning offers unprecedented potential for gaining deeper insights from historical data, as well as filling in gaps in it (Sarafanov et al., 2020).

Despite these advancements, many high-resolution land cover and land use (LCLU) datasets (Descals et al., 2021; Karra et al., 2021; Zanaga et al., 2021), while offering unprecedented detail, do not support multi-decadal analysis (Potapov et al., 2022). However, medium resolution (30m resolution) multidecadal datasets are more widely available (Danylo et al., 2021; Hansen et al., 2013; Potapov et al., 2022, 2021; Turubanova et al., 2018; Tyukavina et al., 2022).

3 Materials and Method

3.1 Data acquisition and selection

Initially, databases such as Web of Knowledge or Google Scholar were searched for GIS and remote sensing studies covering the extent Borneo or Southeast Asia. However, most of the studies that provide the necessary data have been carried out on a global scale. The exerts of the datasets covering Borneo were downloaded and visualized in QGIS (Version 3.30) for initial data exploration. This led to the manual selection of data presented in Figure 2 for the subsequent analysis. Hereafter, the datasets are referred to by the names specified in the content column. All raster datasets were in tif format and the vector data in shapefile format. The research area was defined as the landmass of Borneo, excluding the smaller surrounding islands. This delineation was obtained through the download of the Borneon boundary using the OSMnx python package (Verison 1.3.0), which accesses the Open Street Maps (OSM) database (Boeing, 2017).

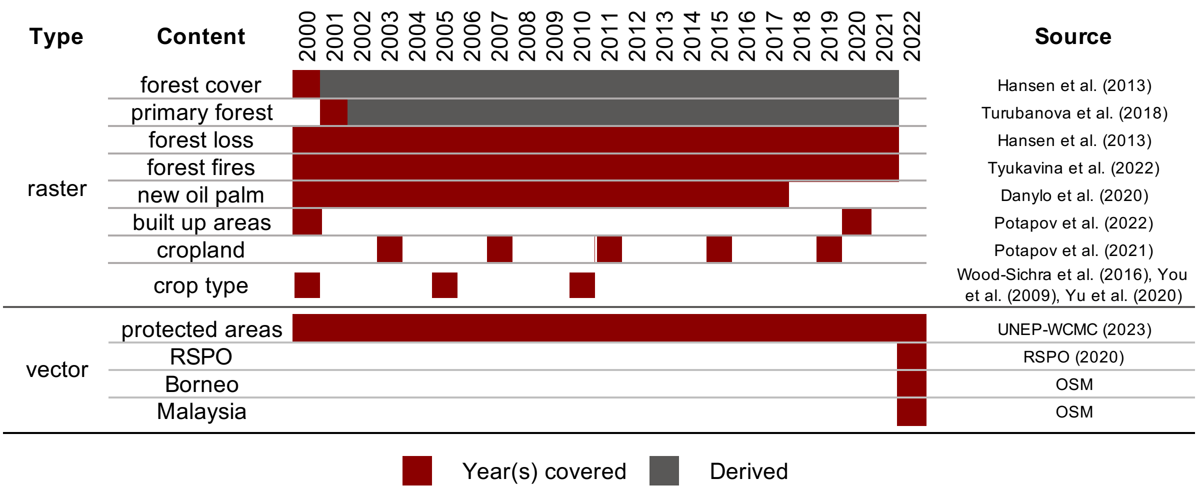


Figure 2: All datasets used in this thesis and the temporal scope they span.

Forest cover shows the percent of closed canopy in the year 2000 of vegetation higher than 5m (Hansen et al., 2013). Turubanov et al. used expert-interpreted training data for detection of patterns recognized as primary forest (2018). The forest loss dataset shows the year of quick changes in forest cover to ~0% closed canopy (Hansen et al., 2013). Forest fires show data shows the forest loss to forest fires in the joint extent of the forest loss dataset (2013; Tyukavina et al., 2022). The new oil palms dataset shows the year oil palm was detected for the span of 1984 - 2017 (Danylo et al., 2021). Oil palms are detected no earlier than 2-3 years after planting (Danylo et al., 2021). The built up areas dataset contains two categories: i) built up areas in 2000 and ii) newly built up areas between 2001 and 2020 (Potapov et al., 2022). The cropland datasets shows land used for agriculture where shrubby plants were consistently cultivated over four years. Even though multiple spatial datasets allocate crop type spatially, none of them is based on remotely sensed data (Grogan et al., 2022; Wood-Sichra et al., 2016; You & Sun, 2022; You et al., 2009; Yu et al., 2020). The Spatial Production Allocation Model (SPAM) takes the most factors into account rendering it the most comprehensive data. The data shows harvest area of multiple crops within a 5 arcminute (~8km) resolution. Protected areas represent those registered in the World Database on Protected Areas (UNEP-WCMC, 2023). Although the RSPO stated in early 2020 that the RSPO concessions will also be made publicly available for Indonesia (RSPO, 2020), this is still not the case as of today. A personal inquiry about this also remained unanswered. Thus, analysis of RSPO concessions could only be carried out for Malaysia. The Borneon and Malaysian boundaries are both derived from OpenStreetMap.

3.2 Software

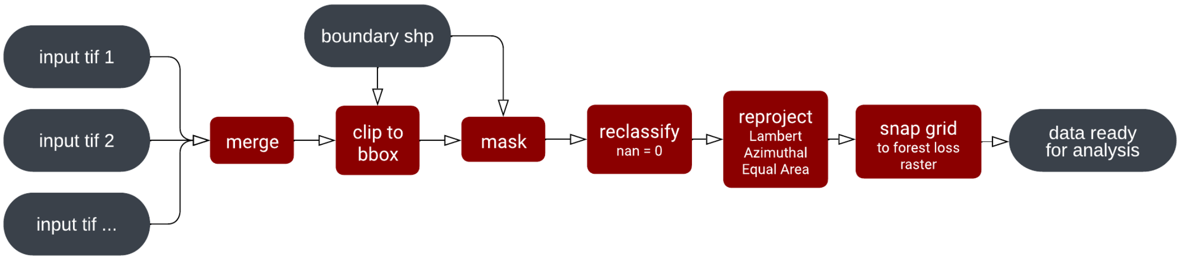
All data preparation and analysis steps were performed using open-source Python packages in Visual Studio Code (Version 1.83.0). Python version was 3.10.9. Rasterio (Version 1.3.6) and NumPy (Version 1.24.3) were the most relevant packages for data processing (Gillies, 2023; Harris et al., 2020). A comprehensive user-friendly set of functions was created. These functions require one or multiple input paths, an output path and optionally a reference file path (e.g. a mask tif, snap tif, etc.) and additional conditions (e.g. mask values). The output file was compressed in lzw form. The full code is available on github.com/pfaffrob/03_vs_code.

OpenAI's Chat-GPT (versions 3.0, 3.5 and 4.0) was used to support code generation. Functions were developed by starting with a minimal example with aid of Chat-GPT. Subsequently, more complex features were implemented through personal adjustments or continuous user feedback to the AI until it met the requirements. The generated code and its output files were carefully inspected to ensure correctness.

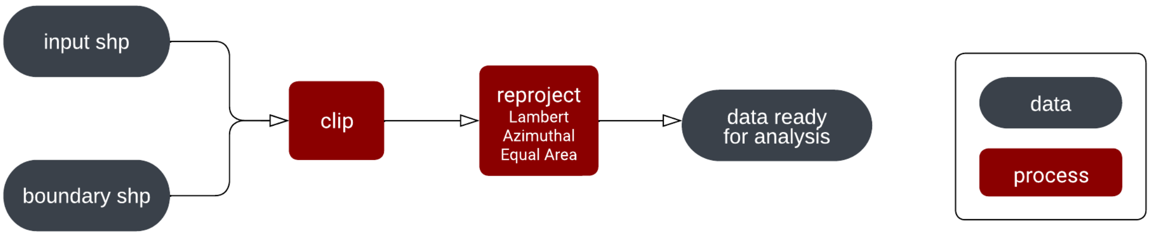
3.3 Data preparation

For area calculations, it is crucial to choose a well-suited coordinate reference system (crs). The use of one UTM zone was considered too inaccurate since Borneo spans four UTM zones. The only crs available covering Borneo is the Timbalai 1948 (Klokan Technologies GmbH, n.d.). But even this projection only adequately depicts the Malaysian part, and thus distorts the larger Indonesian part of Borneo, resulting in biased results. Therefore the Lambert Azimuthal Equal Area Projection was chosen as it is well suited to accurately represent the area at large spatial scales (esri, 2019, 2023). Although this does not affect the area calculations, the origin was manually set to the center of Borneo (115° longitude; 0° latitude) to achieve maps of Borneo with minimal distortion.

All data has been brought into a consistent format. This required merging, clipping, reclassification and snapping, which includes resampling of the data with method nearest neighbour. For the latter, the forest loss dataset was chosen as the reference grid. The workflow for the preparation of raster and vector data is visible in Figure 3. Preparation steps were only carried out if it was required. For example, the datasets for primary forests and forest fires consisted of only one file, hence there was no need for merging.



(a) Processing steps for preparation of raster data.



(b) Processing steps for preparation of shapefiles.

Figure 3: Workflow of data preparation for raster data and **(b)** shapefiles. The steps were applied as necessary. The legend in figure **(b)** also applies to **(a)**.

3.4 Analysis

For answering the simpler questions (annex I) that required only one data set, such as quantifying annual deforestation rates or total primary forest area in 2000, the area calculations could be performed without any further steps. The more complex processing steps are described below. Area calculations were performed by counting the frequency of unique pixel values and multiplying them by the area of one pixel. The maps are also presented online.

3.4.1 Deforestation

The forest cover dataset shows the percentage of canopy cover. A threshold of 75% closed canopy was chosen as the definition of forest, which was also used by Turubanova et al. for comparison of their results with the same forest loss data source (2018). Although areas with >75% closed canopy overlap nearly all of the primary forest areas (see annex II), these were reclassified as forest. The workflow for all forest loss-related analysis steps is shown in Figure 4.

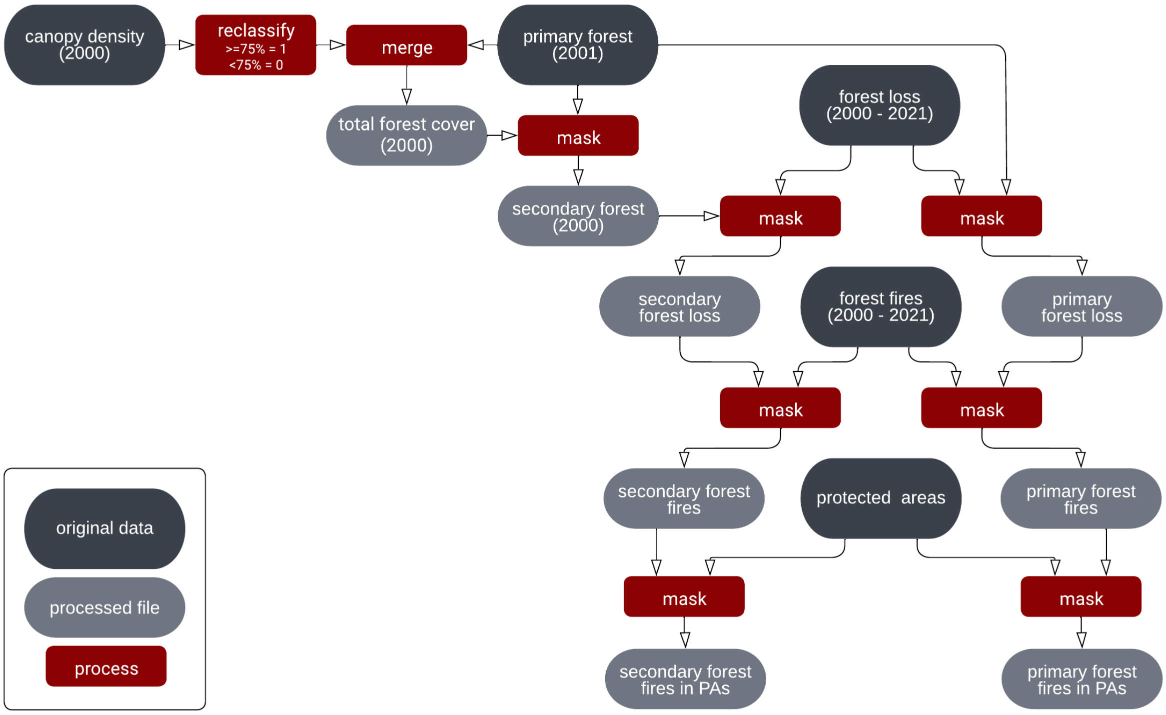


Figure 4: Workflow of deforestation analysis.

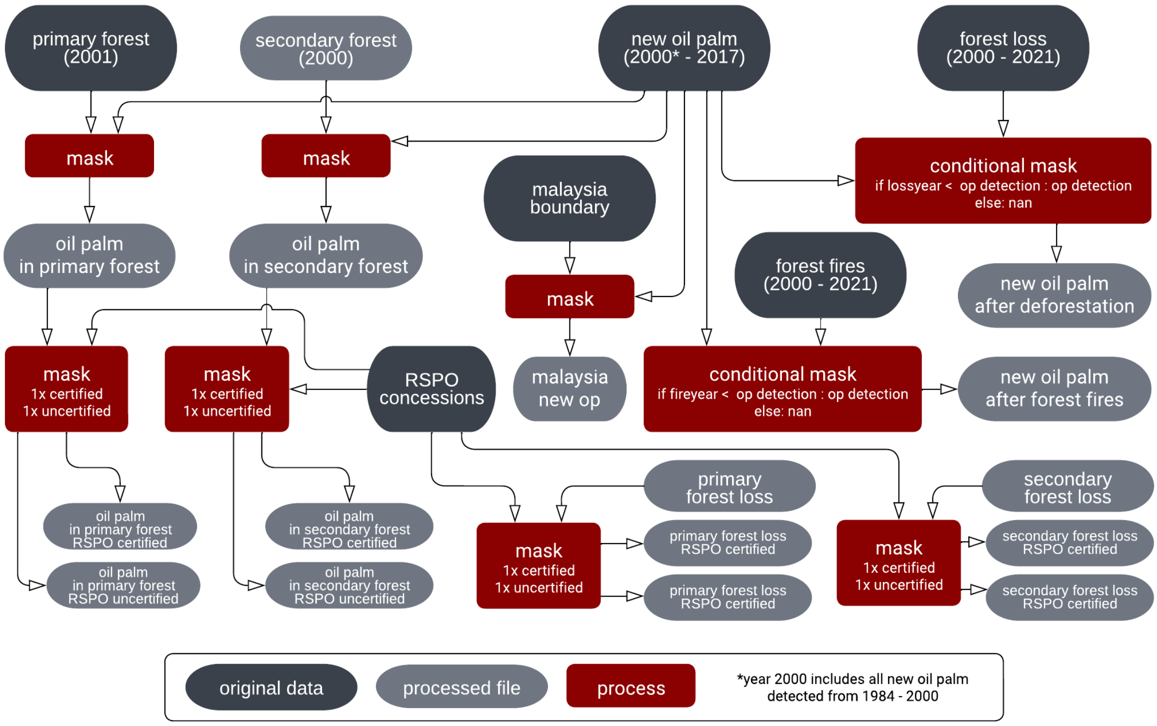


Figure 5: Workflow of oil palm and RSPO concessions analysis.

3.4.2 Oil palm

Multiple processing steps were performed using the created geoprocessing functions for analysis of oil palm and its contribution to defrestation (Figure 5). The new oil palm dataset was already in the preprocessing limited to the study period. RSPO primary forest loss secondary forest loss and new oil palm plantations were analyzed for both RSPO-certified and uncertified concessions.

3.4.3 Infrastructure

The processing steps for infrastructure analysis were conducted using the geoprocessing functions. The workflow is visible in Figure 6.

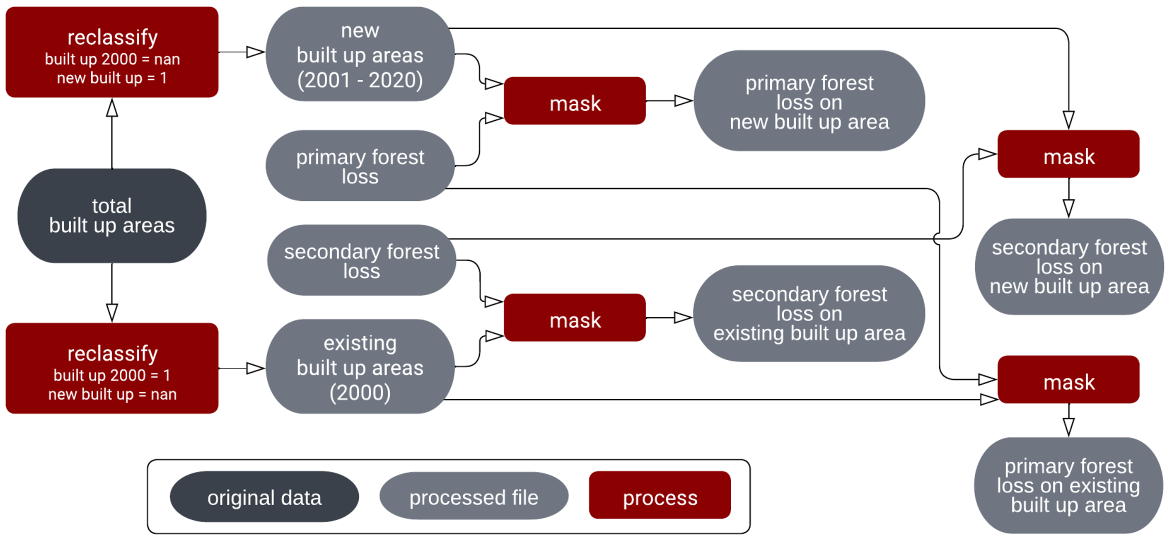


Figure 6: Workflow to determine deforestation due to infrastructure.

3.4.3.1 Buffer infrastructure

To create buffer zones based on the built-up areas, each pixel whose center was located within a radius of 100, 200, 500, 1000, and 2000 meters to a pixel of built up area was used as a mask for further analysis. Existing infrastructure in 2000, new infrastructure created from 2001 to 2020 and the total infrastructure in 2020 were each buffered individually. The workflow of this is visible in Figure 7.

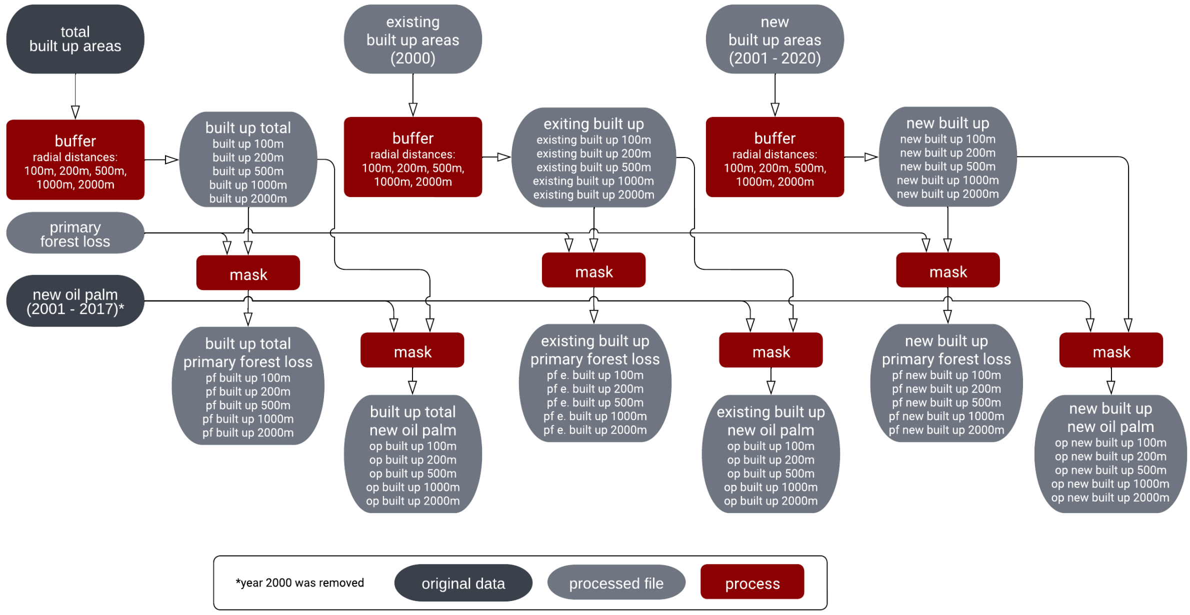


Figure 7: Workflow of buffer maps and subsequent combination with other datasets

3.5 Other crops

The five cropland datasets were each masked with previous forest loss to determine deforestation. An analysis of conversion from other crops to oil palm and vice versa was not conducted because i) the intersection of cropland (at any point in time) with oil palm was considered too small (>0.2% of total oil palm area) and ii) the data on crop types proved to be inaccurate, as it was indicated that more than 1 Mha of land was used to grow non-woody crops (annex VIII), while the remotely sensed data on uniform cropland, which should represent these same crops, was only ~0.2 million ha.

Open source remote sensing data is not available for other perennial woody crops such as coconut rubber or pulpwood.

4 Results

4.1 Borneo in 2000

At the beginning of the millennium, more than half (54.3%) of the island of Borneo, which has an area of 728,799 km^2, was covered with primary forests. The remaining areas were 30.4% covered with secondary forest, and 15.3% in a nonforest state. Figure 8 provides an overview of the composition of vegetation on Borneo at the start of the study period.

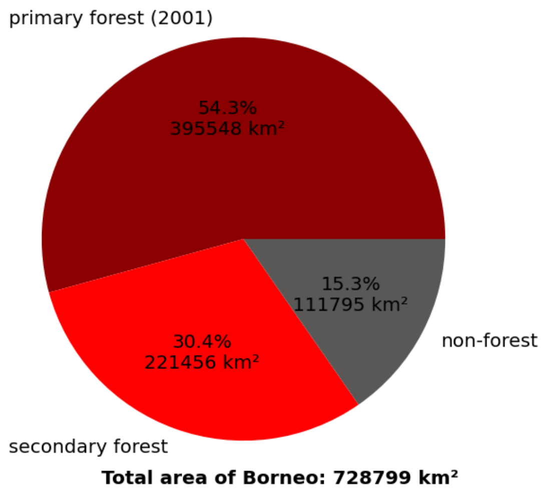


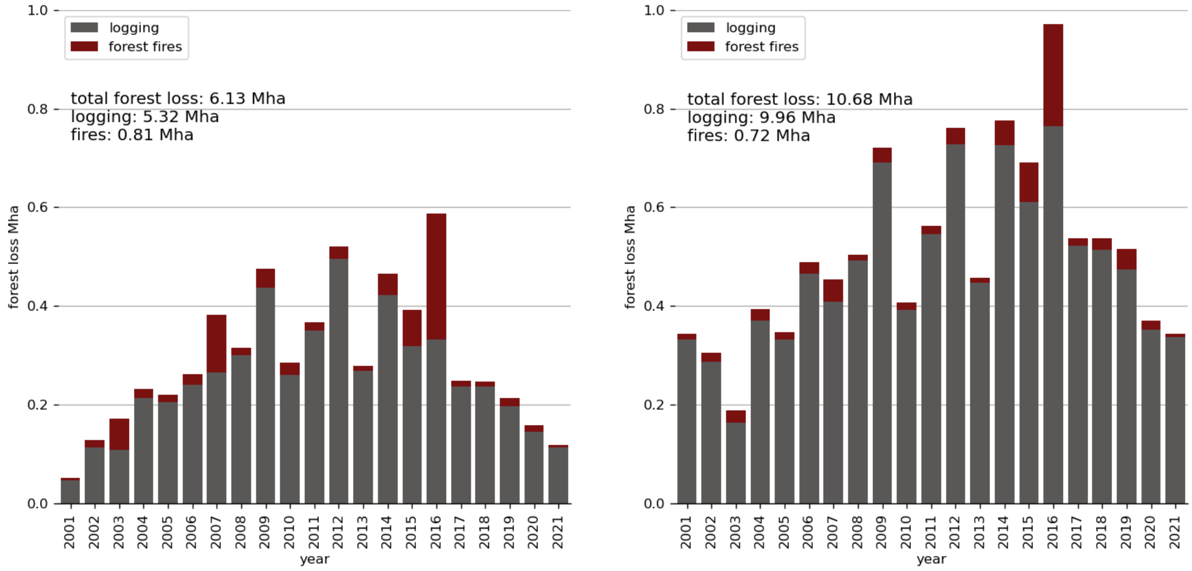
Figure 8: Composition of vegetated areas on Borneo at the start of the study period.

4886 km^2 or 2.2% of the secondary forest cover represent oil palms (detection up to 2003), with a lot of these oil palm plantations being close to typical plantation patterns (see annex III). Another notable characteristic are large areas of secondary forest within primary forest close to rivers, especially with human settlements nearby (see annex V).

4.2 Deforestation

In the years from 2001 to 2021, a total of 16.81 Mha of deforestation occurred. 6.13 Mha of this is within primary forests and 10.68 Mha outside of primary forests. In both, logging was mainly responsible for forest loss, compared to forest fires. While logging rates in secondary forests increased from 0.3 to almost 0.5 Mha per year by 2008, the five most deforestation-intensive years, with 0.61 - 0.75 Mha of forest loss, occurred between 2009 and 2016. After three years of steady deforestation at 0.5 Mha per year, less than 0.4 Mha of forest loss was recorded in 2020 and 2021 Figure 9b. Within primary forests, logging rates increased from 0.11 Mha in 2002 to a maximum of 0.50 in 2012 and declined back to 0.11 Mha in 2021 Figure 9a. Although there was less overall forest loss in primary forests, there were more forest fires therein (0.81 Mha) than outside (0.72 Mha). Both primary and secondary forests had their highest forest fire rates, by a large margin, in 2016 with 208,000 ha (secondary forest) and 255,000 ha (primary forest). Other years with elevated forest fire rates were 2003, 2007, 2009, 2014 and 2015 ranging from 25,000 to 79,000 ha Figure 9.

In general, logging patterns can be separated into two categories. First, large areas of logging in the same year, often with sharp borders (Figure 14), and second, dispersed small-scale

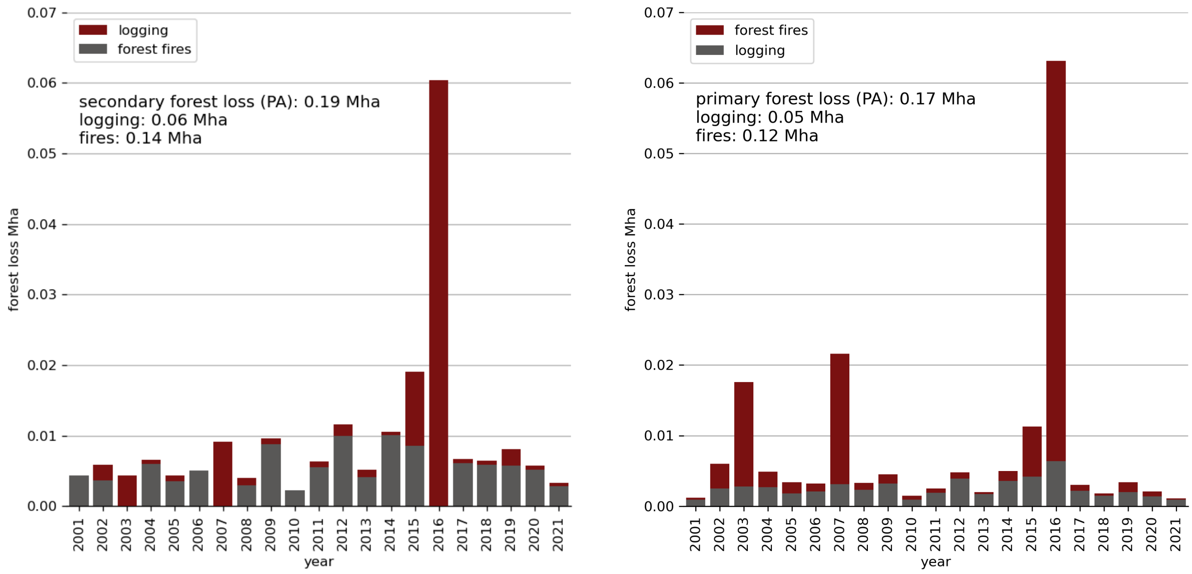


(a) Primary forest loss, peaking in 2016.

(b) Secondary forest loss, peaking in 2016.

Figure 9: Overview of deforestation within **(a)** primary forests and **(b)** secondary forests.

logging (annex VI). This is especially the case in primary forests in the Malaysian part of Borneo, where logging continuously encroaches (Figure 11). Fires in secondary forests have no obvious patterns; they occur randomly and mainly on a small scale (Figure 14).



(a) Annual rates of primary forest loss within protected areas. The total area of primary forest in these areas is 4.72 Mha.

(b) Annual rates of secondary forest loss within protected areas. The total area of primary forest in these areas is 0.08 Mha.

Figure 10: Deforestation within protected areas, with the peak year in 2016.

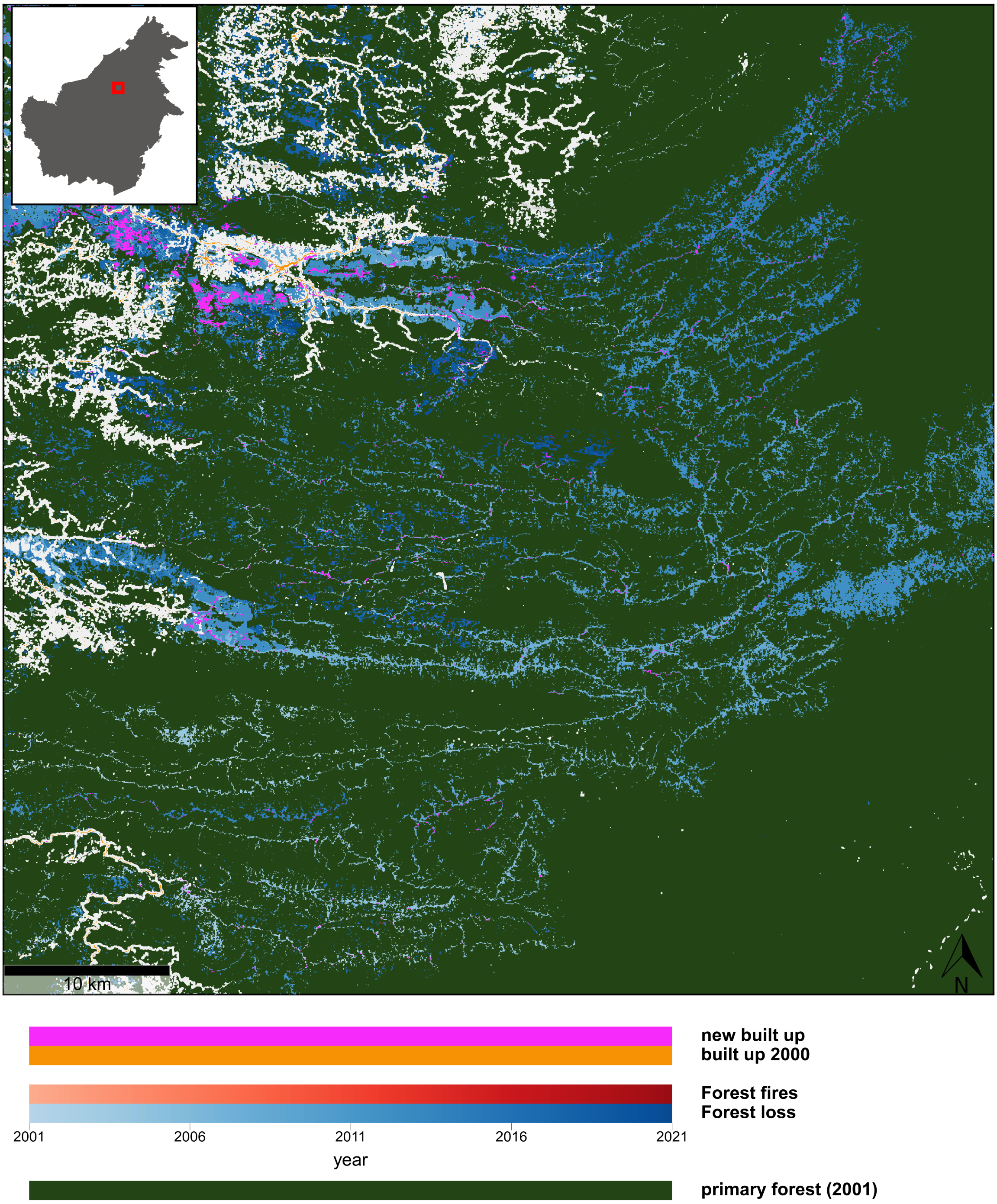


Figure 11: Large areas in the Malaysian part of Borneo where logging activities are penetrating deep into the primary forest.

Protected areas cover 6.24 Mha, of which 0.08 Mha is secondary and 4.72 Mha primary forest. Within protected areas, the main reason for forest loss were fires, regardless of the classification as primary or secondary forest. Forest fire and logging rates are similar (Figure 10). This is remarkable given that secondary forests accounted for a massively smaller proportion of the total area of PAs. Logging in protected areas occurred very limited with an average of ~2,500 ha per year being logged. However, forest fires occurred irregularly, with a major spike in 2016 and other substantial forest fire loss in 2003, 2007, and 2015 (Figure 9a). The majority of these large forest fires were on the edges of the forest spanning large patches (Figure 12).

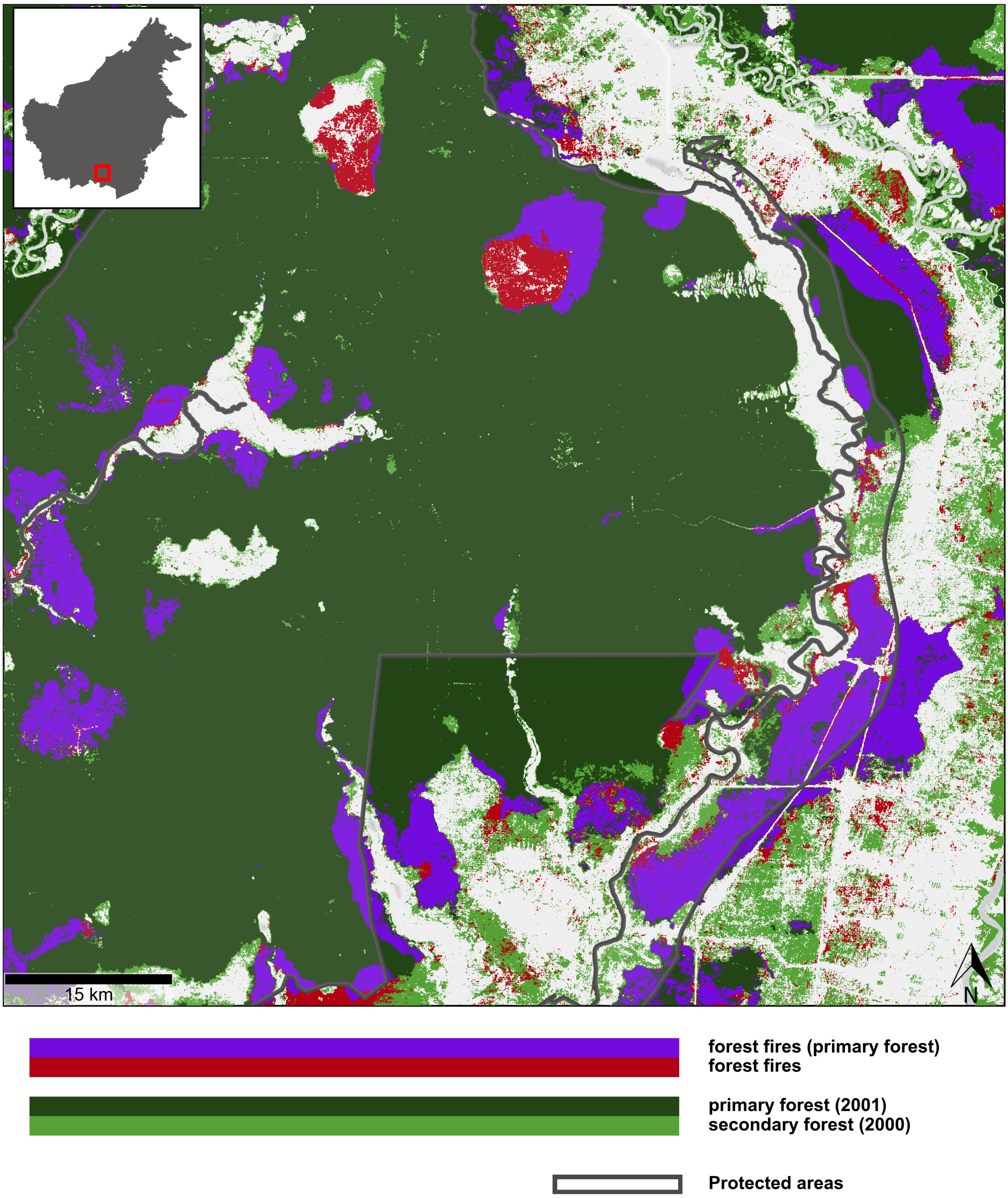
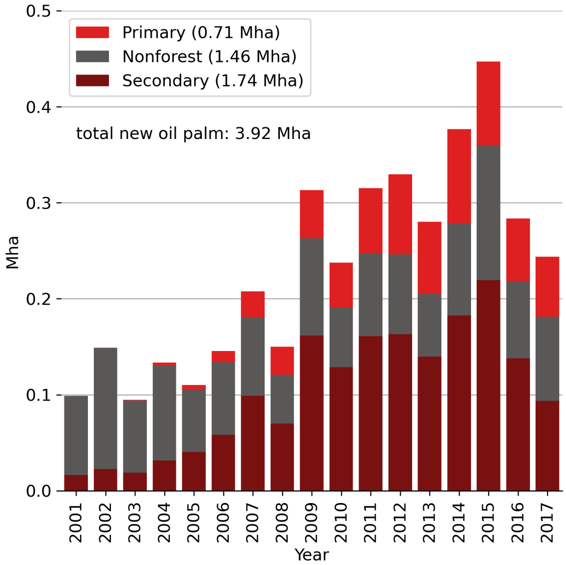


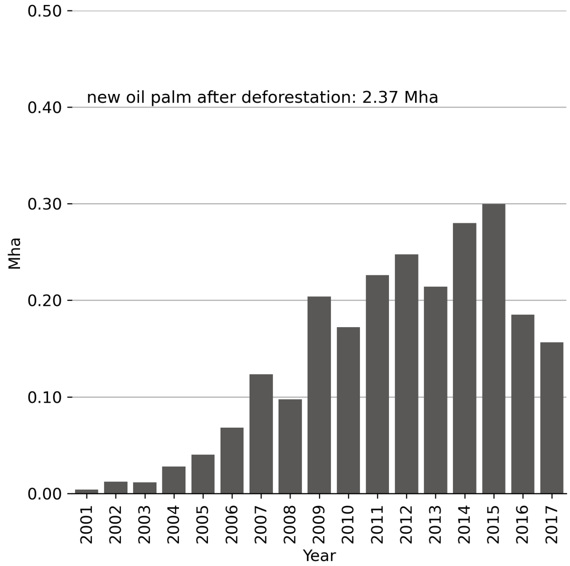
Figure 12: In this protected area it is clearly visible, that forest fires are the main drivers of deforestation within protected areas. Large forest fires like these are the cause of the outlier year 2016.

4.3 Oil palm

Between 2001 and 2017 a total of 3.92 Mha new oil palm plantations were detected. Comparable amounts were found on non-forested areas (1.46 Mha) and secondary forests (1.74 Mha), however, only about half as much was found on primary forests (0.71 Mha). While from 2001-2008 ~0.15 Mha new plantations were recorded annualy, there was almost twice as much in the following years with about 0.3 Mha per year. After the maximum value of 0.45 Mha in 2015, the newly discovered plantations decreased slightly in the most recent available years (Figure 13a). More than half (2.37 Mha) of the new oil palm plantations occurred subsequently to deforestation (Figure 13b). Fires before new oil palm plantations were discovered scarcely (0.07 Mha; annex IX).



(a) Overview of where new oil palm plantations were detected.



(b) Newly detected oil palm plantations after deforestation.

Figure 13: New oil palm plantations where they occur (**a**) and the portion which is found after deforestation (**b**).

New industrial oil palm plantations are emerging in large areas where they can be easily identified with their distinct rectangular patterns, and to a lesser extent, small clusters are also evident. There are some typical rectangular plantation areas classified as deforested (at least 4 years before the last oil palm survey year) where oil palm was not recorded to the edge of these areas. (Figure 14).

4.3.1 RSPO

Except for the outlier years of 2015 and 2016, new oil palm discoveries in uncertified RSPO concessions were similar, despite the smaller total area of them. RSPO concessions accounted for 27.8% (0.47 Mha) of all Malaysian oil palm plantations (1.69 Mha), divided into 15.8% certified (0.27 Mha) and 12.0% uncertified (0.19 million ha) concessions. A noticeable difference is that 1.6% of certified areas are located on primary forest of 2001, compared to 6.4% for the uncertified concessions. The certifications were mainly issued in areas where palm oil was already cultivated before the introduction of the RSPO label (Figure 15).

The highest primary forest loss rates within RSPO certified concessions occured in the years 2002 (1000 ha) and 2004 (1080 ha). While around 200 hectares of primary forest were still being cut down each year until 2010, rates have sharply dropped to almost zero (Figure 16a). In uncertified concessions, two-thirds of primary forest area was lost, with the peak years being 2009 (2570 ha) and 2012 (4125 ha; Figure 16b). Whereas secondary forest loss showed elevated deforestation rates from 2012 onwards in certified concessions compared with the previous decade, the rates in the uncertified concessions were at a continuous level (see annex VII).

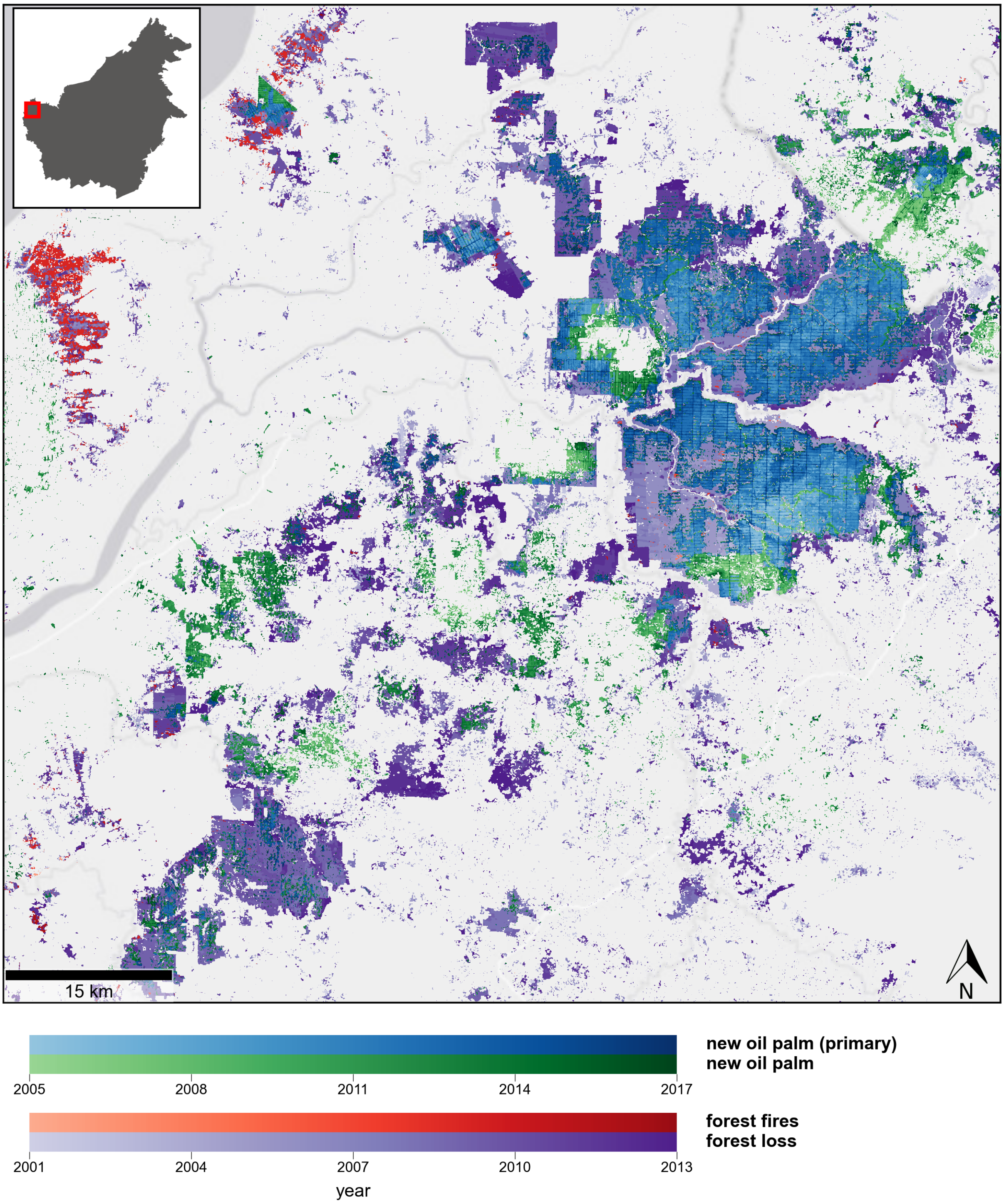
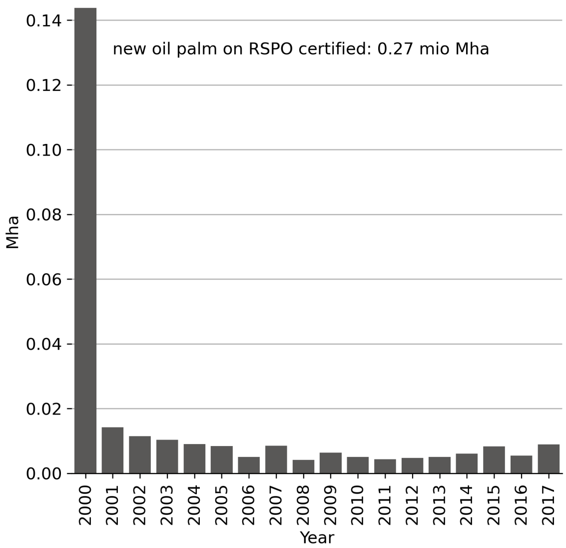
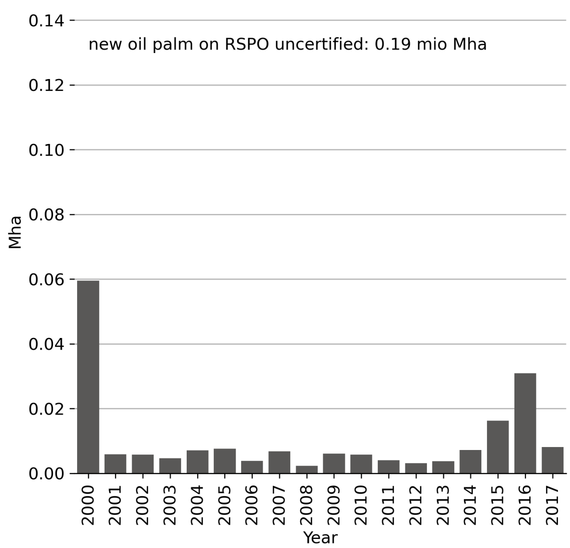


Figure 14: Large deforestation areas are found on and nearby newly detected oil palm data. This extract also shows one of the largest oil palm plantations on previous primary forest. Some small-scale fires are visible in the southwest part of the map.

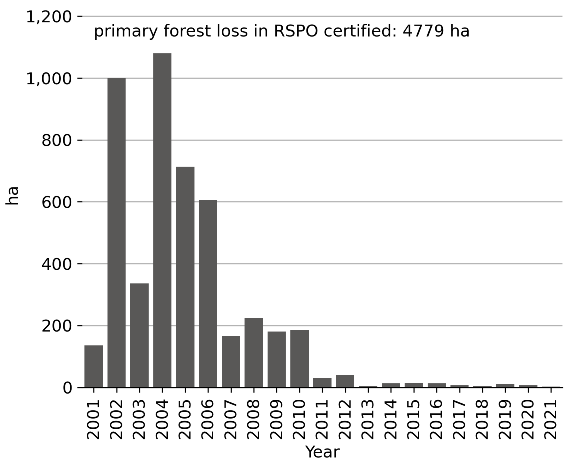


(a) Amount of newly detected oil palm plantations within RSPO certified concessions. Most of the oil palm plantations already existed in the year 2000.

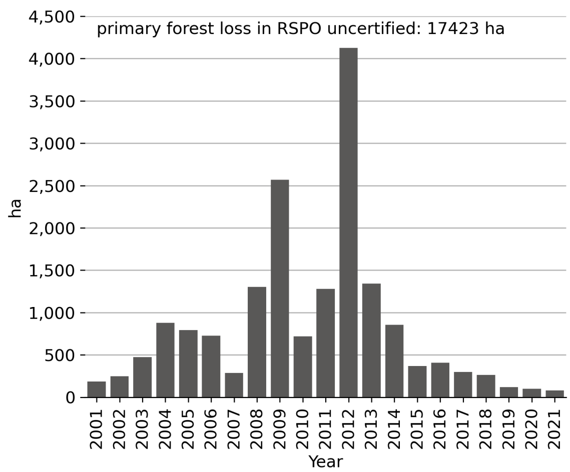


(b) Amount of newly detected oil palm plantations within RSPO uncertified concessions. Besides the majority being already used as oil palm plantations.

Figure 15: Newly discovered oil palm in (**a**) certified and (**b**) uncertified RSPO concessions (status 2023).



(a) Rates of primary forest loss within certified RSPO concessions, with most forest loss occurring before 2007 and halting from 2011.

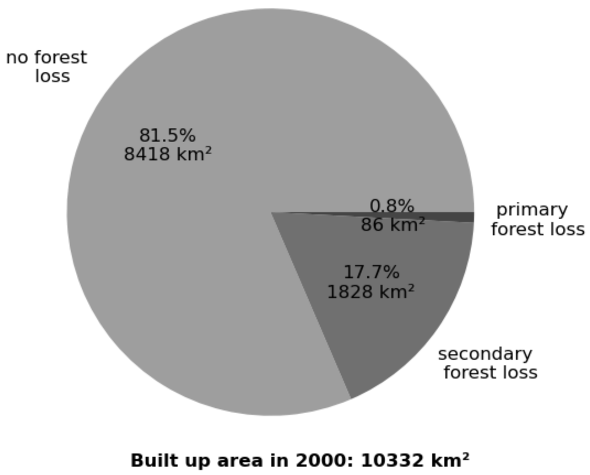


(b) Rates of primary forest loss within uncertified RSPO concessions, with most occurring between 2008 and 2013.

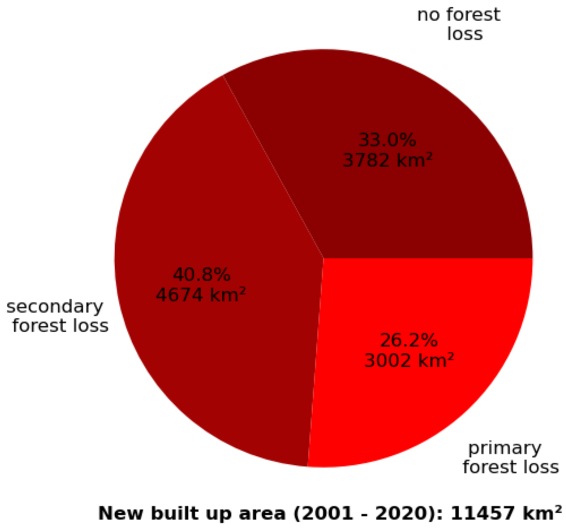
Figure 16: Difference between primary forest loss rates in (**a**) certified and (**b**) uncertified RSPO concessions.

4.4 Infrastructure

The built up areas have increased by 110% from 10,332 km^2 in 2000 to a total of 21,729 km^2 in 2020. There was only modest overlap (0.8%) with forest loss in primary forests from built up areas in 2000, and more substantial (17.7%) with other dense vegetation areas (Figure 17). These are located either near existing built up areas (annex IV) or on sites where oil palm was previously grown.



(a) Location of existing built-up areas in 2000.



(b) Location of new built-up areas in the period between 2001 and 2020..

Figure 17: The built-up area within the study period has more than doubled to a total of 21,789 km^2.

4.4.1 Primary forest loss

Spatial proximity to infrastructure has a direct impact on deforestation rates, with more than 93.0% of deforestation occurring within 2000m. It is evident, that new infrastructure has a higher impact on primary forest loss than existing. Over 90% of deforestation happened within 2000 meters of new infrastructure, which only accounts for 57.3 % of all primary forest area. This ratio, which is about a factor of 1.6, increases to a factor of up to 4 within a distance of 100 meters (Table 1). It can also be said that new infrastructure is built within primary forests, as these buffers cover more primary forest area than those of existing infrastructure (Figure 18). This occurs a lot within the inland primary forest of Malaysia (Figure 11). In addition, new infrastructure lost 22.3% (100 m) and 14.9% (200 m) more forest cover than existing infrastructure.

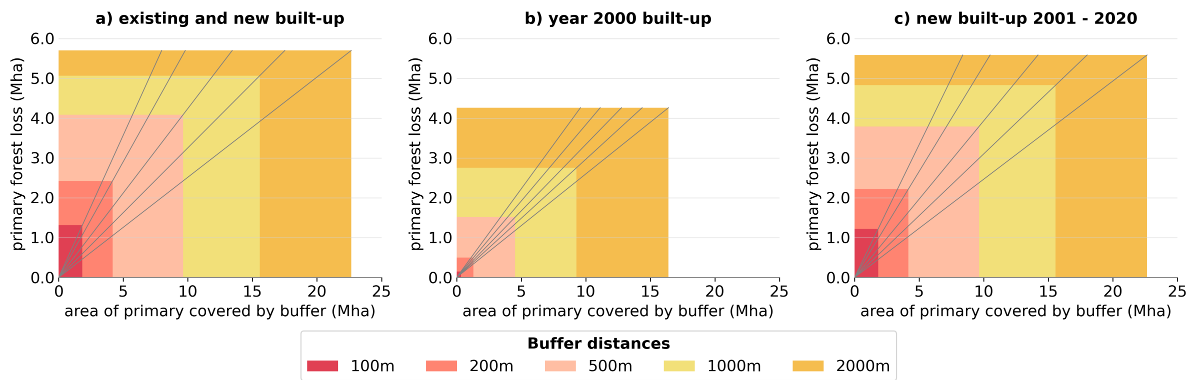


Figure 18: The x-axis shows the primary forest area that falls within the buffer distance. The y-axis shows the amount of primary forest loss. This shows the relationship of infrastructure proximity for **a)** total built-up area 2020 (assumed that no year 2000 areas were removed), **b)** built-up area in the year 2000 and **c)** newly built-up areas between 2000 and 2020.

Table 1: Percentages of primary forest loss within buffer distances from the total primary forest area. The data is categorized into three sections: primary forest (portion of the total primary forest covered by the buffer), loss buffer (portion of forest loss within total primary forest within buffer area), and loss total (portion of the loss within buffer from the total primary forest loss). This is done for **i)** *total* infrastructure in 2020 (assuming no year 2000 built-up area was removed), **ii)** *existing* (year 2000) built up area and **iii)** *new* built-up area (2001 - 2020).

Buffer	**total**			**existing**			**new**		
	primary forest	**loss buffer**	**loss total**	**primary forest**	**loss buffer**	**loss total**	**primary forest**	**loss buffer**	**loss total**
100m	4.6	71.4	21.4	0.9	44.4	2.5	4.6	66.7	19.9
200m	10.6	58.1	39.6	3.3	38.3	8.1	10.6	53.2	36.3
500m	24.4	42.4	66.7	11.4	33.4	24.7	24.4	39.3	61.9
1000m	39.6	32.5	82.7	23.5	29.7	45.0	39.4	31.0	78.8
2000m	57.3	25.2	93.0	41.5	26.0	69.5	57.3	24.7	91.2

4.4.2 Oil palm

Similarly to primary forest loss, proximity to infrastructure is linked to new oil palm occurrences. 98.8% of new oil palms are located within 1000 m of infrastructure (Table 2). In addition, there are more new oil palm plantations established within 1000 m of newly developed areas than within 1000 m of existing infrastructure (Figure 19).

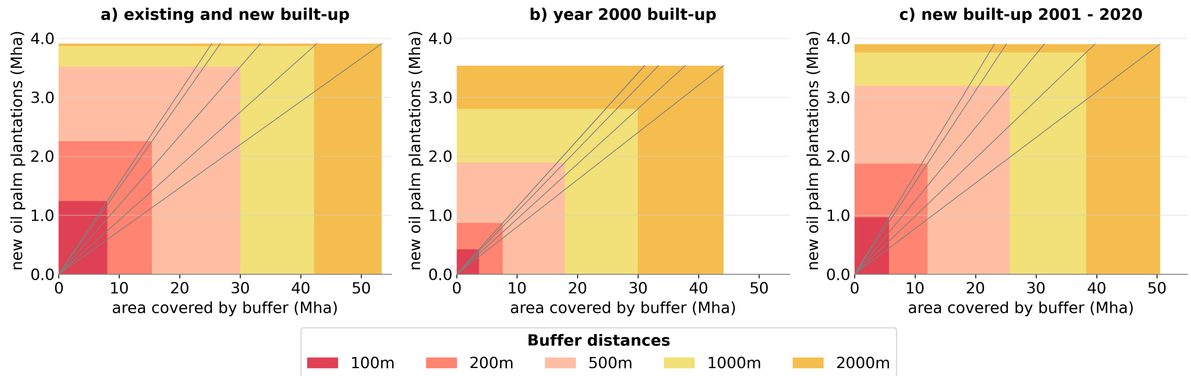


Figure 19: Composition of vegetated areas on Borneo at the start of the study period.

Table 2: Percentages of new and existing oil palm (OP) plantations within buffer distances from the total area of Borneo. The data is categorized into three sections: area of Borneo (portion of the total Bornean Area covered by the buffer; excluding buffer areas that lap over the study extent), new OP buffer (portion newly detected oil palm from 2001 - 2017 within buffer area), and total OP (portion newly detected oil palm from 2001 - 2017 from all new oil palm area). This is done for **i)** *total* infrastructure in 2020 (assuming no year 2000 built-up area was removed), **ii)** *existing* (year 2000) built up area and **iii)** *new* built-up area (2001 - 2020).

Buffer	**total**			**existing**			**new**		
	area of Bor.	**OP buffer**	**total OP**	**area of Bor.**	**OP buffer**	**total OP**	**area of Bor.**	**OP buffer**	**total OP**
100m	11.0	15.5	31.7	5.1	11.4	10.7	7.8	16.9	24.6
200m	21.2	14.6	57.7	10.5	11.4	22.2	16.6	15.6	48.0
500m	41.2	11.7	89.8	24.5	10.6	48.4	35.2	12.4	81.6
1000m	57.9	9.2	98.8	41.1	9.4	71.6	52.6	9.8	96.1
2000m	73.3	7.3	99.9	60.6	8.0	90.3	69.3	7.7	99.7

4.5 Cropland

The land use for non-woody crops increased by 60% from 0.2 Mha in 2003 to 0.33 Mha in 2019. A quarter of the expansion was at the expense of previous forest loss (Figure 20).

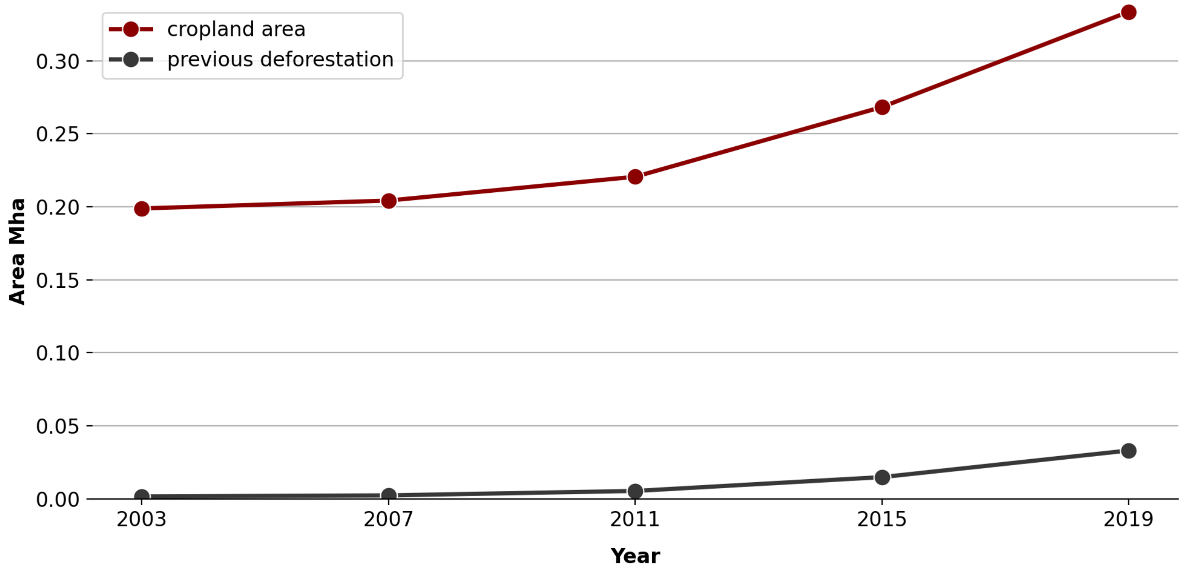


Figure 20: Amount of consisten croplands of shrubby crops.

5 Discussion

5.1 Deforestation

Ongoing deforestation in Borneo continues to threaten valuable biodiversity through further deforestation resulting in habitat loss or degradation. The declining trend of forest loss in recent years (Figure 9a) suggests that efforts such as the moratorium on logging of primary forests in Indonesia are beginning to have an impact, giving endangered endemic species a chance to be preserved. Nonetheless, the trend in reduced forest loss must be confirmed in the coming years to maintain crucial habitat for species conservation in the long-term. But even if human deforestation continues to decline, the effects of past deforestation contribute to increased fire precursors such as increased temperature, wind speed and potential evapotranspiration and decreased humidity, cloud cover and precipitation (Trancoso et al., 2022). In addition, rising levels of atmospheric CO_2 are further increasing the risk of wildfires, whilst also being one of the causes for a phenomenon called El Niño (Wang et al., 2019). This event, caused primarily by unusually warm ocean temperatures, results in significantly higher temperatures during the dry season, causing the soils to become more dry (NASA, 2023; Wang et al., 2019). Ultimately, this leads to small-scale fires set by smallholders to clear pasture spreading much more quickly and across a wider area (NASA, 2023). Therefore, the small-scale fires occurring all over Borneo can not only be attributed to smallholders, but these small-scale fires can also trigger large-scale fires, which are fueled by the El Niño phenomenon and the reason for the outlier years with a lot more forest fires, including those in protected areas. Nevertheless, the low rates of deforestation in protected areas emphasize their importance. This suggests that additional protected areas could be an important tool to ensure the integrity of the relatively untouched primary forests in the inland of Borneo. Additionally, smallholders should be sensitized or at least alarmed, if an El Nino year approaches, to reduce the risk of future large forest fires, especially close to protected areas.

5.2 Oil Palm

Whilst this thesis allocates ~4 Mha to newly detected oil palm plantations on Borneo from 2001 to 2017, another paper states a higher number with ~ 5.5 Mha for the same period (Gaveau et al., 2019). Gaveau et al. only defined industrial plantation >90ha on satellite imagery by eye (2019). Considering the 4-year detection lag of the remotely sensed dataset and the yearly detection rate in these years (~0.3 Mha), the results coincide. However, the data used here is based on a remote sensing approach and includes smallholder plantations, and therefore it is likely that the newly discovered oil palms are underestimated. This is further supported by the fact that many oil palm plantations are located on deforestation clusters that are not completely covered by oil palms (Figure 14). Thus, it can be concluded that the numbers on oil palm and subsequently deforestation prior to oil palm plantations are too low.

Even though Danylo et al. state, that it takes only 2-3 years for newly planted oil palms to be detected (2021), the lag phase in Figure 13b indicates, that it is 4-5 years. As oil palm plantations in primary forests (0.71 Mha) account for 21.4% of all primary forest logging (excluding forest fires) from 2001 to 2013 (3.31 Mha) and considering the underestimation of new oil palms, it can be concluded, that oil palm is an important driver of primary forest loss on Borneo. Nonetheless, even if other areas of primary forest loss would account for conversion to other industrial plantations, this still makes logging the main driver of primary forest loss.

The portion of new oil palm on secondary forest loss areas cannot necessarily be attributed to secondary forest loss. Since oil palm plantations need to be replanted (see Section 2.2), but are also categorized as secondary forest, replanting is categorized as secondary forest loss. Additionally, it would be too facile to attribute all of the deforestation solely to palm oil, since it is not known whether oil palm caused deforestation or merely followed the clearing of land (Fitzherbert et al., 2008). For example, some companies used palm oil concessions to obtain permission to log, and thus make money, without cultivating palm oil on the land (Fitzherbert et al., 2008). However, it is not known if this practice still exists and planting of oil palms is reported to be detected immediately after clearing (Gaveau et al., 2019). In addition, the fine-scaled unorganized patterns for logging (see Figure 11) differ strongly from the rectangle, clear edge and large area clearing (see Figure 14).

Even though plantation expansion has slowed, the recent large price jump (from 601 USD per ton in 2019 to 1276 USD in 2022) is a worrying indicator, that this trend will soon be reversed in the future (World Bank, 2023). This is because the price is closely linked to the expansion of oil palm production (Gaveau et al., 2022) and thus to environmental issues discussed in Section 2.2.

5.2.1 RSPO

While, based on the data information given by the RSPO, it remains unclear what an uncertified RSPO concession is, certified concessions represent with 15.8% roughly the share of the RSPO certified palm oil trade (19%, see Section 2.3). Since most of the concessions are located on predominantly deforested land anyway, it can be said that the palm oil coming from these plantations does not further contribute to a noteworthy loss of primary forest, since no blending takes place in the mills, which is strictly regulated by RSPO regulations (RSPO, 2018).

Although primary forests take up a marginal amount of RSPO concessions and much of it is already logged (Section 4.3.1), the sharp drop in primary deforestation within certified concessions in 2011 (Figure 16a) is still remarkable, as it coincides with the introduction of the Indonesian moratorium of logging in primary forest. Nevertheless, assuming a link here would be highly uncertain due to two factors: i) the small reference area and ii) the availability of RSPO concession data only for Malaysia.

A statement on whether the introduction of the RSPO label has reduced deforestation by palm oil overall cannot be made and would also be an exaggeration since the RSPO has no or at best indirect influence via advising politicians on concessions for new palm oil plantations. In summary, despite the criticism directed at the RSPO (see Section 2.3), it must be said that at least no more primary forest is being lost for their certified palm oil.

5.3 Infrastructure

If both the built up area and the forest loss datased had 100% accuracy, there should not be any deforestation on built up areas from 2000. Whilst the marginal 0.8% overlap with primary forest clearing confirms high accuracy, the 17.7% with secondary forest cannot be attributed to data inaccuracy (see Figure 17a). The reason for this unexpectedly large number can be assigned to maintenance work of constantly overgrowing vegetation near roads (see annex IV).

5.3.1 Buffer

With almost three-quarters of the Bornean land within 2000 m of infrastructure in 2020, accessibility of remote areas has increased by 92557km ^{2} over the study period, leaving only 26.7% of Borneo untouched (Table 2). This increases the pollution pressures described in Section 2.4. However, as the underlying dataset does not separate private roads (e.g. maintenance roads for industrial plantations) from public roads, it remains unclear how much of the increase in accessibility is due to the expansion of public infrastructure versus private development. However, more detailed maps that capture the temporal development of new roads are scarce. Only open street map provides access to historical data going back to 2013, but its completeness depends on the activity of the users and is therefore questionable, especially in early years. Therefore, a new dataset covering infrastructure development (especially roads) in an annual interval would be an important tool for further research in quantifying the impact of new infrastructure. Nevertheless, the relationship between the establishment of new oil palm plantations and deforestation rates could be closely linked to better access through new infrastructure (Table 1, Table 2). Hence, it is crucial to implement sustainable infrastructure development practices and stringent regulations to mitigate the disturbance effects of future infrastructure projects, especially with respect to the planned relocation of the Indonesian capital to Borneo, where Indonesia has the chance to set new standards for sustainable infrastructure development in the tropics (Spencer et al., 2023).

Another often overlooked form of infrastructure are natural waterways, which allow easy access deep into the forests. Thus, the deforestation of primary forest along rivers (see annex V) can also be attributed to (natural) infrastructure.

5.4 Cropland

Due to the small amount of acreage devoted to shrubby crops, their share of deforestation is almost negligible compared to palm oil. However, there are many small wildfires near these croplands, supporting the claim that smallholders are using fire to clear the land near their fields for pasture, which has a high risk of triggering large-scale wildfires (Section 5.1).

Although other tree crops are grown on Borneo in addition to oil palm, they - even though understudied - certainly do not reach anywhere near the scale of oil palm plantations, with Gaveau et al. reporting that oil palm accounts for 88% of industrial plantations in Borneo (2019).

5.5 Conclusions

In summary, Borneo continues to be threatened by deforestation, which endangers its unique biodiversity and habitat integrity. Recent figures show a declining trend in forest loss, likely due to initiatives such as the moratorium on logging in Indonesia's primary forests. However, this trend requires continued confirmation to prof long-term conservation efforts. Furthermore, rising atmospheric CO2 levels and the El Niño phenomenon increase forest fire risk. Protected areas play an important role in maintaining primary forests and biodiversity.

The expansion of oil palm cultivation, which is the second largest contributor to primary forest loss after logging, is showing signs of slowing, although the recent rise in palm oil prices is an alarming indicator. Since 2011, virtually no primary forest has been cut down for RSPO-certified palm oil, making it, despite criticism and the lack of alternative labels, the most viable option for sustainably conscious stakeholders at present. Other crops only play a minor role in deforestation. Infrastructure development has substantially improved accessibility to remote areas, which led to increased deforestation, hence calling for sustainable practices and strict regulations for future projects.

In summary, the problem of deforestation in Borneo can only be addressed with a holistic approach that includes sustainable practices, strict regulations, awareness campaigns, and responsible development to protect the exceptional biodiversity within the remaining primary forests.

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1 Percentages of primary forest loss within buffer distances from the total primary forest area. The data is categorized into three sections: primary forest (portion of the total primary forest covered by the buffer), loss buffer (portion of forest loss within total primary forest within buffer area), and loss total (portion of the loss within buffer from the total primary forest loss). This is done for **i)** *total* infrastructure in 2020 (assuming no year 2000 built-up area was removed), **ii)** *existing* (year 2000) built up area and **iii)** *new* built-up area (2001 - 2020). 25

2 Percentages of new and existing oil palm (OP) plantations within buffer distances from the total area of Borneo. The data is categorized into three sections: area of Borneo (portion of the total Bornean Area covered by the buffer; excluding buffer areas that lap over the study extent), new OP buffer (portion newly detected oil palm from 2001 - 2017 within buffer area), and total OP (portion newly detected oil palm from 2001 - 2017 from all new oil palm area). This is done for **i)** *total* infrastructure in 2020 (assuming no year 2000 built-up area was removed), **ii)** *existing* (year 2000) built up area and **iii)** *new* built-up area (2001 - 2020). . . . 26

Annex

I Detailed research questions

Forest Information 2000 How much forest was there in the year 2000? How much primary forest was there?

1 General Forest loss

1.1 How much forest area was lost yearly and in total?

1.2 How much forest area was lost due to forest fires yearly and in total?

1.3 How much forest gain (area) occured after forest fires (2001 - 2012)?

1.4 How much forest was lost in protected areas yearly?

1.5 How much forest was lost in protected areas excluding forest fires?

2 Primary Forest loss

2.1 How much primary forest area was lost yearly and in total?

2.2 How much primary forest area was lost due to forest fires yearly and in total?

2.3 How much primary forest was lost in protected areas yearly?

2.4 How much forest was lost in protected areas excluding forest fires?

3 Oil Palm related

3.1 How much new oil palm plantations occurred yearly (2000 - 2017)?

3.2 How much new oil palm occurred on previously deforested areas? (2001 - 2017)

3.3 How much new oil palm plantation area occured yearly on areas previously deforested by forest fires?

3.4 How much new oil palm plantation area occured in protected ares?

3.5 How much new oil palm plantation areo occured on non-forest area? (compared to year 2000 forest cover)

3.6 How much new oil palm plantations occurred yearly on primary forest (2000 - 2017)?

3.7 How much new oil palm plantation area occured on previos cropland (and other way around)?

3.8 How much forest area was ganied on previous oil palm plantation area yearly (2000 - 2012)?

3.9 How much area was used for other crops prior to oil palm plantation, and which?

3.10 How much area was used for oil palm plantation prior to other crops, and which?

5 Build up areas 4.1 How Much new build up area was created from 2000 to 2020?

4.2a How much forest loss areas occured on new build up area (yearly)?

4.2b How much primiary forest loss areas occured on new build up area (yearly)?

4.3 How much new build up area occured in non-forest covered area (2020 compared to 2000)?

4.4 How much new build up area occured in forest fire area (2020 compared to 2000)?

4.5 How much new oil palm plantation area occured within 0.1, 0.2, 0.5, 1, and 2 km of year 2000, new_build up and total build up areas?

4.6 How much forest fire area occured within 0.1, 0.2, 0.5, 1, and 2 km of year 2000, new_build up and total build up areas?

4.7 How much deforestation (excluding forest fires) area occured within 0.1, 0.2, 0.5, 1, and 2 km of year 2000, new_build up and total build up areas?

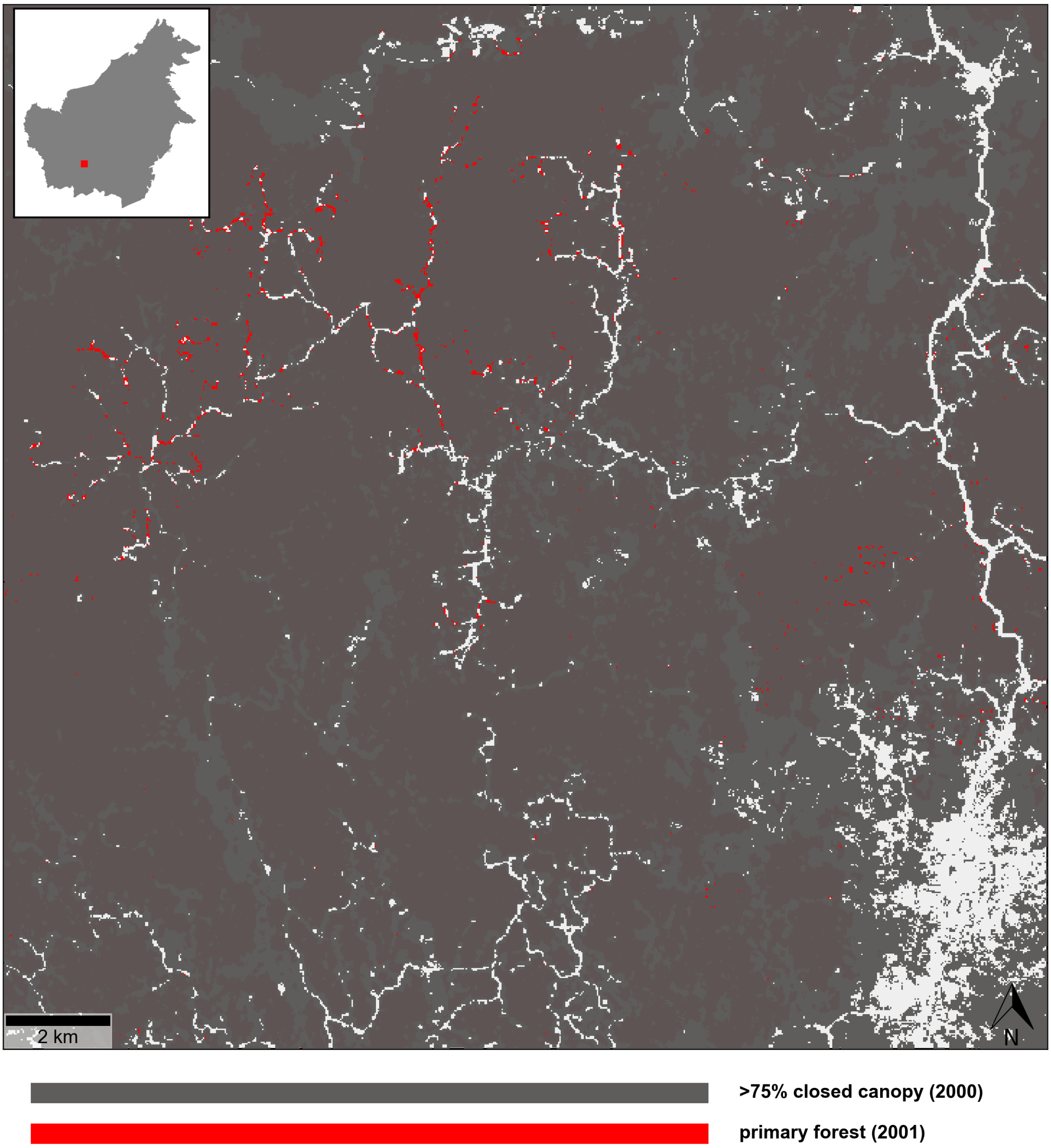
4.8 How much forest area was lost to cropland areas within 1, 2, 5, 10, and 20 km of newly buld up areas?

4.9 How much new build up areas was created on primary forest loss areas (2020 compared to 2000)?

6 RSPO

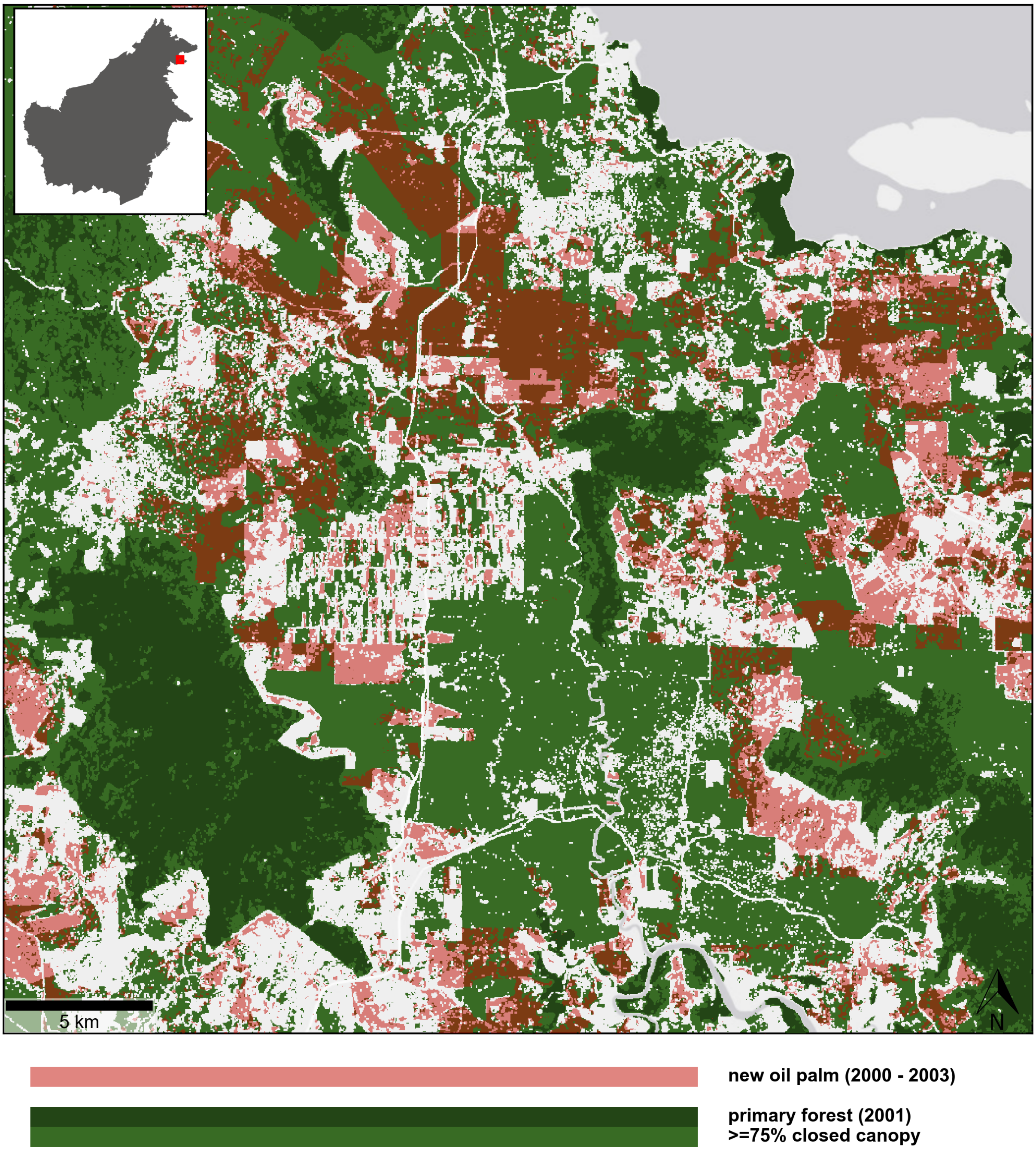
5.1 How much deforestation occurs within RSPO certified concessions?

II Overlap of 75% closed canopy and primary forest



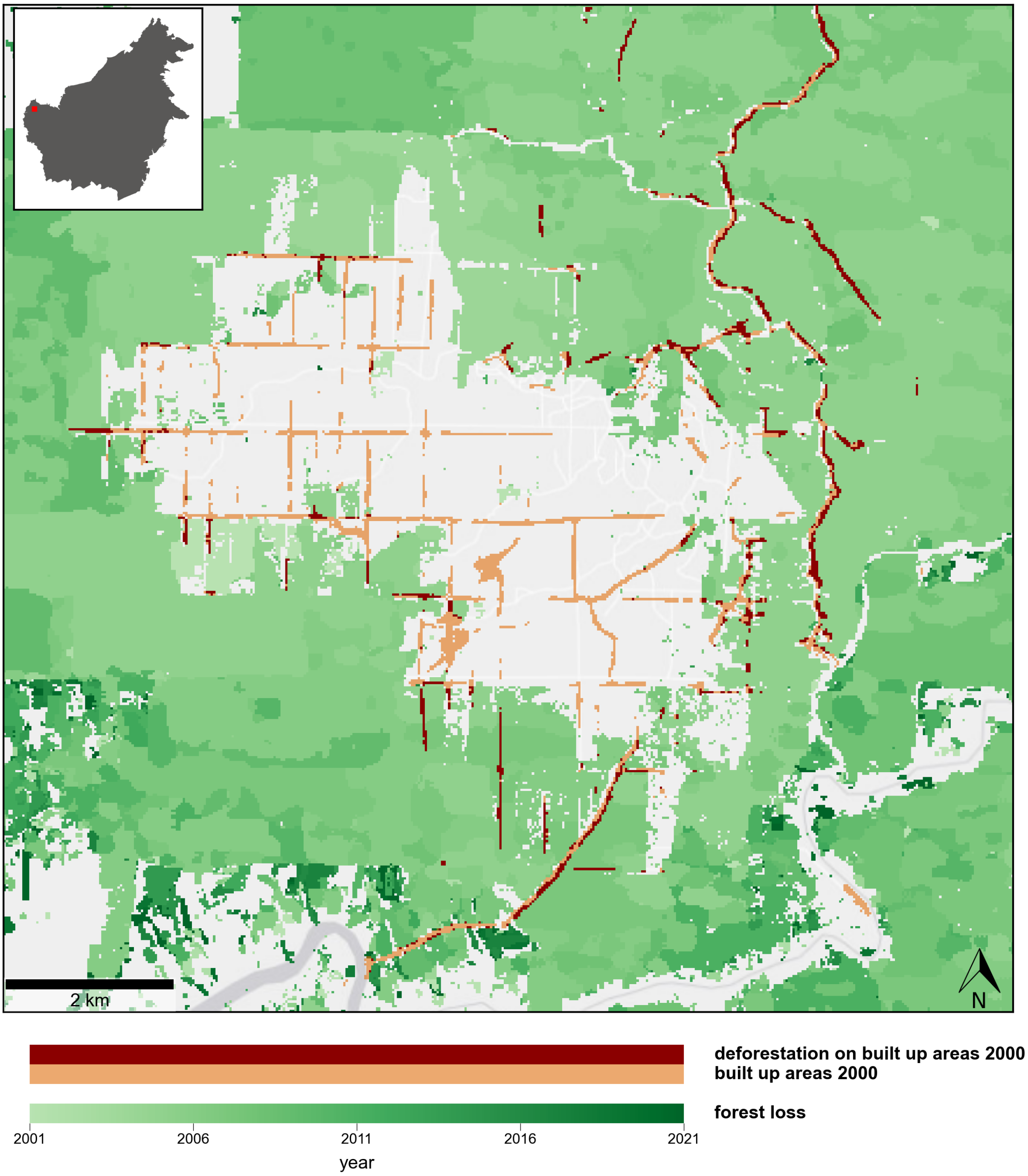
Representative map extract showing that >75% closed canopy of 2000 mostly covers the primary forest of 2001.

III Dense vegetation excluding primary forests



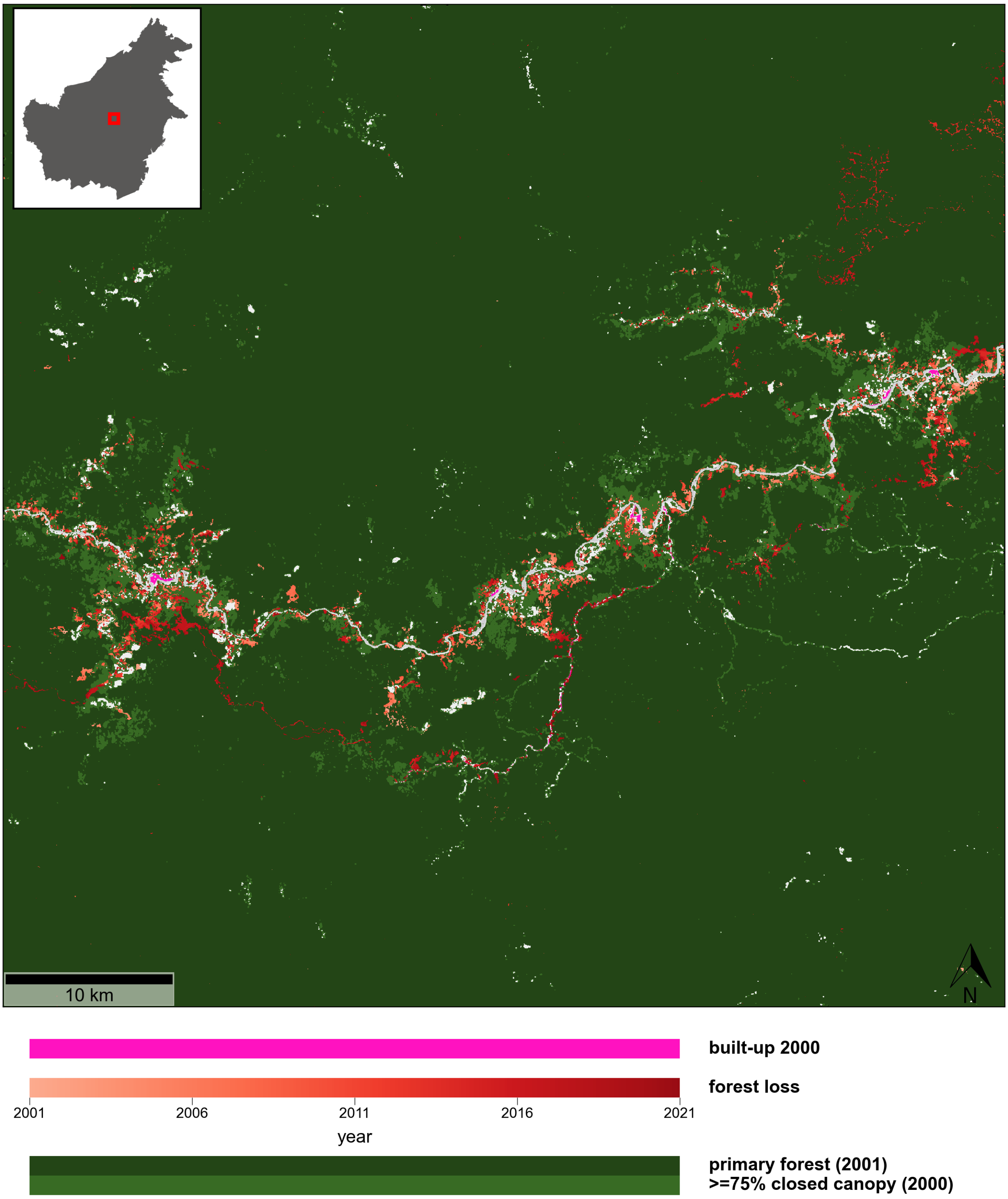
In the dense vegetation outside of primary forests, lage areas are occupied by oil palm. Oil palm data is limited to years 2000 - 2003 as growing oil palms could alread have a closed canopy of >75% in the year 2000.

IV Validation of built up areas in 2000 and deforestation



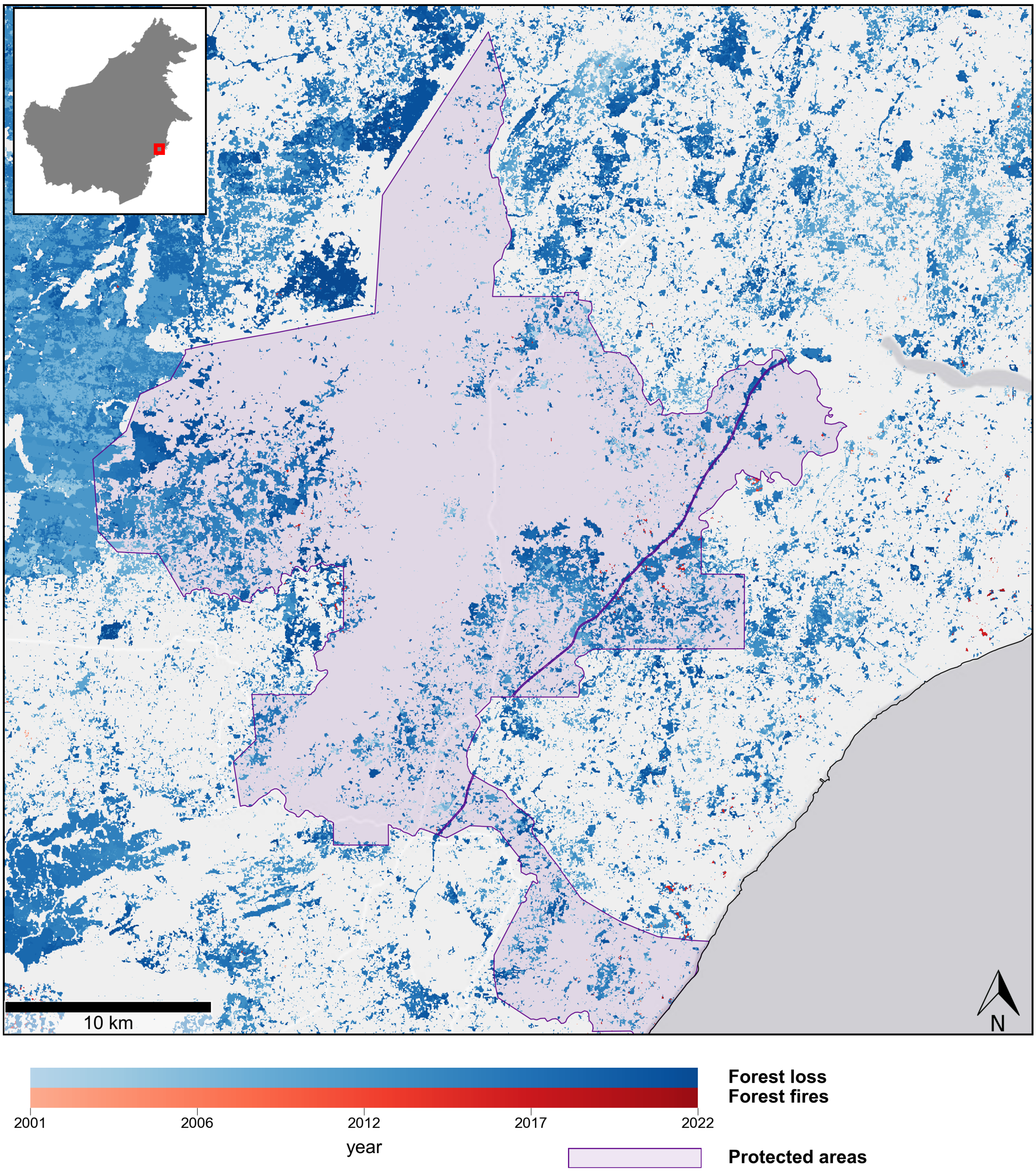
Example of deforestation on year 2000 built up area, where, logically, no deforestation should be. Here it is visible, that these areas are mainly located at the edge, where maintenance led to the removal of closeby trees, which were thus classifiead as forest loss.

V Secondary Forest and proximity to rivers



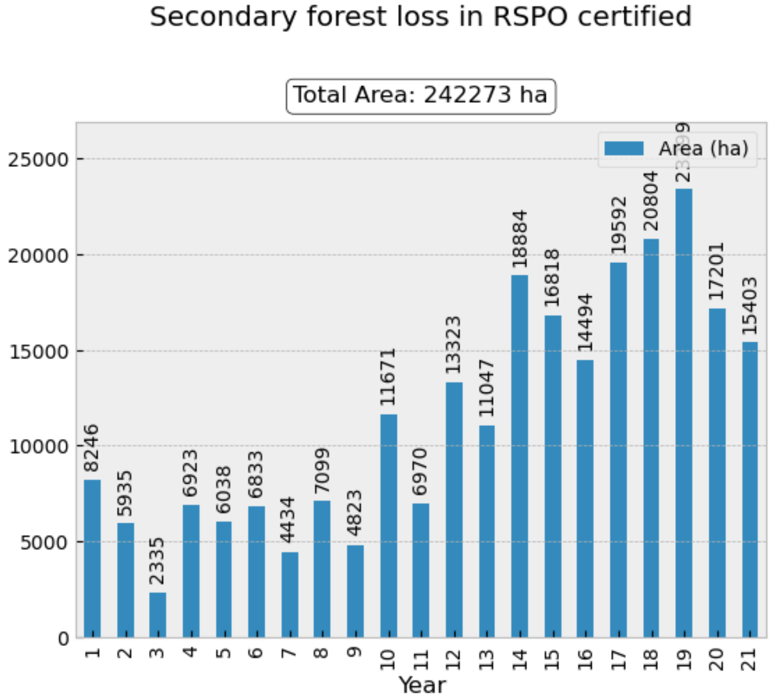
A repeating pattern, with a lot of secondary forest close to rivers, especially with built-up areas nearby.

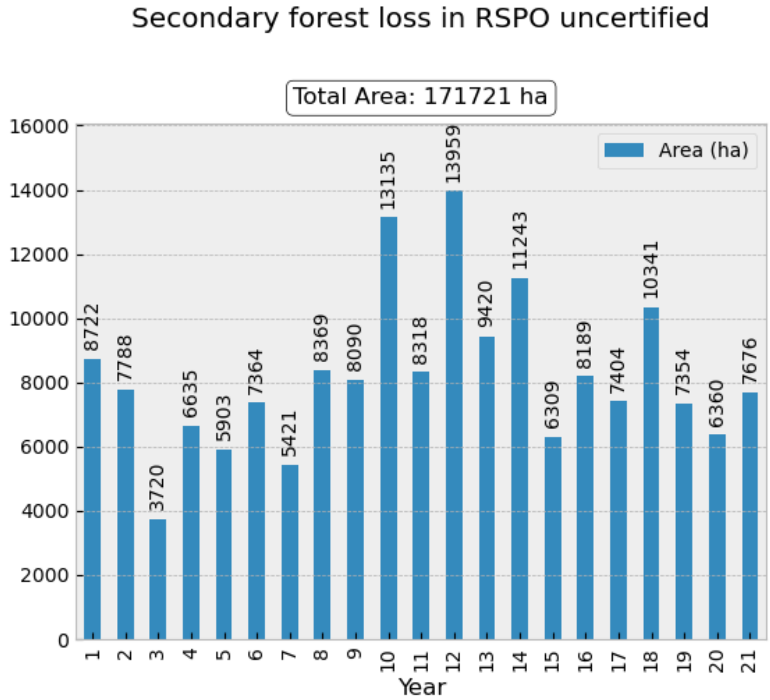
VI Logging in PAs



An exceptional case of a protected PA where much deforestation takes place. A prominent feature is a new road that cuts through the PA.

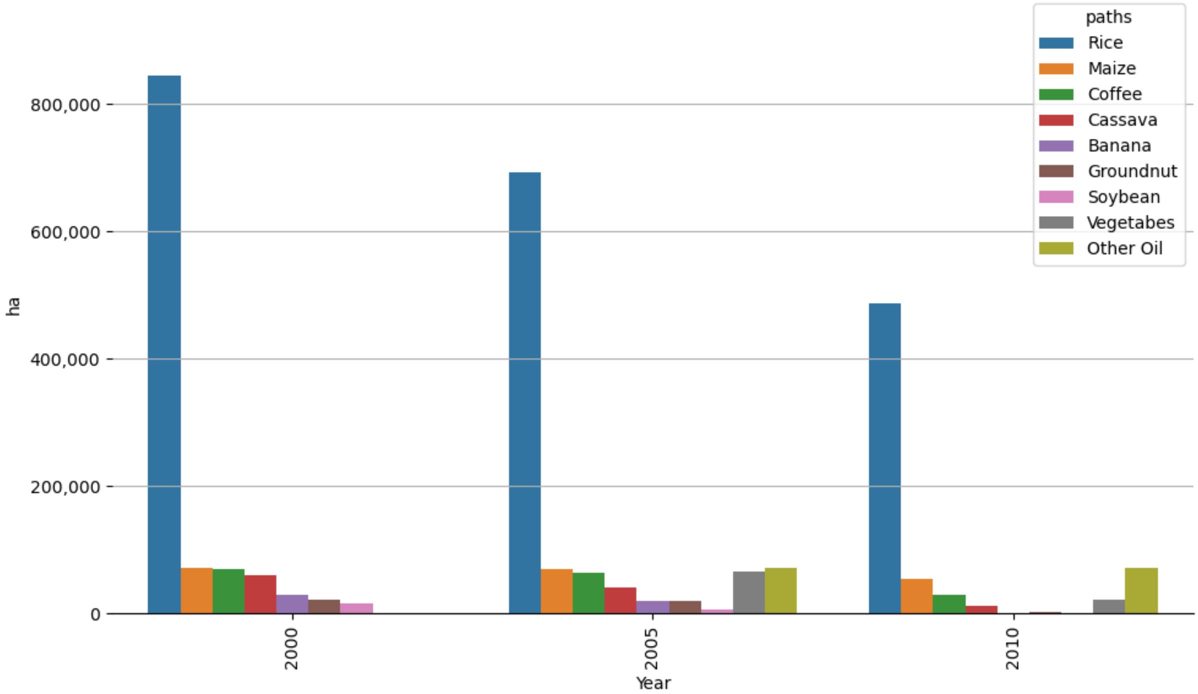
VII Socondary forest loss in RSPO concessions





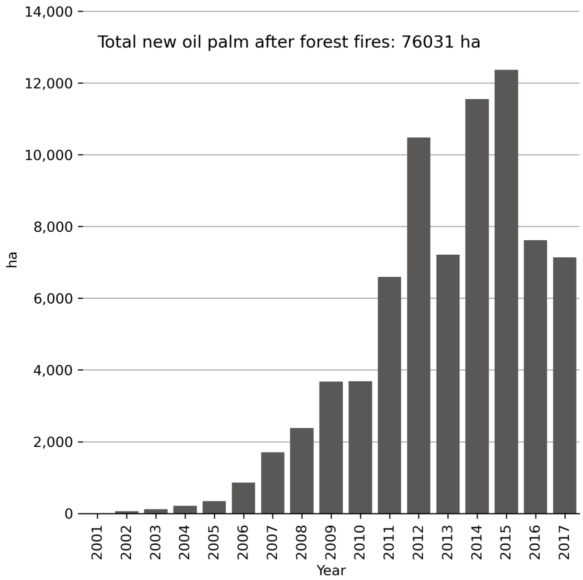
Elevated levels of secondary forest loss in RSPO certified concessions and continuous loss in uncertified concessions.

VIII Harvest area SPAM



These are the harvest areas of shrubby plants given in the crop type datasets, that should be in the same range as the croplands, but they exceed those numbers multiple times indicating their unreliabilty.

IX Oill palm after forest fies



This figure shows, that clearing land for oil palm with fires occurs rarely.

X Plagiarism declaration

Statement of Authorship for Student Work at the School of Life Sciences and Facility Management

By submitting the enclosed

☐ Project
☐ Literature review
☐ Course work
☐ Minor paper
☒ Bachelor's thesis
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Location, date: Wädenswil, 28.10.2023

Student signature: R. Ctelb