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

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by

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Abstract

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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).

Although many recent global datasets provide the basis for analyzing the key drivers of deforestation, the most recent study examining this for Borneo was conducted a decade ago, without focus on other drivers besides oil palm (Gaveau et al., 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).

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 ii 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).

- vielleicht noch mehr auf kreisläufe eingehen/zusammebringen / sequestrierung von CO2 Phosphor, Stickstoff.
- evtl mehr von Houghton 2013

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 globall 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 remoteley 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 ae 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.

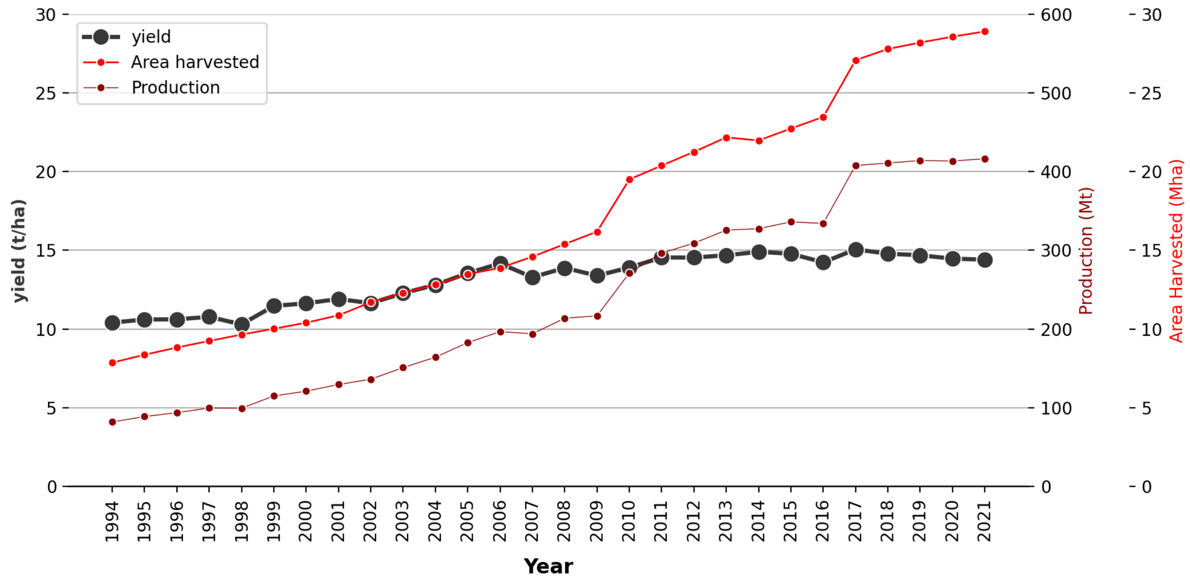


Figure 1: Global harvest area and production of oil palm evolve accordingly, with no yield improvement since 2011 (FAO, 2023).

2.3 Sustainable Palm Oil Labels

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 certified 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% on 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 have replaced primary forest and a High Conservation Values (HCV) assesment is needed 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 for certification (RSPO, 2018). Despite public discussion on oil palm, a study on Swiss consumers showed, that only 9% of the participants were even 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 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). Cocconut 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 remoteley sensed data processing (see Section 2.6).

2.5 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 enourmous 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, 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 enhance 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.

2.6 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 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 wideley available (Danylo et al., 2021; Hansen et al., 2013; Potapov et al., 2022, 2021; Turubanova et al., 2018; Tyukavina et al., 2022).

3 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, Southeast Asia or even a global extent and downloaded. QGIS (Version 3.30) was used for initial data exploration. This led to the manual selection of data shown in Figure 2 for further analysis. Hereafter, the datasets are referred to by the names specified in the content column. The research area was defined as the landmass of Borneo, explicitly 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).

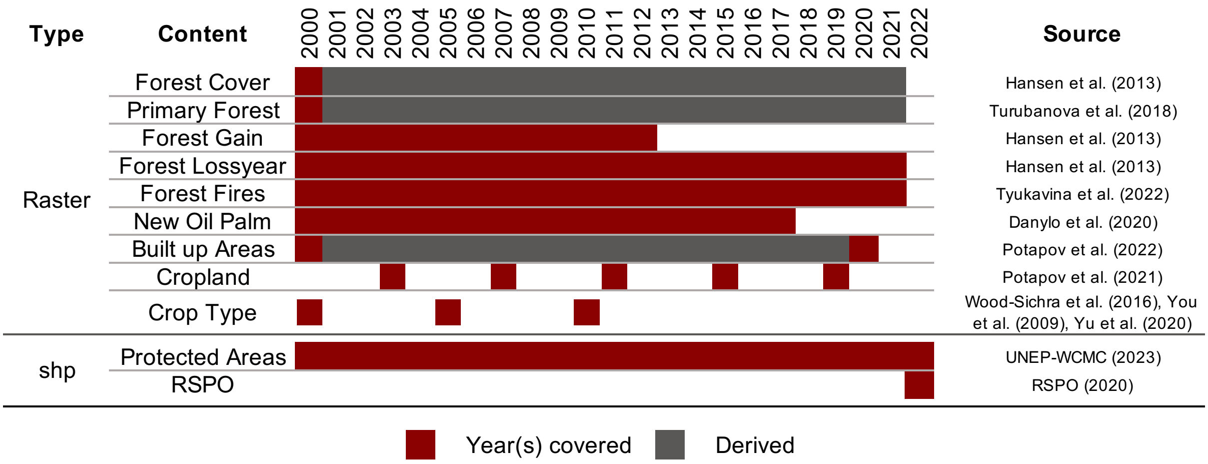


Figure 2: All datasets used in this thesis and the temporal scope they span.

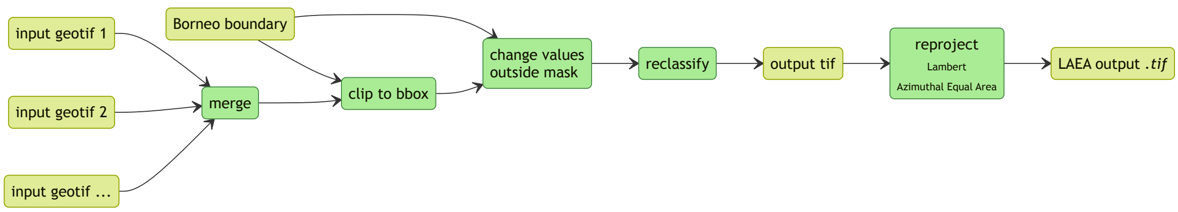
3.2 Software

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). For each step a Python function was developed, which requires an input path(s), optionally a target file path and an output path. 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 created using a minimal example with the help of Chat-GPT. Subsequently, more complex features were implemented into the function through personal adjustments or continuous user feedback to the AI. The generated code was carefully inspected and reviewed to ensure its correctness.

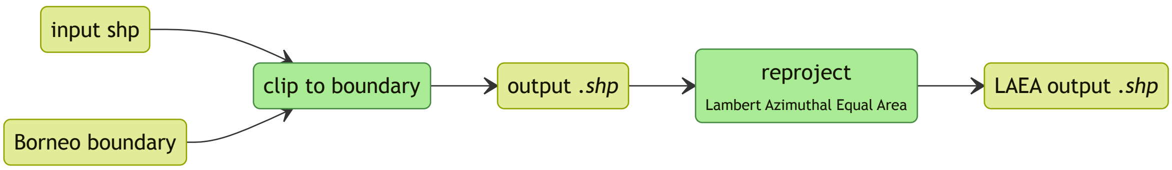
3.3 Data preparation

All data has been brought into a consistent format. This included steps like merging multiple files, clipping to bbox, changing all values outside the mask (e.g. boundary of Borneo) to the *nodata* value, and reprojecting it to a uniform projection. For the analysis, the Lambert Azimuthal

Equal Area Projection was used with the center point being at 115° longitude and 0° latitude. The workflow for the preparation of raster and vector data is visible in Figure 3.



(a) raster data preparation



(b) vector data preparation

Figure 3: Workflow of data preparation. *green: processing steps; yellow: files*

- Farbgebung vereinheitlichen (anpassen an Figure 6a)
- Detaillierter auf die verschiedenen Funktionen eingehen?

3.4 Analysis

For answering the simpler questions 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. For more complex questions, where multiple datasets were involved, they were resampled onto the same grid. 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 the built-up area was used as a mask for further analysis. The workflow of this is visible in Figure 4.

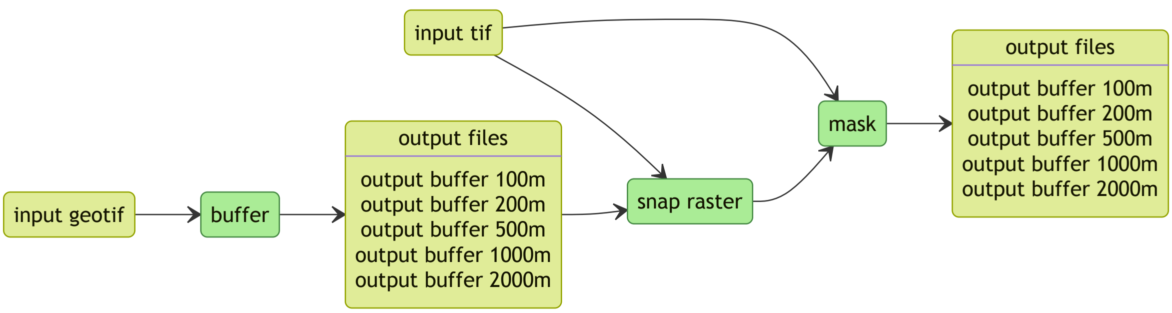


Figure 4: Workflow of buffer maps and subsequent combination with other datasets

- Detaillierter auf die verschiedenen Funktionen eingehen?

3.5 Further definitions

The forest cover dataset shows the percentage of canopy cover. However, Hansen et al. provide no definition of what is considered forest (2013). Therefore, a threshold of 75% closed canopy was chosen, which was also used by Turubanova et al. for comparison of their Results with GFW data (2018). However, Turubanov et al. used expert interpreted training data for detection of patterns recognized as primary forest (2018). Although areas with >75% closed canopy overlap nearly all of the primary forest areas (see Annex **XY**), these were reclassified as forest (see Figure 5).

Aggregated plants and perennial woody plants such as coconut and oil palm were manually removed from subsequent analysis due to the cropland definition in the used dataset (Potapov et al., 2021), as well as crops with a total physical harvest area lower than 10000 ha within the project extent in any of the three datasets.

- Leider macht es trotz erfolgreicher Methodenentwicklung wenig Sinn dies genauer zu analysieren, da die intersection mit den Anbauflächen sehr gering ist. (Siehe Chapter 5)

4 Results

4.1 Forest status 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 >= 75% closed tree canopy, and 15.3% with less dense vegetation, respectively. Figure 5 provides an overview of the composition of vegetation on Borneo at the start of the study period.

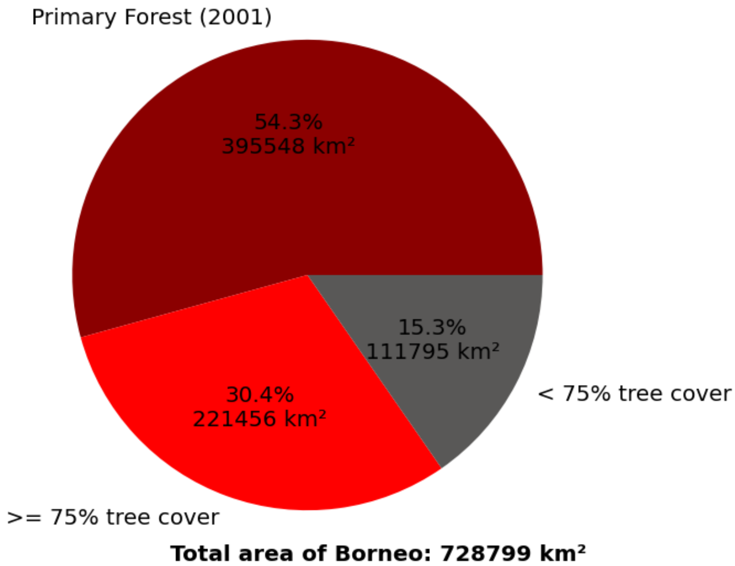
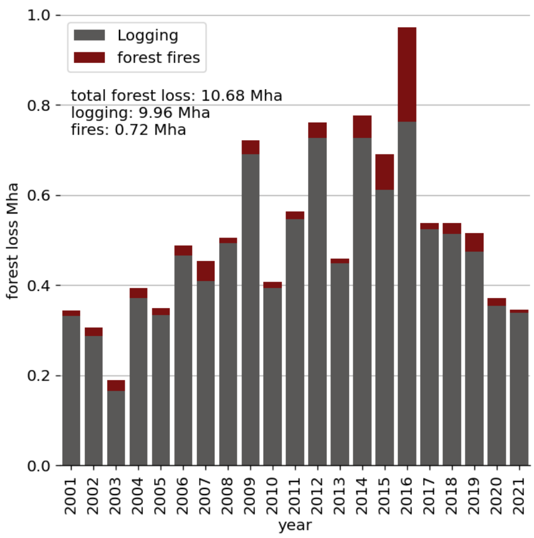


Figure 5: Composition of vegetated areas on Borneo at the start of the study period.

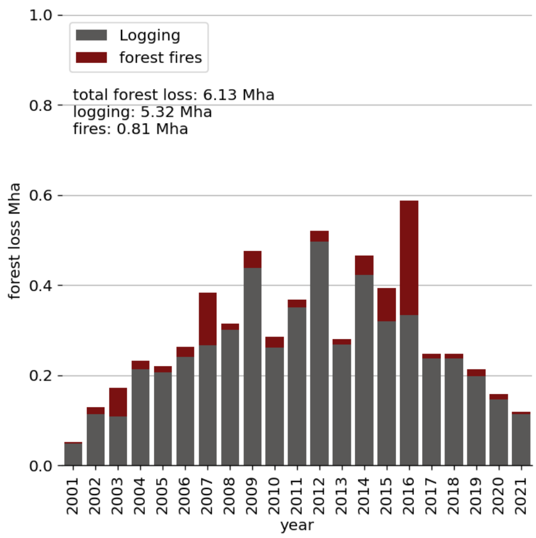
The >= 75% closed canopy consits of secondary forests as well as plantations. 4886 km^2 or 2.2% of the >75% forest cover represent oil palms (stand 2000 or detection up to 2003), with a lot of these oil palm plantations being close to typical plantation patterns (see annex IV). Another notable characteristic are large areas close to rivers, especially with human settlements nearby, that have lot of dense vegetation right next to primary forests (see annex V).

4.2 Deforestation

In the years from 2001 to 2021, a total of 16.81 Mha of deforestation occured. 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 6a. 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 6b. 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 6.



(a) Secondary forest loss, peaking in 2016.



(b) Primary forest loss, peaking in 2016.

Figure 6: Overview of deforestation within **(a)** secondary forests and **(b)** primary forests.

In general, logging patterns can be separated into two categories. First, large areas of logging in the same year, often with sharp borders, and second, dispersed small-scale logging (Figure 10, Figure 14). This is especially the case in primary forests in the malaysian part of Borneo, where logging continously encroaches (Figure 7). Fires in secondary forests have no obvious patterns; they occur randomly and mainly on a small scale.

Protected areas cover 6.24 Mha, of which 0.08 Mha are secondary forest and 4.72 Mha is primary forest. Within protected areas, the main reason for forest loss were forest fires, regardless of the classification as primary or secondary forest. Forest fire area and logging rates are similar (Figure 8). This is remarkable given that secondary forests accounted for a massively smaller proportion of the total area of PAs. Logging in protected areas occured very limited with an average of ~2,500 ha per year being logged. However, wildfires occurred irregularly, with a major spike in 2016 and other substantial forest loss to fires in 2003, 2007, and 2015 (Figure 6b). These majority of these forest fires were on the edges of the forest spanning large patches (Figure 9).

4.3 Oil Palm

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. Looking at the maps, these can be attributed mainly to maintenance work and the corresponding cutting back of adjacent vegetation, as well on a smaller scale to the clearing of oil palm plantations for replanting. Annex III provides an representative example.

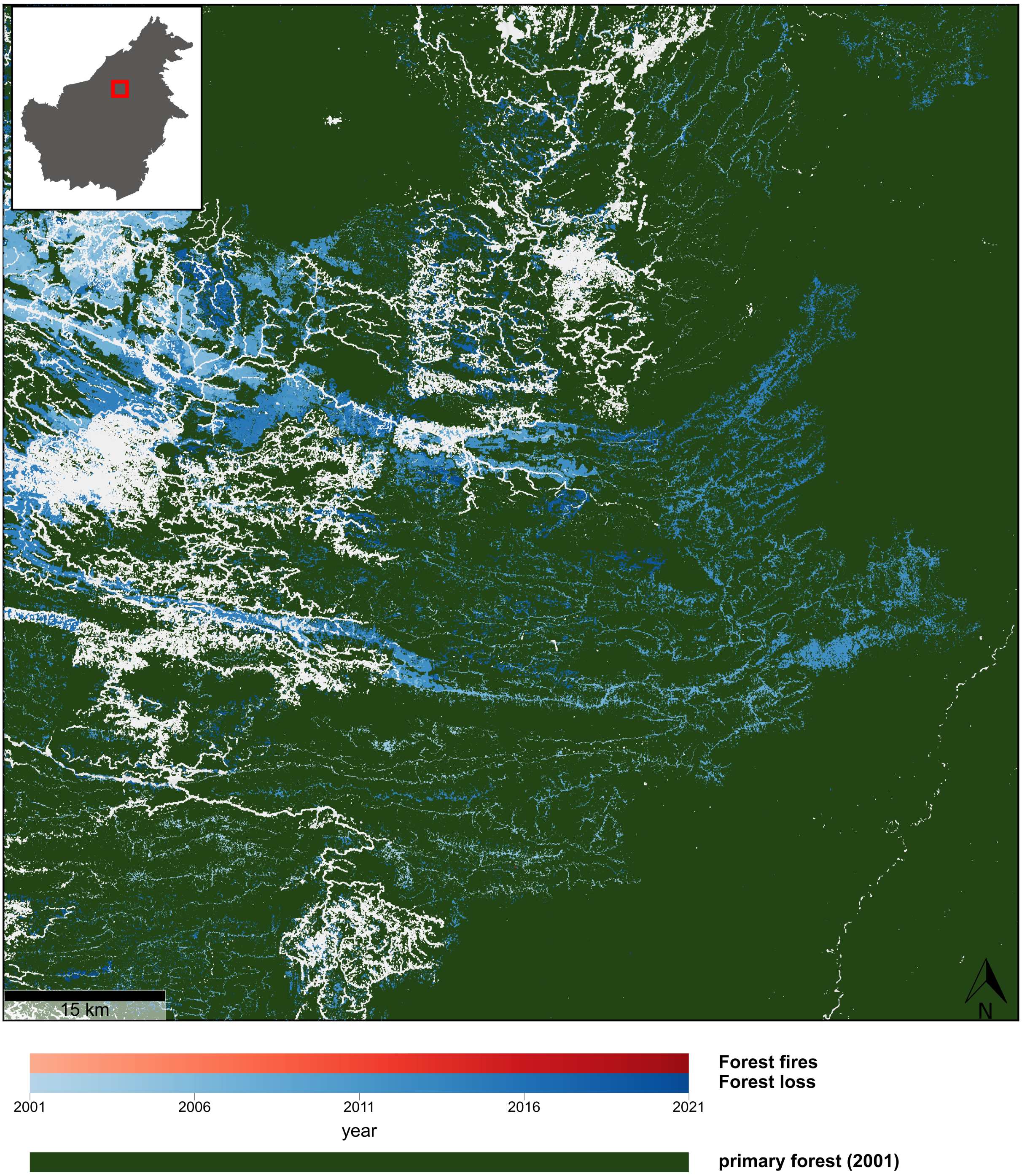
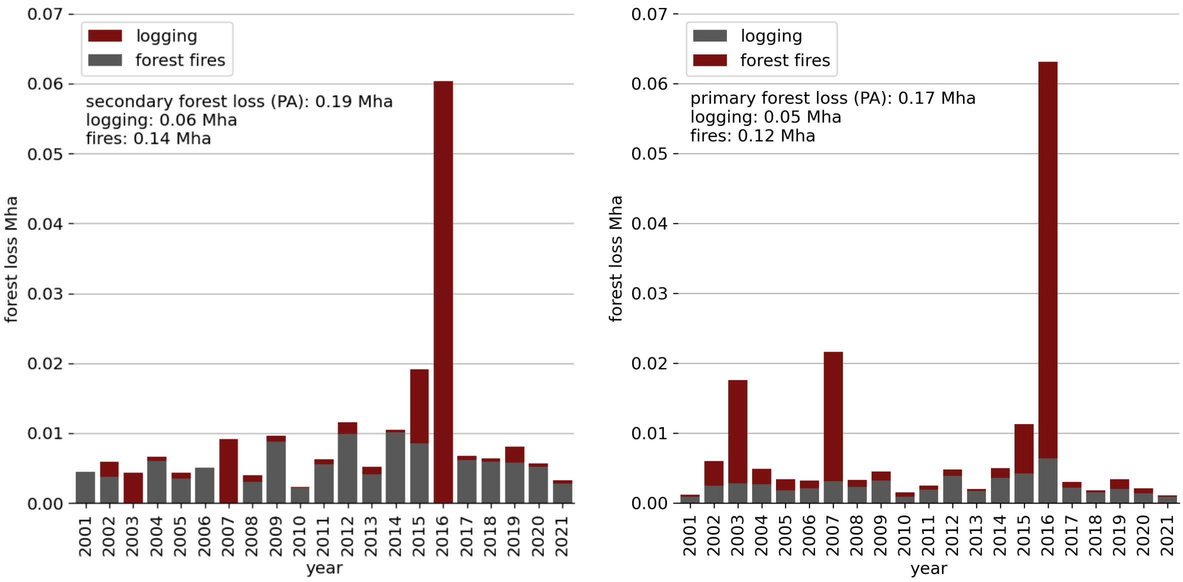


Figure 7: Large areas in the Malaysian part of Borneo where logging activities are penetrating deep into the primary forest.



(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 8: Deforestation within protected areas, with the peak year in 2016.

Table 1: The percentages of primary forest loss are calculated within the confines of the primary forest that lies within certain buffer distances. The exposure of the primary forest to deforestation intensifies as its proximity to infrastructure increases.

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

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), 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 Borneo	new OP buffer	total OP	area of Borneo	new OP buffer	total OP	area of Borneo	new 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

Buffer		total			existing			new	
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

Table 2 Table 2, table 2

Additional map extracts are provided in Appendix 3. For best data exploration, visit *link to storymap*.

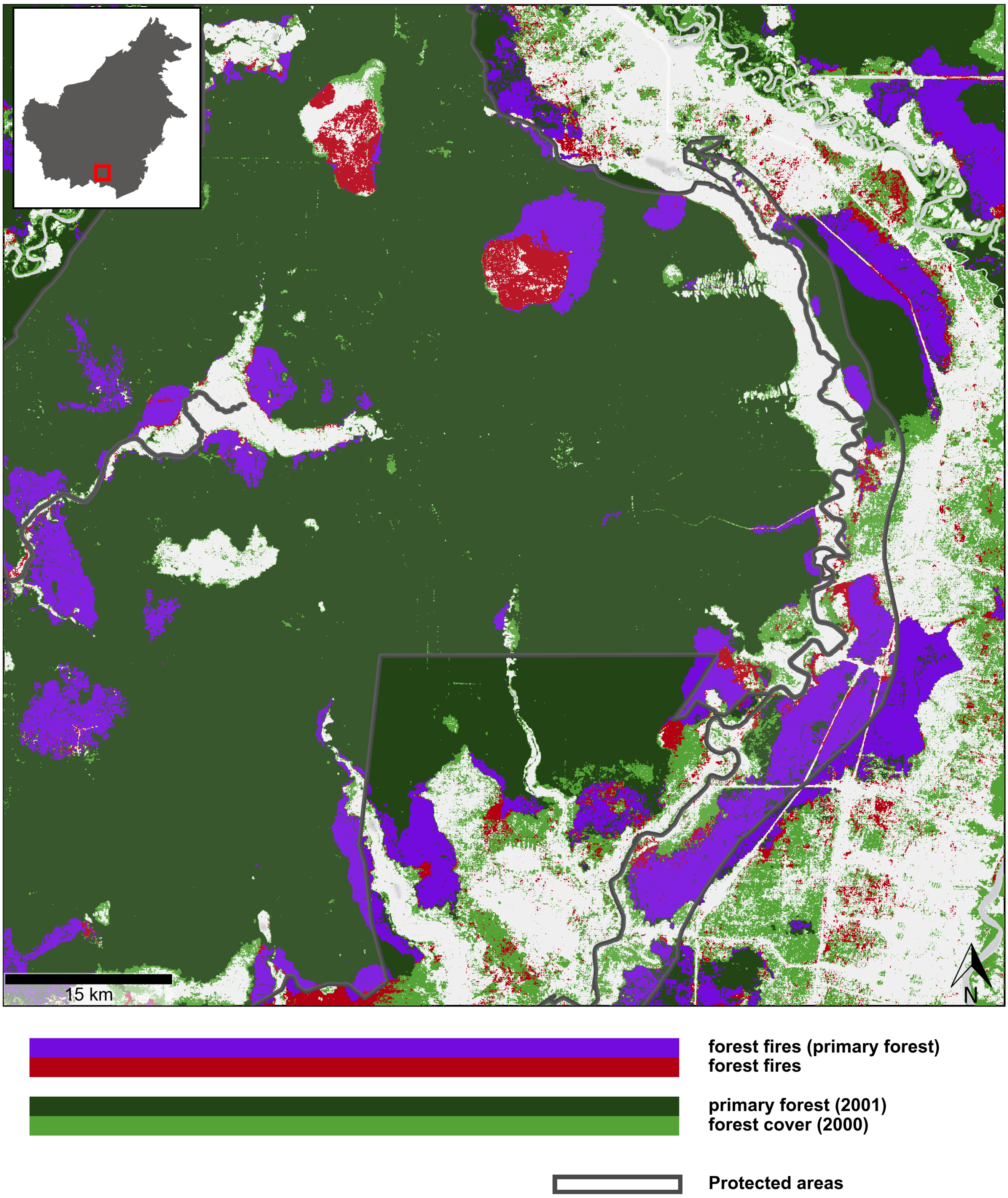


Figure 9: In this protected area it is clearly visible, that forest fires (red) are the main drivers of deforestation within protected areas. Large forest fires like these are the cause of the outlier year 2016.

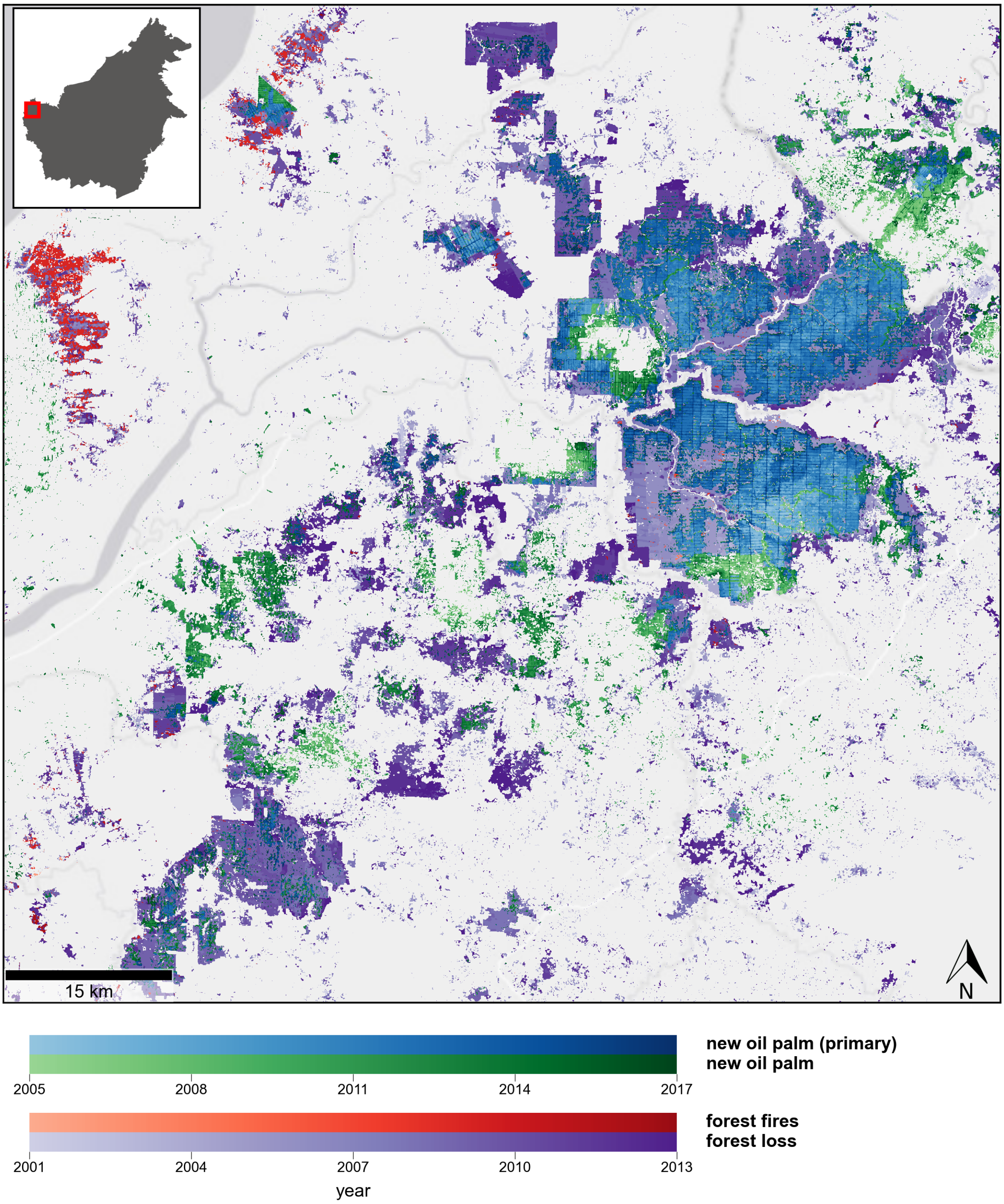
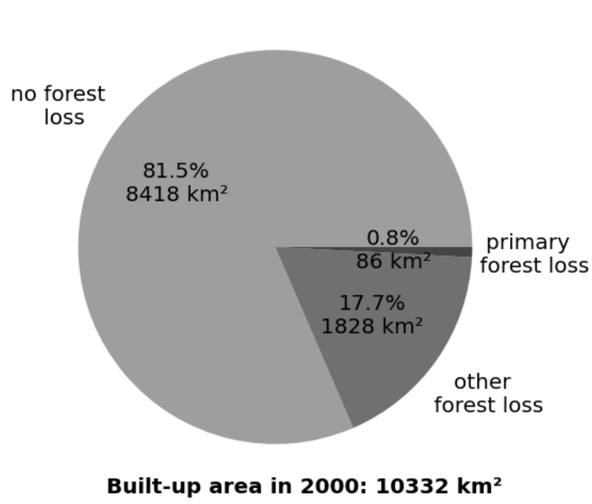
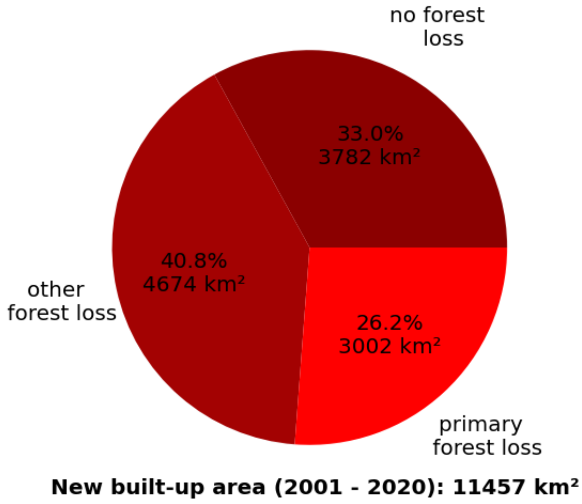


Figure 10: Large deforestation areas are found on and nearby newly detected oilpalm data. This extract also shows one of the largest oil palm plantations on previous primary forest.



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



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

Figure 11: The built-up area within the study period has more than doubled to a total of 21,789 km^2.

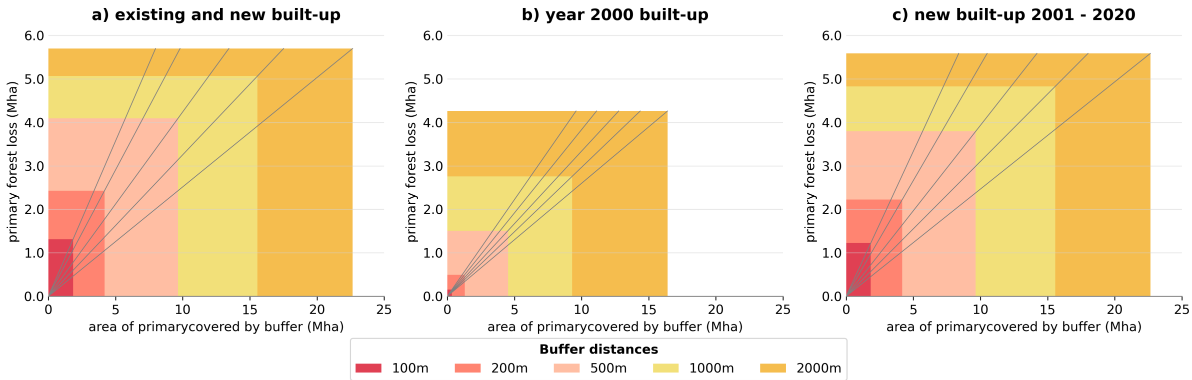


Figure 12: The x-axis shows the primary forest area that falls within the buffer distance. The y-axis shows the amount of primary forest loss. This shows the relationship of infrastructure proximity for **a)** total built-up area 2020 (assumed that no year 2000 areas were removed), **b)** built-up area in the year 2000 and **c)** newly built-up areas between 2000 and 2020.

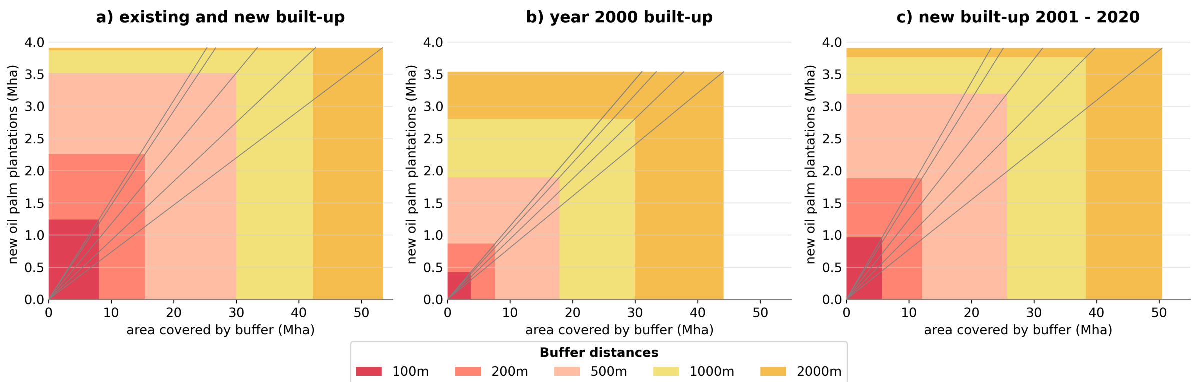


Figure 13: Composition of vegetated areas on Borneo at the start of the study period.

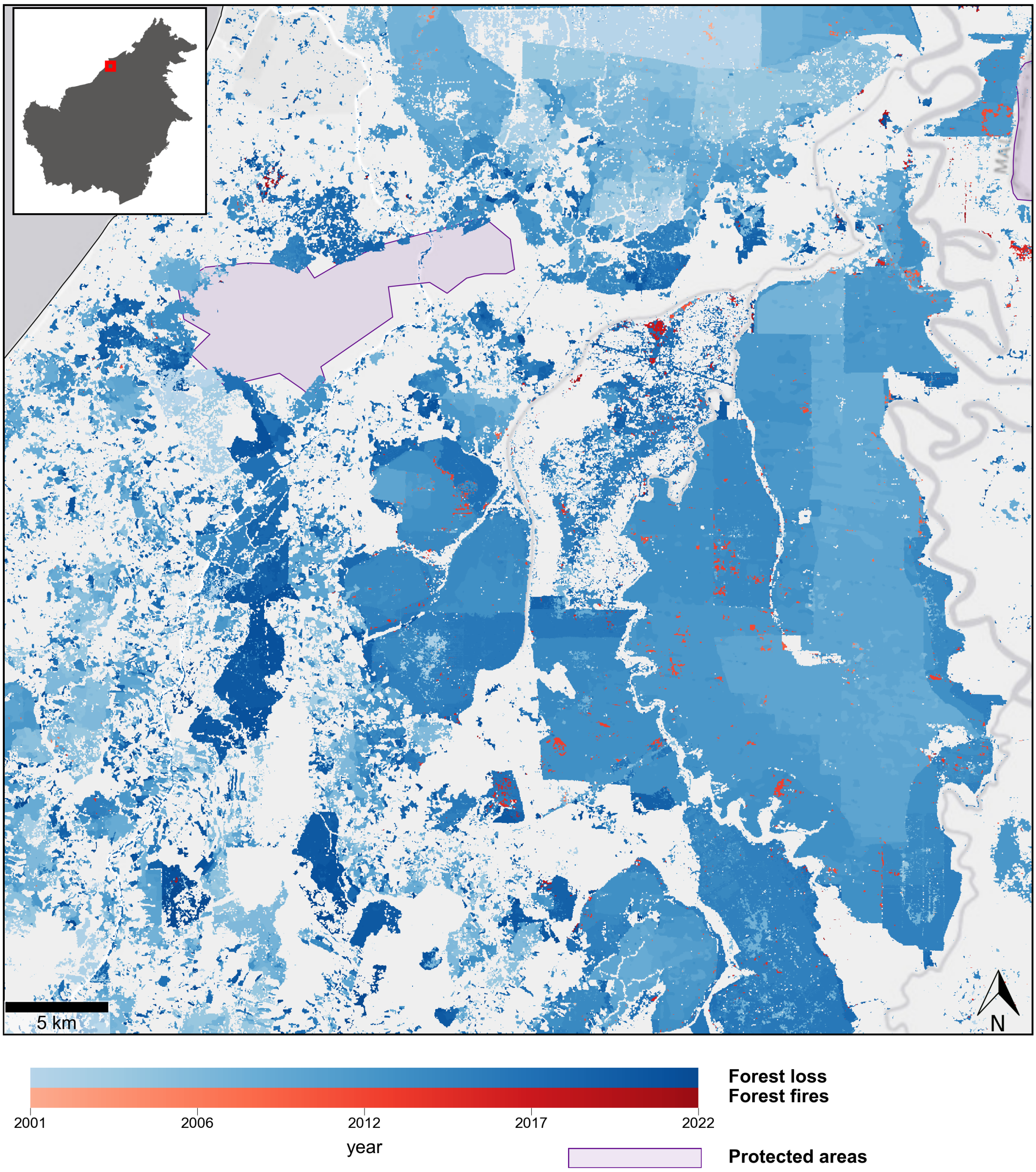


Figure 14: Typical deforestation patterns in eastern Borneo with a few large areas of deforestation inland, smaller scale near the coast, and a clear delineation to protected area with very little forest loss.

5 Discussion

However, the data showing forest gain in the span of 2001 - 2012 is inaccurate. Analysis showed that 32% of the alleged forest gain represents newly established palm oil plantations. Thus, all new palm oil cultivation areas established between 2001 and 2012 have been removed from the forest gain dataset.

5.1 Data selection

5.1.1 Crop harvest area

Existing mapping of cropland all take a similar approach. They disaggregate national and subnational statistics and estimate their allocation to low-resolution grid cells of 5 arcminutes (Wood-Sichra et al. (2016); You et al. (2009); Yu et al. (2020); Grogan et al. (2022)). Among them, the Spatial Production Allocation Model (SPAM) takes the most factors into account rendering it the most comprehensive data. (You & Sun (2022)) Additionally, the dataset family currently contains data for the years 2000, 2005 and 2010, which makes it the most suited choice for the present work (Wood-Sichra et al. (2016); You et al. (2009); Yu et al. (2020)). However, due to improvements in the method of creating the datasets, the more recent ones are a more accurate representation of the physical harvest area and are more finely broken down into distinct crops. (Wood-Sichra et al. (2016); Yu et al. (2020)). This is why coconut is missing in the year 2000 even though it was an important crop for both Indonesia and Malaysia at that time (FAO, 2023).

Although a more recent dataset called Global Agro-ecological Zones (GAEZ v4.0) was available for harvested crops in 2015, no analysis was conducted with it because the data lacked the necessary quality and therefore could not be compared to the SPAM datasets. Just like the SPAM dataset, FAO statistics complemented with national data on FAO gaps, were used to calculate crop yield in a 5 arcminute resolution grid. However, the pixel values in the GAEZ 2015 dataset are based upon the GAEZ 2010 (GAEZ v3.0) dataset, whose download portal does not work anymore (FAO/IIASA (2010)). It was calculated by multiplying the year GAEZ 2010 pixel value by the countries' change in the given crop over the last 5 years. As a result, any spatial displacement in the harvest area of a given crop to another region is incorrectly mapped rendering the intended analysis inadequate.

Another available dataset for 2000 was neglected because the SPAM datasets were all created using the same method, which reduces inconsistency when comparing spatiotemporal differences. In addition, only the harvested area was available in the alternative dataset. This means that areas that were harvested several times per year were also counted multiple times, biasing the total physically cultivated area.

Nevertheless, SPAM data is also subject to non-negligible drawbacks, since ### !!!NOCH ERGÄNZEN!!! ### (Joglekar et al. (2019)).

5.2 Processing

For area calculations, it is crucial to choose a well-suited coordinate reference system. Taking a UTM zone was considered too inaccurate, as Borneo spans over 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 one part, or more precisely the Malaysian part, and thus distorts the larger Indonesian part of Borneo. Therefore the Lambert Azimuthal Equal Area Projection was chosen since it is well suited for accurately showing the area in large spatial extents.(esri, 2019, 2023). Although this does not affect the area calculations, the center was manually set to the center of Borneo to achieve a visualization of Borneo that minimizes distortion. As indicated before, merging data from different sources is challenging. This is especially true for the croplands in higher resolution (~30 m) with the physical harvest area for the individual crops in lower resolution (5 arcminutes). Especially because the two datasets were created with fundamentally different methods. While the dataset of the cultivated areas was created by analysis of satellite data time-series and showing their precise extent (Potapov et al. (2021)), the physical harvested area maps of the different crops were by a complex model based on statistics and estimates (Wood-Sichra et al. (2016); You et al. (2009); Yu et al. (2020)). Even though a method to aggregate these datasets was developed, the main reason why crops were not further analyzed was that the intersection area of newly detected oil palm plantations was below a total of 80 km² for all of Borneo over the span from 2000 to 2017. Since this represents only such a small fraction of the total cropland (~2000 - ~3500 km²) and

5.3 Forest

One reason primary forests do not extend to the riverbanks is that the river helps shape the surrounding forest through bank shifting or flooding. Much more likely, however, is that the rivers serve as transportation routes and thus provide easy access for logging. This assumption is also supported by the fact that logging occurred adjacent to the river during the study period (see Annex V).

It is important to note, that the forest cover dataset only represents tree crowns. This means, that

Large interconnected forests, including primary forest still exist on Borne… Central Borneo possesses one of the last interconnected large forest fragments, rendering it especially important to protect it (Haddad et al., 2015).

hansen et al weist auf erster seite hin, dass indonesiische regierung 2011 neue regulierungen eingeführt hat zu abholzung.

Due to the method applied for forest loss detection, there was also some deforestation outside secondary forest or dense vegetation.

5.4 Infrastructure

Theoretically, there should not be any deforestation on built up areas from 2000. While the marginal 0.8% overlap with primary forest clearing confirms the accuracy of the data, the 17.7% with residual dense vegetation cannot be attributed exclusively to this cause (see Figure 11a).

5.4.1 Oil Palm

Whilst this thesis allocates ~4 Mha to newly detected oil palm plantations, another paper states a higher number with ~ 5.5 Mha (Gaveau et al. (2019)). –> different crs (crs not given), falsely classified to pulp wood as difficult to distinguish.

However, it would be too simple to blame this deforestation only to palm oil as the single driver as it remains unknown whether oil palm caused or simply followed deforestation (Fitzherbert et al., 2008). Companies use palm oil concessions to obtain permission to log, and thus make money, without cultivating palm oil on the land (Fitzherbert et al., 2008).

Even though plantation expansion has slowed, the recent large price jump (from US$601 per ton in 2019 to US$1276 in 2022) is a worrying indicator (World Bank, 2023). This 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.

5.4.2 Biodiversity

If the deforestation drivers are not addressed, biodiversity will continue to decline, as examined in a case study of the Borneo orangutan (Voigt et al. (2022)).

Our results show the importance of protecting forests from anthropogenic modifications. Protection of hyperdiverse tropical forests results in a positive feedback, since they reduce biological invasions, which will in turn safeguard native species richness and abundance, ensuring their continued ecosystem services (IPBES, 2019b). (Mungi et al., 2021)

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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?

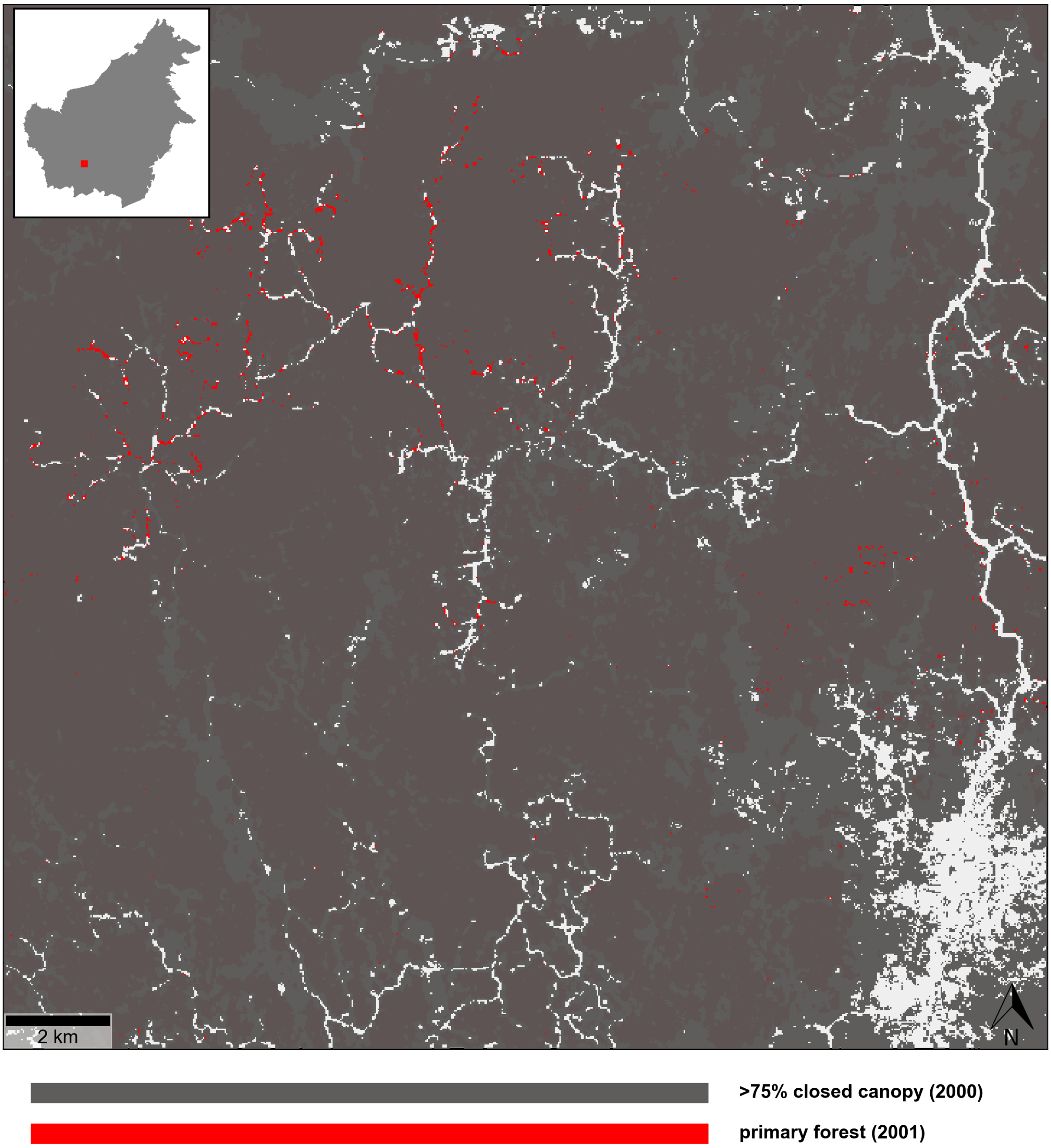
4.8 How much forest area was lost to cropland areas within 1, 2, 5, 10, and 20 km of newly buld up areas?

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

6 RSPO

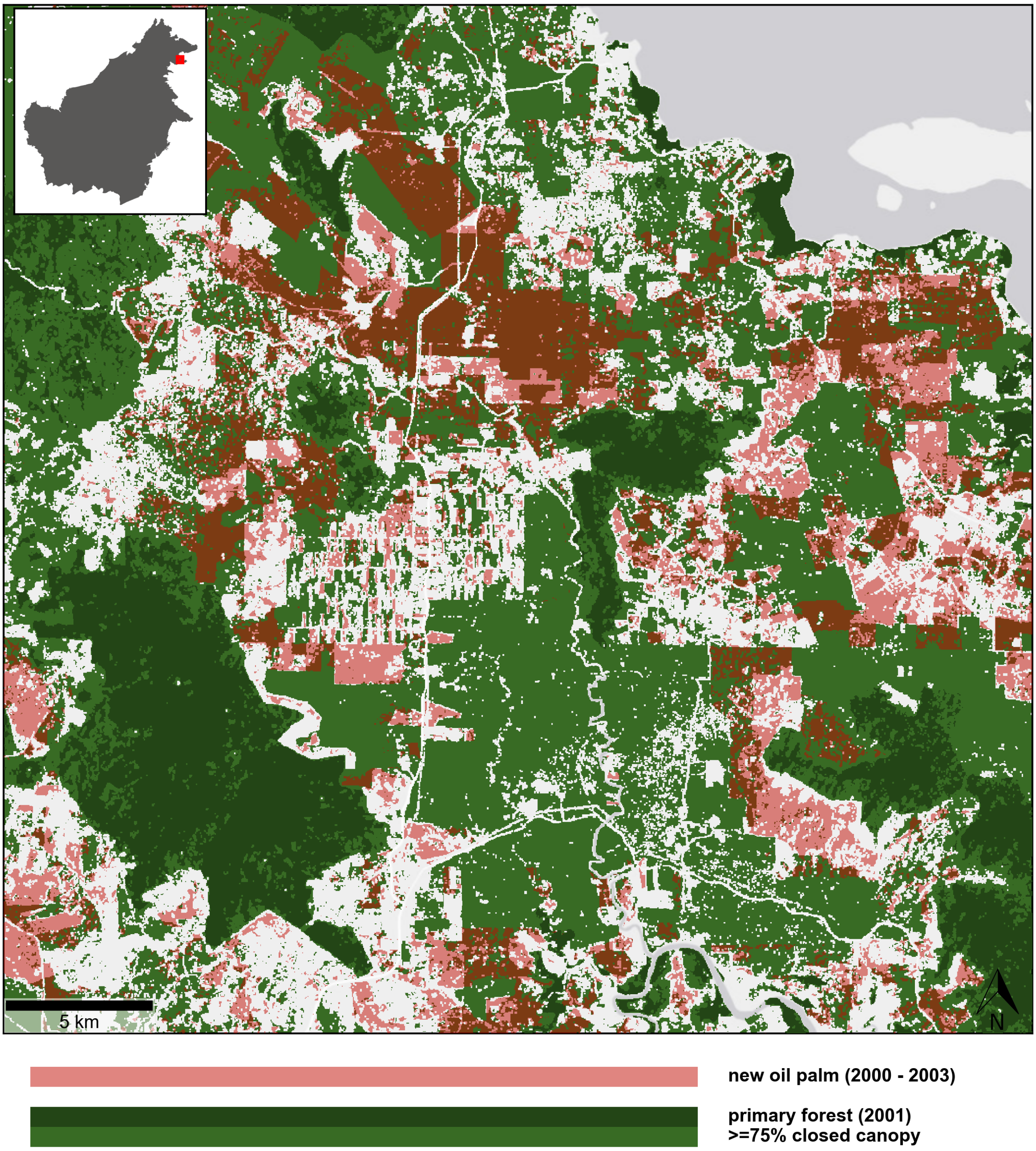
5.1 How much deforestation occurs within RSPO certified concessions?

II Overlap of 75% closed canopy and primary forest



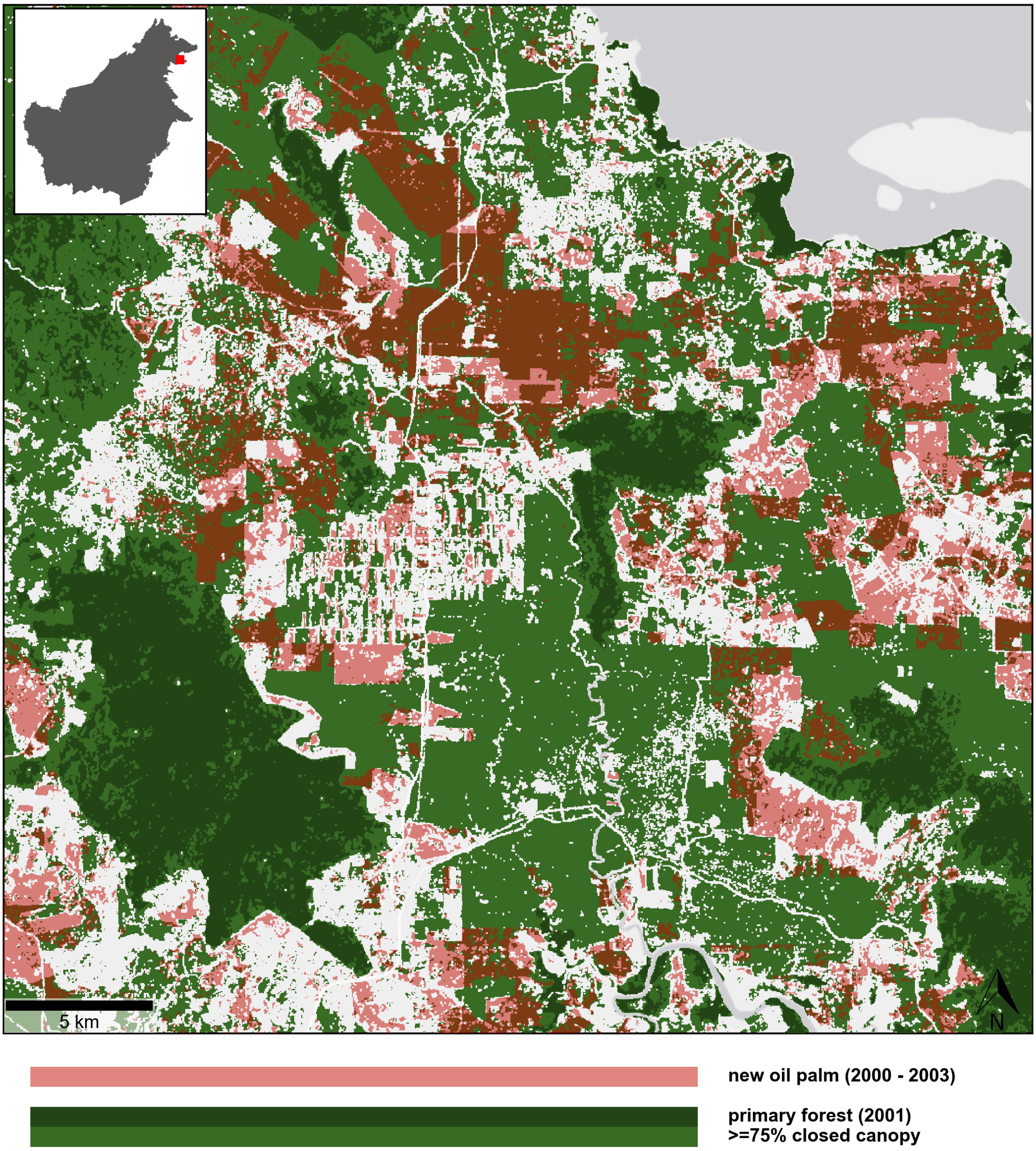
Representative map extract showing that >75% closed canopy of 2000 mostly covers the primary forest of 2001.

III Dense vegetation excluding primary forests



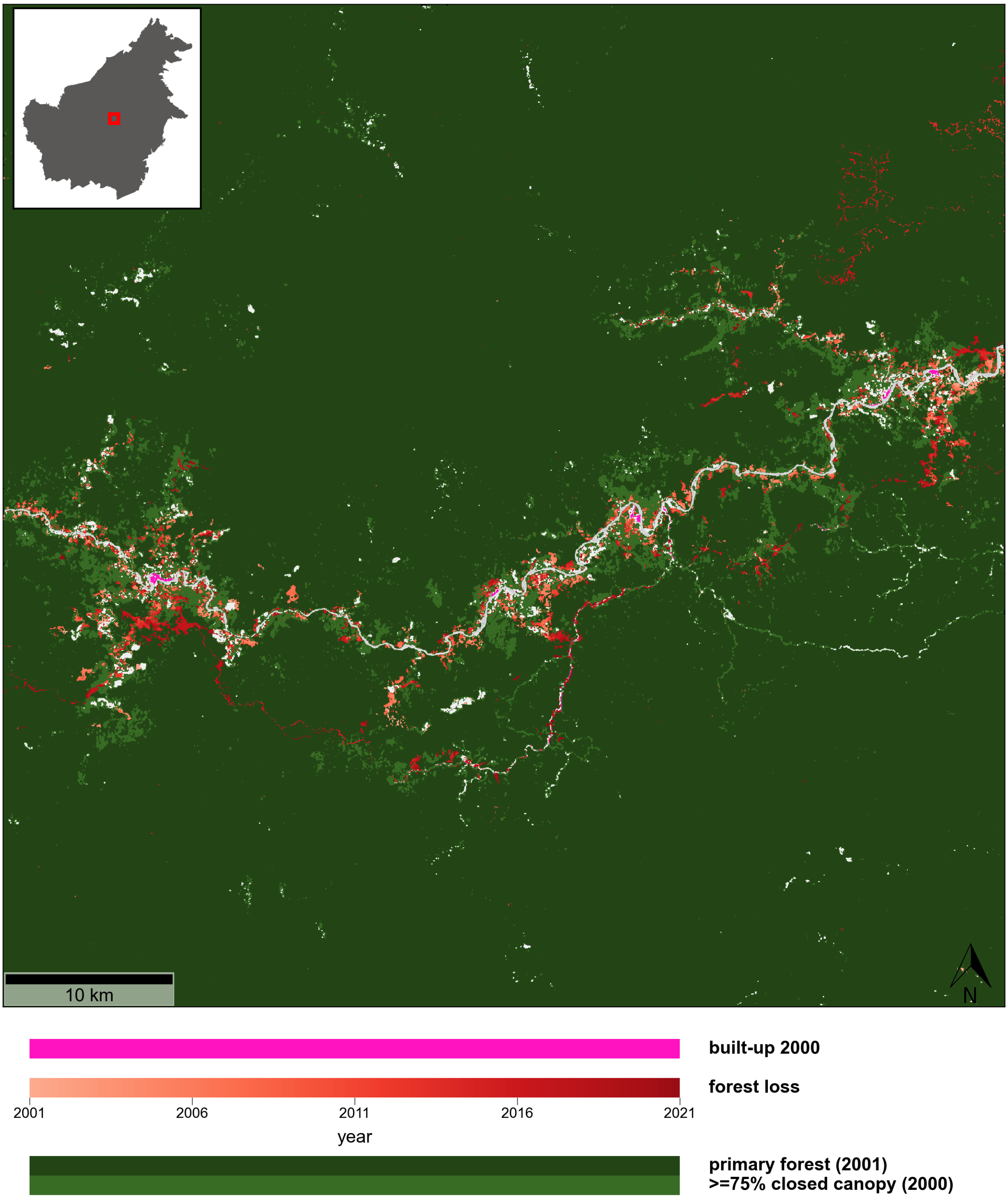
In the dense vegetation outside of primary forests, lage areas are occupied by oil palm. Oil palm data is limited to years 2000 - 2003 as growing oil palms could alread have a closed canopy of >75% in the year 2000.

IV Validation of built up areas in 2000 and deforestation



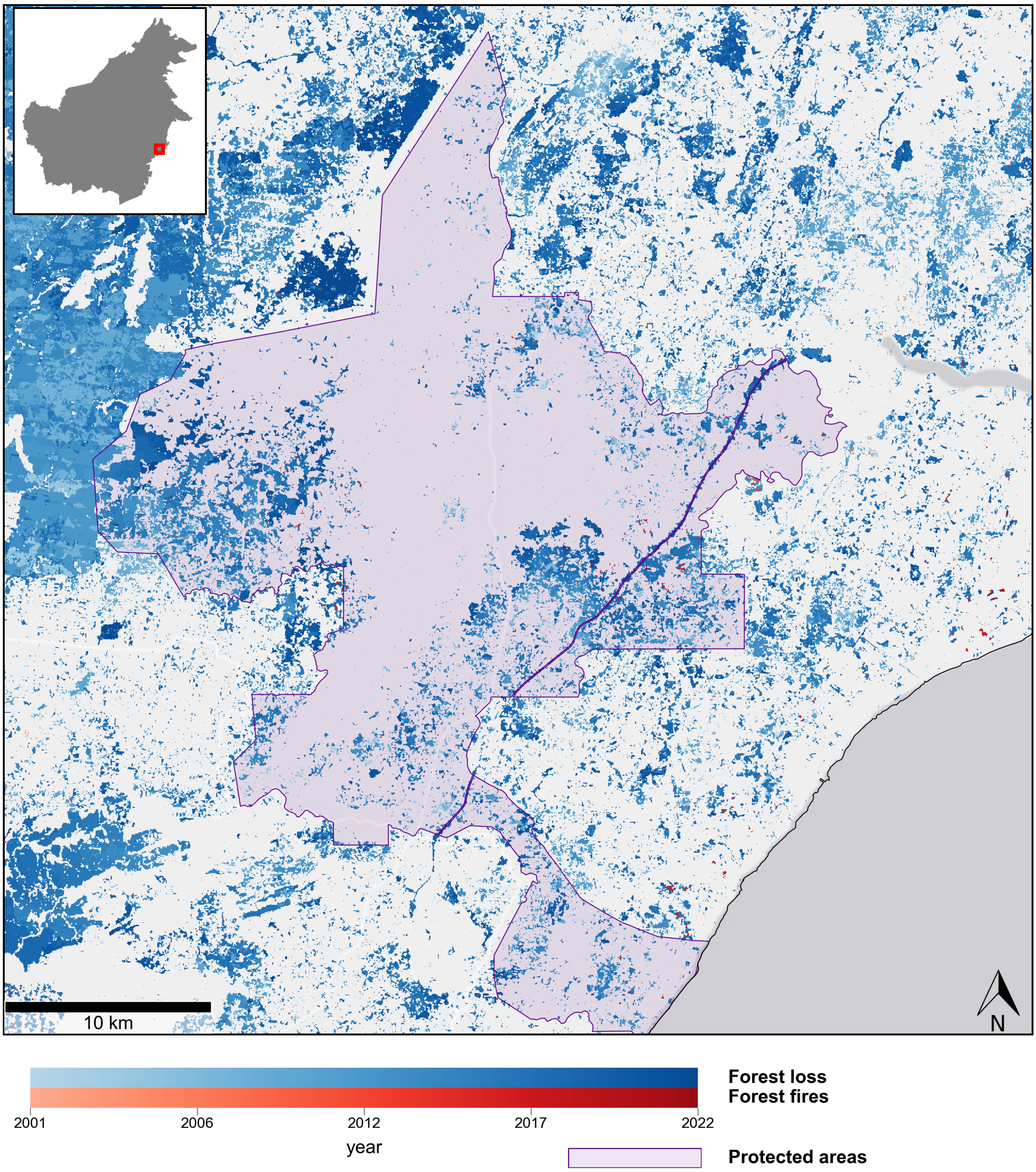
Example of deforestation on year 2000 built up area, where, logically, now deforestation should be. Here it is visible, that these areas are mainly located at the edge, where maintenance led to the removal of closeby trees, which were thus classifiead as forest loss.

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.

V Secondary Forest and proximity to rivers



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

X Plagiarism declaration

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

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