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Evaluation of different peatland management scenarios to reduce GHG emissions from fires. A case study in tropical peatlands in Ogan Komering Ilir, Indonesia

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In September 2015, I left my country to undertake a new experience on the other side of the world. The goal was to do a master's and doctoral program, to learn a new language and to get to know a new culture. Today, in 2020, I return to my country with the objective fulfilled, and with many more experiences that surprised me along the way. I want to thank all the people who made me feel at home and who made this experience much more enriching and welcoming for me.

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Extended abstract

Three percent of total land mass is covered by peatlands, predominately in boreal zones (83 %), followed by tropical (12.7 %) and temperate (4 %) zones. Of this, the 12.7% of tropical peatlands in South America constitute the largest area (46 %), followed by Asia (36 %) and Africa (18 %). This type of ecosystem in the tropics plays an important role as a carbon pool, storing approximately 350,000 Tg of carbon. In Southeast Asia, the carbon stored in peatlands is estimated at around 68,500 Tg.

Over the last decades, changes in land use and land management practices in forestry and agricultural plantations have led to a significant amount of carbon loss. On peatlands, land preparation for agricultural or pulpwood plantations requires drainage and fires in order to create proper conditions for more intensive agricultural uses. Cleaning fields with fire is a traditional practice used by migrant farmers, private companies and government agencies. During a peatland fire, the aboveground biomass is combusted, as is a layer of peat soil. Peat soil fires are usually characterized by smoldering combustion. Smoldering combustion implies a slow and persistent process, largely responsible for expanding fires. This type of combustion can continue to expand underground, vertically until it reaches the water table, or horizontally as residual smoldering combustion (RSC) after surface fires. Recent fires in Indonesian peatlands released a large amount of greenhouse gases (GHGs) into the atmosphere. These fires also affected the economy and the human health of the inhabitants of Indonesia and its neighboring countries. Among the most relevant episodes are the ones that occurred in 1997-98, 2006 and 2015, during the El Niño-Southern Oscillation event.

To address this problem of peat fires that affect Indonesia and its neighboring countries, the government adopted policies, regulations, technical innovations, developments in fire monitoring and incentives to improve land management. After the fire episode of 2015, the fire alerts decreased. However, despite these measures, the fires continue in the region. The main reasons why fires continue include the failure to apply policies and regulations, the lack of incentives, the lack of technical knowledge and information about not burning clear land, and cultural aspects (e.g., the traditional use of fire).

In this thesis, we evaluated different mitigation scenarios as an option to reduce fires, converting aboveground biomass into bioenergy or other bio-products instead of burning it and, at the same time, creating incentives for the local population.

The main three objectives of the thesis are: (i) to determine the greenhouse gas emissions associated with the current fires in agricultural and forest areas on tropical peatlands; (ii) to quantify avoided emissions of peat soil combustion and to evaluate the sustainability of alternative scenarios based on the use of aboveground biomass for bioenergy production and other by-products; and (iii) to identify socio-economic and political determinants to promote the use of biomass on peatlands for bioenergy production. These objectives are developed in four chapters.

In ***Chapter 1***, we propose a general equation to estimate GHG emissions from fires on peatlands. We used Monte Carlo simulation, meta-analyses, and an analytical expression of variance. The contribution of each parameter to the variance of the estimated GHG emissions was also evaluated. GHG emissions of a single fire episode were estimated at 842 Mg ha^{-1} CO_2-eq, with a standard deviation of 466 Mg ha^{-1} CO_2-eq. Our estimated GHG emissions were close to the amount estimated from the default values provided by the IPCC. The main parameters contributing to variance were: the depth of burn: 94.2 %; followed by bulk density: 5.5 %; and emission factors:

0.3 %. When the depth of burn was assessed by remote sensing, the main contributor to variance became the fire-damaged area, followed by the depth of burn. The contribution of each parameter to variance, as estimated in this study, made it possible to prioritize the effort in uncertainty reduction. Combining Monte Carlo simulation and an analytical expression of variance could be a promising way of obtaining more reliable confidence intervals.

Chapter 2 contains three parts. Part I presents the study area, Ogan Komering Ilir (OKI) and the context in which the assessments were carried out. I focused on the three major land uses on peat soils in OKI, which are also considered for their potential biomass for valorization: (i) degraded peatlands; (ii) oil palm plantations; and (iii) pulpwood plantations. Pulpwood plantations cover most of the plantation area.

In Part II, an analysis of the fire occurrence in OKI was carried out to estimate the GHG emissions from peat combustion for the three aforementioned land use types at the regional level for the period 2002-2018. The results showed that 70%, 45% and 76% of the pixels in degraded peatlands, oil palm plantations and pulpwood plantations, respectively, were affected by fires during the period 2002-2018. The total GHG emissions from peat soil combustion estimated for this period was $76x10^6$ Mg CO_2-eq for degraded peatlands, $36x10^6$ Mg CO_2-eq for oil palm plantations and $321x10^6$ Mg CO_2-eq for pulpwood plantations. Pulpwood plantations were the greatest contributor of GHG emissions in OKI due to the large area of the plantations in the study area, the highest percentage of pixels with fire occurrence and the largest fire-damaged area affected by pixels among the three land uses.

In Part III, a distance assessment for biomass transportation to five potential industry locations was performed. The objective was to estimate the influence of the distance of biomass transportation on the total GHG emissions calculated in Chapter 3, and the influence of the distance on transportation costs in Chapter 4. The distance assessment performed is based on the geodata of roads and waterways provided by recent studies in the same area. We found that waterways provided the widest access to the study zone. The average distance from any point to the nearest waterway was 49 km (min=0, max=233), whereas the average distance to the nearest road was 122 km (min=0, max=347). The average distance to the nearest road or waterway in the study area was 23 km (min=0, max=133). We noted that Palembang, Pedemaran and Secukai have access to both types of networks, which allows a greater access to biomass resources throughout the year. APP and Sungai Lumpur locations were limited to waterways. This assessment made it possible to identify the most distant areas, which were then evaluated in detail in the next chapters using different indicators.

In ***Chapter 3***, several mitigation scenarios of land management are analyzed to compare their global contribution to climate change in terms of CO_2-eq with business as usual (BAU) scenarios. For this purpose, three types of biomass corresponding to the three land uses analyzed in this study were considered for bioethanol production, combined heat and power generation and panel manufacturing. The five scenarios evaluated are: (1) BAU with fire occurrence; (2) BAU without fire occurrence; (3) prospective biomass valorization in drained conditions, (4) prospective biomass valorization in non-drained conditions; and (5) peatland restoration. The impact of each scenario for the three land uses considered in this study was estimated on the basis of life cycle assessment methodology. GHG emissions estimated for BAU with a fire occurrence scenario in degraded peatland, oil palm plantations and pulpwood plantations were 70.60±30, 139.40±31 and 159± Mg CO_2-eq ha^{-1} yr^{-1}, respectively. For BAU without a fire occurrence scenario in degraded peatland, oil palm plantations and pulpwood plantations, the GHG emissions were 18.45±12, 85.08±21 and

108.3±15 Mg CO_2-eq ha^{-1} yr^{-1}, respectively. Regarding the restoration scenario, the estimated GHG emissions were the same for the three land uses: -0.9 Mg CO_2-eq ha^{-1} yr^{-1}.

Regarding scenarios of biomass valorization with a functional unit of 1 hectare during a year (1hayr), in the case of degraded peatland, valorizing the biomass reduces the GHG emissions by about 74 % in drained conditions and 99 % in non-drained conditions, compared with BAU with a fire occurrence scenario. For oil palm plantations, valorizing the biomass reduces the GHG emissions by about 60 % in drained conditions compared with BAU with a fire occurrence scenario. In pulpwood plantations, the reduction for valorizing the biomass is about 40 % of GHG emissions in drained conditions compared with BAU with a fire occurrence scenario.

The scenarios in non-drained conditions significantly reduce the GHG emissions in comparison to BAU because they reduce the flux gases from peat oxidation and allow carbon sequestration in peat soil. However, scenarios in non-drained conditions are only considered for degraded peatland because waterlogging conditions are not adequate for oil palm and pulpwood cropping systems. The scenarios of biomass valorization in non-drained conditions are an example of paludiculture systems, where the plantations could be managed in waterlogging.

Regarding the carbon balance at the regional level, we predicted a reduction of the impact by 2-10 % of the GHG emissions for implementing biomass valorization. Biomass valorization is an option to decrease the haze from fires that have an impact on climate change as well as causing other kinds of problems such as health issues caused by fine particular matter ($PM_{2.5}$) or economic losses associated with the haze for land management with fires.

In ***Chapter 4***, we assessed the socio-economic factors for implementing mitigation scenarios in the three main land uses studied in this work for the OKI district. We focused on the factors that are critical for fire mitigation through biomass valorization. We compared different strategies toward potential reduction of GHG emissions and costs for the three main land uses. We computed the areas where the biomass market is feasible according to each potential factory location. We found that valorizing the biomass in the areas where the biomass market is feasible reduced GHG emissions by 4-6 %, compared with BAU in OKI. The rest of the biomass contained in the areas where the biomass market is not feasible cannot be valorized by the industry. Boosting the biomass market in the feasible areas identified in this study can reduce the GHG emissions without governmental investments in these areas. This makes it possible to prioritize government investments aimed at reducing GHG emissions from peatlands in areas where the biomass market is not feasible. In addition, the land management scenarios evaluated here can provide a new income for local populations that could take advantage of the biomass residues that are currently combusted on peatland.

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Introduction

1. Peatlands in the world

Three percent of total land mass is covered by peatlands, predominately in boreal (83 %) followed by tropical (12.7 %) and temperate (4 %) zones. The main areas in boreal and temperate zones are in Canada, the British Isles, Fennoscandia, the Baltic States and Russia (Leifeld & Menichetti, 2018). In tropical zones, South America constitutes the largest area of tropical peatlands (46 %), followed by Asia (36 %) and Africa (18 %) (Gumbricht et al., 2017).

Peatlands are included in the wetlands classification defined by the Ramsar Convention on Wetlands. Ramsar (2016) defines wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters". Peatland refers to the area where peat accumulates at the surface with or without vegetation (Biancalani & Avagyan, 2014; Joosten & Clarke, 2002).

According to the international soil classification (IUSS Working Group WRB, 2015), peat soils belong to the "histosols" or "organic soil" classes. Soils are qualified as such when dead organic matter accounts for at least 30 % of their dry mass (FAO, 1998), in addition to high water saturation levels and low levels of oxygen (Biancalani & Avagyan, 2014; FAO, 1998). Peat soils have high carbon contents, 55 % on average in the tropical zones (Hu et al., 2018; Konecny et al., 2016; Limin et al., 2004; Page et al., 2011) and 47% in the boreal zones (Cancellieri et al., 2012; Hatch et al., 2015; Hu et al., 2018).

The main ecosystem services provided by peatlands are carbon storage, climate regulation and water regulation (Kimmel & Mander, 2010). Peat areas are also used for installing agriculture, horticulture and forestry plantations.

2. Peat formation and carbon dynamics

Peat formation is a very slow process resulting from the fact that net primary production is higher than the decomposition rate (Chimner & Ewel, 2005; Joosten et al., 2012). The biomass can come from grasses, shrubs, crops or any type of vegetation that grows in these areas. Peat formation also requires waterlogging, which leads to the anaerobic conditions responsible for the slow decomposition (Page et al., 2004; Ritzema & Wösten, 2006).

The peat system is composed of two layers. The upper layer, known as the acrotelm, corresponds to the 10-75 cm aerobic layer with high hydraulic conductivity (Clymo, 1984; Ingram, 1978; Lindsay et al., 2010). The second layer, underneath, is older and usually several meters deep. It is known as the catotelm and usually presents anaerobic conditions and low hydraulic conductivity (Clymo, 1984; Ingram, 1978). The acrotelm is composed of living plant material, bacteria, microorganisms and dead organic matter. The catotelm is an inert carbon accumulation layer, fed by the acrotelm layer, where the biomass decomposition rate is lower than in the upper layer (Lindsay et al., 2010).

Plant parts with high lignin content accumulate in the acrotelm and contribute to peat formation (Parish et al., 2008). Leaves are almost always decomposed, even in anaerobic conditions (Gomez & Yule, 2009), and the roots and thick stems are the greatest contributors to peat formation in the tropics (Brady, 2004; Chimner & Ewel, 2005; Hoyos-Santillan et al., 2015). Organic matter accumulation in the acrotelm layer is a key condition for peat formation and accumulation in the catotelm layer. However, in waterlogging conditions, even without any input of organic matter, the peat layer is preserved from decomposition. In aerobic conditions, for example, when the water table lowers due to drainage or climatic phenomena such as the El Niño-Southern Oscillation (ENSO) event, the carbon stored in peat soil is released into the atmosphere by peat oxidation. Under conditions of water saturation and low oxygen, carbon is mostly emitted as methane (CH_4) (Bridgham et al., 2013; Eggleston et al., 2006). This process is known as heterotrophic respiration and only involves the microbial decomposition of soil organic matter (Matysek et al., 2018).

This type of ecosystem in the tropics is a major carbon pool (Leng et al., 2019), storing approximately 350,000 Tg of C (Gumbricht et al., 2017). In Southeast Asia, the carbon stored in peatlands is estimated at around 68,500 Tg of C (Page et al., 2011).

3. Management issue in Southeast Asian peatlands

Over the last decades, the forest cover in Southeast Asian peatlands has decreased by around 42% due to land use change (Miettinen & Liew, 2010). These land use changes release a significant amount of carbon into the atmosphere due to peat oxidation. The peat subsidence in oil palm (*Elaeis sp.*) and acacia (*Acacia mangium*) plantations is estimated to be approximately -4 and -5 cm yr^{-1}, which is explained by the water table level (Evans et al., 2019; Khasanah & van Noordwijk, 2019). One of the reasons for these land use changes is the increasing demand for palm oil and pulpwood that has led to an increase in planting areas (Fig. 1). Today, in South Sumatra, approximately 60 % of the land cover on peatlands consists of oil palm and pulpwood plantations, with a majority of industrial plantations (Miettinen et al., 2016).

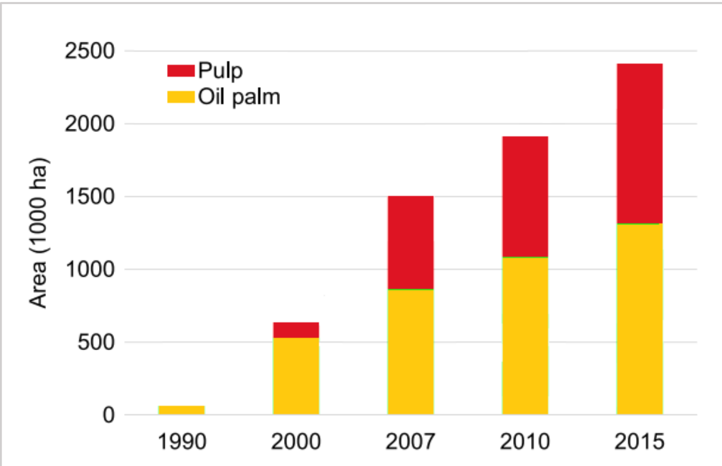

Figure 1. Expansion of industrial plantations in the peatlands of Sumatra. Adapted from Miettinen et al. (2016).

On peatlands, land preparation for agriculture or forestry plantations requires drainage and fire in order to create proper conditions for more intensive agricultural uses (Farmer et al., 2011).

Cleaning fields with fire is a traditional practice used by migrant farmers, private companies and government agencies (Page et al., 2002). Land clearing is the major cause of fire but fires can also result from land tenure, resource extraction, hunting or by accident (Applegate et al., 2001).

Peat soil fires are usually characterized by smoldering combustion. Smoldering combustion implies a slow and persistent process, largely responsible for expanding fires (Huang & Rein, 2018). This type of combustion can keep expanding underground, vertically until it reaches the water table, or horizontally as residual smoldering combustion (RSC) after surface fires (Akagi et al., 2011; Bertschi et al., 2003; Usup et al., 2004). Smoldering combustion can spread for days or months, and if not stopped it can even reignite the fire in the next dry season (Huang & Rein, 2018). Although the moisture content slows down its propagation, the fire can continue drying peat soil layers and spreading through them below the ground surface, even at a 200% moisture content (Prat et al., 2013). Due to the fire behavior and high carbon content of peat soil, around 70% of total carbon emissions come from the burning of peat soil. The remaining 30% come from aboveground biomass burning (Page et al., 2002; Van der Werf et al., 2010).

Recent fire episodes in Indonesian peatlands released large amounts of GreenHouse Gases (GHGs) into the atmosphere. These fires also affect the economy and human health of the inhabitants of Indonesia and its neighboring countries. Among the most relevant are the fire episodes that occurred in 1997-98, 2006 and 2015, during ENSO events (Fig. 2) (Huijnen et al., 2016). To illustrate the magnitude of these fire episodes influenced by ENSO events, in 1997-98, fires affected an area of between 1 and 7 million hectares, including large areas of peat bogs in Sumatra, Indonesia, representing between 13% and 40% of global anthropogenic carbon emissions from fossil fuel (Page et al., 2002).

The haze produced during fires and RSC causes air pollution at levels harmful to humans (Hansson & Dargusch, 2017). In addition to carbon, the smoke contains sulfur, benzene, methylene chloride, nitrogen oxides, particulates, volatile organic compounds and other components, prevailing particulate matter PM2.5, as well as PM10 and PM1 (Blake et al., 2009). These compounds are highly irritating and some are carcinogenic. It is estimated that they caused 100,000 premature deaths in Indonesia, Malaysia, and Singapore during 2015 and cost the Indonesian economy some US$16.1 billion (World Resources Institute, 2016; Hansson & Dargusch, 2017).

4. Peatland policies in Indonesia

After the 2015 fire episode, Indonesian President Joko Widodo declared a national state of emergency for fires. The same year, Indonesia made a commitment to the United Nations Framework Convention on Climate Change (UNFCCC) to reduce its GHG emissions by 29% by 2030 and ratified the target in the Paris Agreement in November 2016 (Wijaya et al., 2017). The five priority sectors considered by the government for the reduction of GHG emissions are: forestry and peatlands, agriculture, energy and transportation, industry and waste. This PhD mainly focuses on peatland fires in Indonesia, involving priority sectors such as agriculture and energy and their relationships with peatlands.

In an attempt to address this issue of Indonesian peatland fires, which affects the entire region, the government adopted the Fire Management Interventions (FMI) program that includes policies, regulations, technical innovations and developments in fire monitoring, as well as incentives for improved land management (Carmenta et al., 2017). FMI are supported by the intergovernmental Association of Southeast Asian Nations (ASEAN), through the Agreement on Transboundary Haze Pollution, Peatland Management Strategy, Sustainable Use of Peatland and Haze Mitigation programs, among others (ASEAN, 2019; Sunchindah, 2015). In addition to these programs, in 1999, the ASEAN Ministers of Environment adopted the “Zero-burning” policy to be applied to agricultural and forestry plantations with the aim of avoiding transboundary haze pollution (Secretariat, 2003). Several techniques of “Zero burning” were implemented, mostly in oil palm plantations.

Regarding the Indonesian peatland policies and regulations, the four main peatland government regulations are: (1) control of natural damage and/or pollution related to land and forest fires; (2) guidance for the utilization of peatland for oil palm cultivation; (3) improvement of governance of natural primary forest and peatland; and (4) protection and management of peatland ecosystems (Uda et al., 2018).

In 2016, the Indonesian president created the Peat Restoration Agency (Badan Restorasi Gambut; BRG) with the objective of restoring 2.1 million hectares of peatlands by 2020, with a priority on those burned in the fire episode of 2015 (CIFOR, 2016). In the same year, the president issued Presidential Decree No. 9/2016 on the acceleration of the implementation of One Map. One Map is a tool for identifying overlapping licenses of forest concessions, industrial forest plantations and mining areas with protected natural forests in order to avoid land tenure conflicts, especially due to the use of fire as a means of land clearing (Shahab, 2016).

Municipal governments have been working with non-governmental organizations (NGOs) and academic researchers to comply with these regulations. Mainly, they attempt to implement zero-burning techniques, peatland restoration, water table monitoring and responsible oil palm plantation such as the Roundtable on Sustainable Palm Oil (RSPO), and to plan possible paludiculture programs (e.g., Indonesia Wetlands International, WWF Central Kalimantan, Walhi, WARSI-Jambi, FFA, etc.) (Uda et al., 2018). For example, the NGO "Free Fires Alliance" (FFA) has been working since 2016 with incentive programs that have proven themselves to be successful, e.g., "No burn village rewards" that are awarded at the end of the dry season: IDR 100 mill for a burnt area of less than 1 ha, and IDR[1] 50 mill for a burnt area of less than 10 ha (FFA, 2016). After the fire episode of 2015, the alerts decreased, in part thanks to the policies, regulations and efforts of the NGOs and the communities involved. However, the fire alerts continue in the region and underwent a major increase in 2019, aggravated by a very dry season (Fig. 2).

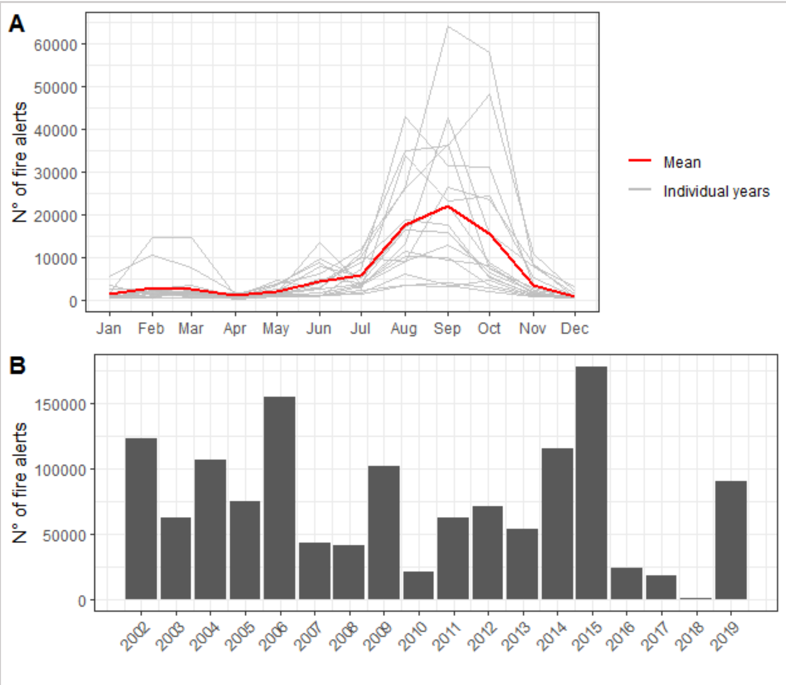

Figure 2. Number of fire alerts for the period from June 2002 to December 2019. Data source from Aqua-Terra satellites, NASA. (A) Fire alerts per year for the period from June 2002 to February 2020, and the mean of fire alerts for the same period. (B) Mean of fire alerts per year.

[1] IDR: Indonesian Rupiah

The main reasons why fires continue were a failure to apply policies and regulations, the lack of technical knowledge and information about not burning clear land, cultural aspects, e.g., traditional use of fire, and lack of incentives (Carmenta et al., 2017; Tacconi, 2016; Uda et al., 2018).

5. Current state of renewable energy in Indonesia

Providing electricity in an archipelago of 17,000 islands is technically challenging. Nevertheless, in 2014, Indonesia had access to electricity over 84 % of its territory (Asian Development Bank, 2016). This proportion increased to 95.35 % in 2017 (PwC Indonesia, 2018). The area with the least access to electricity corresponds to the southeast part of Indonesia. In 2017, the power capacity was 60.7 GW, 57.2 % of which comes from coal, 24.8 % from gas, 5.8 % from oil and 12.5 % from renewable energy. Among renewable energy sources, hydropower and geothermal are the main renewable energy sources, contributing 7.3 % and 5 %, respectively, to the total renewable energy. The rest (0.2 %) comes from bioenergy and solar. However, the 2018 Price Waterhouse and Coopers (PwC) Indonesia report estimated a bioenergy potential of 32.6 GW that can be harnessed.

Regarding energy policies, the “State-owned electricity company” (PLN) plans to increase the renewable energy share to 23 % by 2025 and 31 % by 2050. This increase would involve raising the current energy shares by 10 % for bioenergy, 7 % for geothermal, 3 % for hydropower and 3 % for other new and renewable energies. In order to encourage the public and private sectors to implement new projects on renewable energy, the government has established fiscal incentives such as a reduction in taxable income, an extended tax loss, accelerated depreciation and amortization rates, and exemption for imports via import parity prices involved in renewable energy (PwC Indonesia, 2018).

6. Research positioning and objectives

Economic development in poor or developing countries denotes, in the majority of cases, the exploitation of natural resources to the point of threatening environmental sustainability (Purvis et al., 2019). This disproportionate economic development has led to social and environmental issues. This has engendered concepts such as ‘eco-development’ (CIDA, 1979) or ‘sustainability development’ (WCED, 1987), with the objective to find a fair “balance between the economic and social systems and ecological conditions”. This is also known as the “three pillars” or the “triangle of sustainability” (Keiner, 2005). In this thesis, I evaluated the business as usual peatland management in Ogan Komering Ilir (OKI) and then compared it with other scenarios that propose to continue economic activities on peatlands but that implement practices that would make it possible to find an environmental balance.

The French Agricultural Research Centre for International Development (CIRAD) contributed to the creation of the “Center of Excellence” (COE) project, together with Airbus Malaysia, the Aerospace Malaysia Innovation Centre (AMIC), the UPM (Universiti Putra Malaysia) and the Malaysian Industry-Government Group for High Technology (MIGHT). The objective of the COE is to carry out a bio-jetfuel project based on the use of agricultural residues to reduce fossil fuel consumption. CIRAD has been working on biomass recovery in Malaysia and Indonesia for bio-jetfuel production, as well as transportation and cost scenarios concerning biomass.

Within the framework of the COE and taking the issue of fire haze in Indonesia into account, biomass valorization has been suggested as an option to reduce fire occurrences and to convert aboveground biomass into bioenergy or other bio-products instead of burning it.

In accordance with this and focusing on the reduction of fires, we defined the following objectives of the thesis:

1. Determine the greenhouse gas emissions associated with the current fires in agricultural and forest areas on tropical peatlands.

2. Quantify avoided emissions of peat soil combustion and evaluate the feasibility and sustainability of alternative scenarios based on the use of aboveground biomass for bioenergy production and other bio-products.

3. Identify socio-economic and political determinants to promote the implementation of different mitigation scenarios in OKI.

7. Thesis overview

My thesis project is developed in four main chapters (Fig. 3):

Chapter 1: Greenhouse gas emissions from peat soil combustion in wildfires on Indonesian peatlands

Chapter 2: General assessments

Chapter 3: Life cycle greenhouse gas emissions of different land use management scenarios in OKI

Chapter 4: Socio-economic assessment of emission mitigation scenarios in OKI

In ***Chapter 1***, I focused on the main problem that motivated this thesis: the fires in tropical peatlands. This chapter provides a perspective of the current situation in Southeast Asian peatlands and an estimate of the GHG emissions from peat soil combusted in wildfires in terms of CO_2-eq ha^{-1}.

Given that fires are a local problem but have an impact at a larger scale, i.e., transboundary haze in Southeast Asia and a direct impact on climate change, we analyzed, from Chapter 2 onwards, different land management scenarios through a case study at Ogan Komering Ilir (OKI). ***Chapter 2*** provides the basic information and the parameters used throughout the thesis to develop the different scenarios of land management on peatlands in OKI. Specifically, Part I presents the study area, and Part II provides an estimate of the GHG emissions resulting from peat combustion related to fire activity for the whole study area. This estimate was a prerequisite for Chapter 3 in which it stands for a “Business as usual” scenario in comparisons with different mitigation scenarios. Finally, in Part III, an assessment of the distance related to biomass transportation was performed, assuming different factory locations. This assessment was also used to evaluate the impact of biomass transportation in terms of GHG emissions in Chapter 3 and the transportation cost of biomass to the factories in Chapter 4.

In keeping with this, in ***Chapter 3,*** I estimated the GHG emissions of the business as usual and mitigation scenarios in OKI. The mitigation scenarios are based on different land use management scenarios where potential biomass valorization is evaluated as an alternative to cleaning peatlands with fires. The impact of each scenario was estimated in terms of CO_2 equivalent.

Finally, in ***Chapter 4,*** I assessed the socio-economic factors for implementing mitigation scenarios in the three main land uses investigated in this study for the OKI district. Different strategies for the potential reduction of GHG emissions and costs were compared for the three main land uses. The main parameters were fire occurrence, potential biomass and transportation costs.

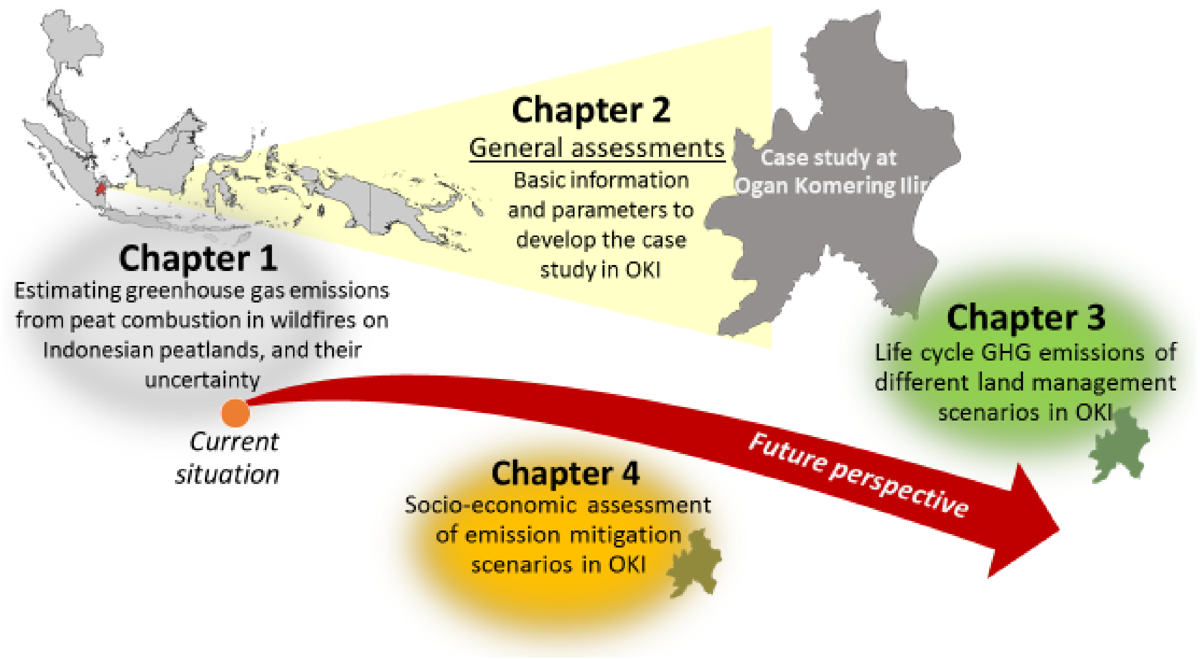

Figure 3. Overview of the thesis.

Chapter 1

Estimating greenhouse gas emissions from peat combustion in wildfires on Indonesian peatlands, and their uncertainty

Scope of Chapter 1.

In Chapter 1, we focused in the central issue that motivated this thesis: wildfires in peatlands. This chapter offers a perspective of the current situation in Southeast Asian peatlands and provides an estimate of the impact on climate change of the peat soil combusted in wildfires in terms of CO_2-eq. The uncertainty and the contribution of each parameter involved in the estimation are provided. This estimate is used in the following chapters to establish the business as usual scenarios and to then compare them with the other land management scenarios proposed.

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1. Introduction

Since 1982, the peatlands of Southeast Asia have suffered from depletion due to economic pressure and the demand for natural resources, often caused by fires on forest and agricultural land. The rate of land use change in Indonesia has been increasing due to pulpwood plantations and agriculture, mainly for oil palm plantations (Evers et al., 2016; Miettinen et al., 2016; Padfield et al., 2019).

On peatlands, land preparation for agriculture or pulpwood plantations requires drainage in order to create proper conditions for more intensive agricultural uses (Farmer et al., 2011). When the peatland is drained, the carbon stored in peat soil is released into the atmosphere by peat oxidation under aerobic conditions. Besides the emissions from drainage, another way for the carbon of peatlands to enter the atmosphere is through fires. Around 70 % of total carbon emissions following peatland fires come from the burning of peat soil, while the remaining 30 % come from aboveground biomass burning (Page et al., 2002; Van der Werf et al., 2010).

Fires in Indonesian peatlands can have an important impact on climate change because of the large amount of GreenHouse Gases (GHGs) they released in the atmosphere. These fires also affect the economy and human health of the inhabitants of Indonesia and neighboring countries. Important fire episodes in Indonesian peatlands occurred in 1997-98 and 2015, both during the ENSO event (Huijnen et al., 2016). During the episode of 1997-98, fires affected an area between 1 and 7 million hectares, including large areas of peat bogs in Sumatra, Indonesia, representing between 13 % and 40 % of global anthropogenic carbon emissions estimated for 1998 (Page et al., 2002).

The impact of peatland fires in terms of carbon emissions has been addressed in many studies (Ballhorn et al., 2009; Konecny et al., 2016; Page et al., 2002; Van der Werf et al., 2010). While estimated carbon emissions vary greatly across the different fire episodes, there is a constant in these studies: the estimates are all subject to large uncertainties. There are actually many parameters involved in estimating carbon emissions and the uncertainty surrounding each one of them is not well known. In many studies, the authors had to rely on the best guess when it came to estimating the uncertainty related to certain parameters. Moreover, when those studies provided uncertainty in the estimated carbon emissions, it remained unclear as to which parameter induced the greatest share of uncertainty.

The IPCC guidelines (Hiraishi et al., 2014) provide a general equation to estimate the impact of peatland fires in terms of GHG emissions, as well as default values for the mass of fuel available for combustion. However, the appraisal of each parameter is rarely provided. The mean and the variance of the parameters change, even within the same geographical area, with the values sometimes being very different. This variability is conditioned by factors such as the fire episode, land use and water table level (Heil et al., 2007).

In this study, we conducted a literature review on GHG emissions from peatland wildfires in Southeast Asia, and a meta-analysis on the parameters used to estimate their impact on climate change in terms of CO_2 equivalent. Using CO_2 equivalent made it possible to consider the combined global warming potential of different GHG in the atmosphere and to compare the relative contributions of GHG (Myhre et al., 2013). The objectives were to 1) define a general equation to estimate GHG emissions, 2) define default values for its parameters based on what is currently known of the different fire episodes and 3) evaluate the individual contributions of those parameters to the uncertainty of estimated GHG emissions.

Two approaches were taken to estimate GHG emissions and evaluate the uncertainty related to that estimate. The first was a “retrospective” approach and the second was a “prospective” approach.

The retrospective approach assumed that the fire episode has already occurred and that some parameters were already available. The prospective approach consisted of obtaining more accurate default values and providing recommendations for the use of certain parameters when estimating GHG emissions during future fire episodes.

2. Materials and Methods

2.1 Estimating the impact of peatland wildfires on climate change

In the literature, the impact of peatland wildfires on climate change is estimated through two indicators: GHG emissions and carbon loss. The first seeks to quantify GHG emissions and is described in the IPCC guidelines (Hiraishi et al., 2014). It can be expressed as follows:

$$L_{fire} = A \times M_B \times C_f \times G_{ef} \times 10^{-3} \qquad (1\text{-}1)$$

where L_{fire} is the emission of a particular GHG (Mg), A is the total fire-damaged area (ha), M_B is the mass of fuel available for combustion (Mg ha^{-1}), C_f is a dimensionless combustion factor, and G_{ef} is the emission factor of that particular GHG (kg Mg^{-1} of dry matter burnt). Note that the 10^{-3} factor ensures proper unit conversion. The total GHG emissions are then estimated by summing the L_{fire} of the individual GHGs after their conversion into CO_2 equivalent through their respective Global Warming Potential (GWP).

The second method focuses on carbon losses only (Ballhorn et al., 2009; Boehm et al., 2001; Page et al., 2002). It can be expressed through the following equation:

$$\mathrm{C_{loss}} = \mathrm{A \times P \times BD \times CC} \times 10^{4} \qquad (1\text{-}2)$$

where C_{loss} is emitted carbon (Mg), A is the total fire-damaged area (ha), P is the average depth of burn (m), BD is the average bulk density of peat soil (Mg m^{-3}) and CC is the average carbon content of peat soil (Mg of C per Mg of peat soil). Again, the 10^4 factor ensures proper unit conversion.
Eq. 1-1 and 1-2 have different purposes and therefore different expressions. However, the quantification of GHG emissions in Eq. 1-1 is more appropriate than the quantification of carbon losses in Eq. 1-2 to estimate an impact on climate change, since it takes into account different forms of carbon emissions (CO_2, CO, CH_4) and other GHG emissions (N_2O, NO_x).

Apart from these considerations of carbon forms and other GHGs, Eq. 1-1 and 1-2 also differ in the way they estimate the amount of burned peat. According to Eq. 1-1, the amount of GHG is considered as proportional to the product of the mass of fuel (M_B) by a combustion factor (C_f). The mass of fuel is "determined by measuring the depth of burn, along with soil bulk density and carbon content" (Hiraishi et al., 2014). These guidelines also specify that under the Tier 1 approach, "the default combustion factor [Cf] is 1.0, which implies that all fuel is combusted (Yokelson et al., 1997)" (Hiraishi et al., 2014). In Eq. 1-2, the amount of burned peat is proportional to the product of the depth of burn by the bulk density. As a matter of fact, Eq. 1-2 can be considered as an elementary expression of Eq. 1-1 under the Tier 1 approach.

In this study, we standardized Eq. 1-1 and 1-2 in order to obtain a more comprehensive estimate of the impact of peat wildfires on climate change. We then chose to quantify GHG emissions as in Eq. 1-1, and to use the elementary structure of Eq. 1-2 to estimate the amount of burned peat, in order to be explicit in the parameters used. As for Eq.1-1, we adopted the emission factor G_{ef}, where the carbon content is included. Lastly, we explicitly added the GWP of each gas and the sum of the contributions of all GHGs to express the impact on climate change in terms of CO_2 equivalent. The resulting equation is given below:

$$E_{fire} = A \times P \times BD \times \sum_i (G_{ef,i} \times GWP_i) \times 10 \qquad (1\text{-}3)$$

where E_{fire} is the amount of GHG emissions (Mg of CO_2-eq), A is the total fire-damaged area (ha), P is the average depth of burn (m), BD is the average bulk density of peat soil (Mg m^{-3}), G_{ef} is the average emission factor for each gas (kg Mg^{-1}dry matter burnt) and GWP is the global warming potential for each gas (Mg CO_2-eq/Mg of gas). All the estimates of GHG emissions in this study were obtained using Eq. 1-3.

2.2 Data collection

In order to make Eq. 1-3 useable, its parameters needed to be estimated. We gathered studies related to the depth of burn of recent fire episodes, the bulk density of peat soil and CO_2, CO, CH_4 and NO_x emission factors from the existing literature. Their results were assembled into datasets, which were then analyzed using a meta-analysis approach. This approach has been widely used in many fields of study (Cooper et al., 2019; Gurevitch et al., 2018) and allows for more accurate parameter estimates. The models behind the different meta-analyses that we carried out are detailed in the Meta-analyses section.

Different studies provided the average depth of burn for some fire episodes, through either remote sensing or post-fire field measurements. We managed to retrieve seven of these (Table 1-1). The majority of the studies were conducted in Central Kalimantan during fire episodes that occurred between 1997 and 2011, with the exception of Simpson et al. (2016), who carried out their study in Sumatra.

Table 1-1. Collected data for the estimation of depth of burn.

Author	Sample size	Fire episode	Number of fires	Fire-damaged area (ha)	Depth of burn (m)
Page et al. (2002)	43	1997	1	729 500	0.51
Ballhorn et al. (2009)	41	2006	1	256 783	0.33
CIMTROP in Ballhorn et al. (2009)	40	2006	1	n/a(ii)	0.30
Simpson et al. (2016)	5305	2015	1	5.2	0.23
Boehm et al. (2001)	100	1997	1	796906	0.40
Konecny et al. (2016)	16016	1997-2011(i)	1-8	100 000	0.17
Limin et al. (2004)	108	2002	1	79 609	0.21

(i)Corresponds to fire episodes in 1997, 2001, 2002, 2004, 2005, 2006, 2009 and 2011
(ii)n/a: not available

For average bulk density (BD), we found 22 estimates in seven studies from Central Kalimantan, Riau and Jambi in Indonesia, as well as one study from Sarawak, Malaysia (Table 1-2). The area description provided in each publication was used to classify each measurement according to a land cover class. However, the limited information found in the publications and the discrepancies in land cover terminology only allowed to distinguish two classes: disturbed and undisturbed. We classified as disturbed all the study areas that were described as shrubs and ferns, drained, burned, degraded land or agricultural plantations. Likewise, the study areas that were characterized by low drainage, unburnt, forested locations or tropical peat swamp forest were classified as undisturbed, as shown in Table 1-2. For studies that provided information about the density of the soil profile, we used only the data for the first 85 cm, because our emphasis was on the potential depth of burn (see Depth of burn in the Meta-analyses section).

Table 1-2. Collected data for estimation of the bulk density of a tropical peat soil

Author	Sample size	Type	Classification	Depth (cm)	Bulk density (Mg m^{-3})
Page et al. (2004)	13	Peat swamp forest	Undisturbed	0-90	0.076
Page et al. (2011)	1	Peat swamp forest	Undisturbed	_	0.090
Saharjo and Nuhayati (2005)	3	Shrubs and ferns	Disturbed	0-20	0.200
Konecny et al. (2016)	48	Low drainage, unburnt, forested locations	Undisturbed	10-40	0.117
Konecny et al. (2016)	60	High-drainage forest	Disturbed	10-40	0.125
Melling et al. (2012)	2	Oil Palm plantation	Disturbed	0-50	0.230
Melling et al. (2012)	2	Tropical PSF	Undisturbed	0-50	0.110
Melling et al. (2012)	2	Logged PSF	Disturbed	0-50	0.110
Könönen et al. (2015)	3	Undrained forest	Undisturbed	10-15	0.130
Könönen et al. (2015)	3	Undrained forest	Undisturbed	40-45	0.140
Könönen et al. (2015)	3	Undrained forest	Undisturbed	80-85	0.150
Könönen et al. (2015)	3	Drained forest	Disturbed	10-15	0.170
Könönen et al. (2015)	3	Drained forest	Disturbed	40-45	0.220
Könönen et al. (2015)	3	Drained forest	Disturbed	80-85	0.150
Könönen et al. (2015)	3	Degraded open peatland	Disturbed	10-15	0.200
Könönen et al. (2015)	3	Degraded open peatland	Disturbed	40-45	0.120
Könönen et al. (2015)	3	Degraded open peatland	Disturbed	80-85	0.140
Könönen et al. (2015)	3	Agricultural open peatland	Disturbed	10-15	0.180
Könönen et al. (2015)	3	Agricultural open peatland	Disturbed	40-45	0.170
Könönen et al. (2015)	3	Agricultural open peatland	Disturbed	80-85	0.130
Husnain et al. (2014)	35	Oil palm	Disturbed	0-20	0.150
Husnain et al. (2014)	72	Oil palm	Disturbed	0-20	0.210

Four gases were considered for emission factors (G_{ef}): carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) and nitrogen oxides (NO_x). We gathered the estimates from four studies (Table 1-3). Stockwell et al. (2016) estimated an average emission factor for each gas. However, the authors provided their data, so we were able to use their observations instead of their estimates.

Emission factors can actually change depending on dominating combustion conditions, either flaming or smoldering (Akagi et al., 2011). The emissions factors used in this study were measured under conditions of smoldering combustion, as determined by the modified combustion efficiency (MCE) (Table 1-3). MCE is an index of the degree of combustion, flaming or smoldering combustion, based on the amount of CO_2 and CO emitted (Briggs et al., 2016):

$$MCE = \frac{\Delta CO_2}{\Delta CO_2 + \Delta CO} \quad (1\text{-}4)$$

where ΔCO_2 and ΔCO are the carbon concentrations expressed by the emission factors of CO_2 and CO, respectively. MCE calculation yields a value between 0 and 1. O_2 is rapidly consumed in flaming combustion, producing oxidized gases such as CO_2, H_2O, NO_x and SO_2. On the other hand, in smoldering combustion, pyrolysis and gasification mechanisms occur, producing CO, CH_4, non-methane organic compounds and primary organic aerosols (Akagi et al., 2011; Stockwell et al., 2016). Nevertheless, flaming and smoldering combustion can occur simultaneously, and their contribution can be estimated from the MCE value. A very high MCE (>0.90) designates flaming (0.99 pure flaming), a lower MCE (<0.9) designates smoldering (0.65–0.85 pure smoldering) and an MCE of 0.90 represents similar amounts of biomass combusted as flaming and smoldering (Akagi et al., 2011; Christian et al., 2003; Levine, 1999; Stockwell et al., 2014, 2016). Lastly, the IPCC global warming potentials based on a 100-year time horizon (Myhre et al., 2013) were used to express the impact of each GHG on climate change.

Table 1-3. Hundred-year Global Warming Potentials (GWP) of the GHGs and the studies that were used to estimate their average emission factors (kg Mg^{-1} of dry matter burnt).

	Study area	**Measurement**	**MCE**	**Sample size**	**CO_2**	**CO**	**CH_4**	**NO_x**
GWP (Mg CO_2-eq/Mg of gas)[(i)]					1	2.65[(ii)]	28	-19[(iii)]
Emission factors (kg Mg^{-1})								
Stockwell et al. (2016)	Kalimantan	In situ	0.772	35	1564	291.0	9.51	0.31[(iv)]
Huijnen et al. (2016)	Kalimantan	In situ	0.862	1[(v)]	1594	255	7.4	-
Christian et al. (2003)	Sumatra	Laboratory	0.838	1	1703	210.3	20.8	1
Stockwell et al. (2014)	Kalimantan	Laboratory	0.816	3	1637	233	12.8	1.9
Smith et al. (2018)	Malaysia	In situ	0.800	10	1579	251	11	-

[(i)] Global Warming Potential according to Myhre et al. (2013)
[(ii)] GWP of CO was taken as the average of the range of GWP values given by Myhre et al. (2013) for global CO.
[(iii)] GWP of NO_x was taken as the average of the range of GWP values given by Myhre et al. (2013) for tropical NO_x.
[(iv)] The number of observations for NO_x was 24.
[(v)]The sample size was not mentioned and consequently, we assumed that they only had one sample each.

2.3 Meta-analyses

A meta-analysis consists of taking advantage of existing studies to obtain a more accurate estimate of a particular population parameter (Hedges, 1992). The accuracy of the estimates provided in a particular study can be affected by the context and the methodology. Consequently, when comparing estimates from different studies, two variance components can be identified: a between-study variance component and a within-study variance component. The common linear regression only considers fixed effects and it assumes that the effect size parameters are fixed between studies (Hedges & Vevea, 1998). As a consequence, it cannot distinguish the aforementioned variance components.

Meta analyses are usually based on mixed-effect (both random and fixed) models (Hedges, 1992). By specifying a study random effect, mixed-effect models make it possible to estimate the two variance components and to obtain unbiased estimates of the parameter of interest (Bolker et al., 2009). Apart from methodological differences, the sample size affects the precision of estimates. In statistics the larger the sample size, the smaller the variance of the estimate is. In fact, the variance of the mean estimate asymptotically decreases with the sample size, i.e.

$$V(\hat{\mu}) = \frac{\sigma^2}{n} \qquad (1\text{-}5)$$

where $V(\hat{\mu})$is the variance of the mean estimate, $\sigma^2$is the variance of the population and *n* is the sample size. Estimates based on small sample sizes are therefore less precise than those based on large sample sizes. However, the idea of a meta-analysis is not to rule out a study based on a small sample size, even if it is imprecise, since it still provides information (Borenstein et al., 2010). The aim is to estimate the parameter in a range of studies without being excessively influenced by a single study (Higgins et al., 2009). Under the assumption of a common population variance, the variance of the different estimates can be weighted by their inverse of the sample size. In our meta-analyses, we included a study random effect and a weight for the sample size whenever this was possible. The individual meta-analyses are described in the next sections.

2.3.1 Depth of burn

The depth of burn can change depending on the water table level, soil moisture, peat fuel and oxygen content (Usup et al., 2004). Other physical factors may also affect the depth of burn, but to a lesser extent. For example, a build-up of char and post-fire ash impedes the flow of oxygen, limiting the burned depth (Ballhorn et al., 2009). In contrast, Boehm et al. (2001) and Ballhorn et al. (2009) found rare burned depths of more than 1.1 m, caused by the presence of flammable trunks and roots. Apart from these two studies, the deepest burned area in the studies that were collected was 0.85 m found by Page et al. (2002). This drove us to consider 0.85 m as a potential depth of burn.

All the aforementioned factors that affect depth of burn were usually unobserved in the different publications. They can therefore be seen as a sort of random effect associated with the fire episodes. The study by Konecny et al. (2016) differs from the other studies in the sense that the authors estimated an average depth of burn from up to eight fire episodes. Statistically speaking, the mean of these eight random effects should have a variance eight times lower than that of a single fire under the assumption that the fire random effects are independent of each other. For this reason, in the meta-analysis, the fire random effect was specified in interaction with the inverse square of the number of fires. Note that in this meta-analysis, there was only one estimate of burned depth per study and, consequently, it was impossible to specify a study random effect as it was confounded with the residual error.

We also assumed that major fires, such as the one during the ENSO event of 1997, were less frequent than low intensity fires (Harrison et al., 2009; Tacconi, 2003). To reflect this asymmetry, we modelled the logarithm of the depth of burn. The log transformation of the response variable implies a bias when it comes to back transforming to the original scale (Duan, 1983). Unbiased predictions were obtained by adding half the variance to the prediction on the log transformed scale before back transformation (Duan, 1983).

2.3.2. Bulk density

In agricultural fields, bulk density is usually higher near the surface than deeper in the soil due to the compaction and drainage caused by land preparation (Bizuhoraho et al., 2018; Könönen et al., 2015; Melling et al., 2011). According to Melling et al (2011), compaction is a pre-requisite for oil palm cultivation on tropical peatland, causing an increase in bulk density near the surface and reducing the amount of oxygen. The compaction alter the hydrology of the peat soil (Evers et al., 2016). The bulk density also plays an important role as predictor of the CH_4 emission factor of peat soil combustion. Smith et al. (2018) found a strong positive correlation between both parameters, showing an influence of the physical properties of peat soil on the emissions factors of peat soil combustion. Conversely, the bulk density near the surface in peat swamp forests is usually low and can increase their vulnerability to fire during the dry season due to greater oxygen availability. This was suggested by Ballhorn et al. (2009) in Central Kalimantan, where fires in peat swamp forests usually burn deeper than fires on deforested or disturbed peatlands.

Bulk density can also change in relation to the soil profile. For example, in agricultural tropical peatlands, Könönen et al. (2015) estimated the bulk density at 0.18 Mg m^{-3} between 0.10 and 0.15 m from the surface and at 0.13 Mg m^{-3} between 1.10 and 1.15 m in depth.

Since different estimates of bulk density were provided by the same authors, we specified a study random effect in the meta-analysis. Moreover, we tested the effect of the land cover class ("disturbed" versus “undisturbed”, see Table 1-2), in order to determine the potential influence of the land cover on bulk density.

2.3.3 Emission factors of peat combustion

Carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and nitrogen oxides (NO_x) are gases commonly produced by peat soil fires. Volatile organic compounds (VOCs) are also emitted in smaller proportions. They were not considered in this study, but they are of interest for human health (Blake et al., 2009). The meta-analysis was conducted with a study random effect in order to account for methodological differences in measurements and it was weighted to account for different sample sizes.

2.4 Retrospective and prospective approaches

Before obtaining an estimate of GHG emissions and the uncertainty related to that estimate, two approaches were considered. The first was a “retrospective” approach. It assumed that the fire had occurred and that some parameters in Eq. 1-3 were already measured or estimated for that particular fire. Typically, the depth of burn and fire-damaged area are estimated after each fire episode using remote sensing, aerial photographs or field measurements. This context corresponds to the vast majority of the studies that focused on the estimation of carbon losses after peatland fires (Ballhorn et al., 2009; Konecny et al., 2016; Limin et al., 2004; Page et al., 2002; Simpson et al., 2016).

Bulk density is rarely measured in those studies. The authors usually rely on a mean estimate of 0.1 Mg m^{-3} (Ballhorn et al., 2009; Boehm et al., 2001; Limin et al., 2004; Page et al., 2002).

When bulk density has not been measured for a particular fire episode, our meta-analysis can provide a default average bulk density. The same applies to emission factors. To represent the retrospective approach, the GHG emissions were estimated using the data of Page et al. (2002), Limin et al. (2004), Ballhorn et al. (2009), Simpson et al. (2016) and Konecny et al. (2016). The first four studies correspond to the fire episodes of 1997, 2002, 2006, 2015, respectively, whereas the last represents an average of eight fire episodes between 1997 and 2011.

The second approach was a prospective approach. It consisted of making projections of future emissions by peat combustion. This approach also applies to the estimation of GHG emissions after a fire for which no measurement would have been taken. In this context, the depth of burn, bulk density and emission factors estimated in our meta-analyses can be considered as default values. The fire-damaged area was not used in this approach and the resulting estimated emissions were reported on a hectare basis. The sources of the parameters used to estimate GHG emissions according to both approaches are shown in Fig. 1-1.

2.5. Estimating and propagating uncertainty

The variance of GHG emissions can be estimated analytically using the (Goodman, 1960) formula (see Annex 1). According to this formula, the variance of the product of two random variables can be estimated as follows:

$$\hat{V}(\hat{x}\hat{y}) = \hat{x}^2\hat{V}(\hat{y}) + \hat{y}^2\hat{V}(\hat{x}) - \hat{V}(\hat{x})\hat{V}(\hat{y}) \qquad (1\text{-}6)$$

where $\hat{V}$ is the estimated variance and $\hat{x}$ and $\hat{y}$ are the estimated parameters. Goodman's formula can easily be used recursively to provide an unbiased estimate of the variance for the estimated emissions (see Annex 2). Variance alone does not allow for confidence intervals and the distribution of the estimate is needed. In the context of this study, there is no certainty that the estimate of L_{fire} follows a normal distribution. Indeed, although $\hat{x}$ and $\hat{y}$ follow normal distributions, their product does not (Gaunt, 2018; Seijas-Macías & Oliveira, 2012).

In order to determine the distribution of the estimated GHG emissions, we carried out a Monte Carlo simulation with 100 000 runs (Tibshirani & Efron, 1993). Most parameters represented average values and, following the Central Limit theorem, it could reasonably be assumed that their estimates followed normal distributions (Casella & Berger, 2002).

The only exception was for the depth of burn in the prospective approach, which was assigned a log-normal distribution due to its heterogeneous variance (Fig. 1-1), as explained under Depth of burn in the Meta-analyses section.

Monte Carlo simulation was used in both the retrospective and prospective approaches. Realized parameters were drawn from probability density functions with the mean and variance as estimated through the meta-analyses, or as reported by the authors of the different studies (Fig. 1-1). The estimated fire-damaged area provided in each study was assumed to have a relative error of ±15 %, and to follow a normal distribution according to French et al. (2004). The estimated variance shown in Eq. 1-6 was used to validate the estimated variance we obtained from Monte Carlo simulation in both approaches. The contribution of each parameter estimate to the total variance of estimated GHG emissions was assessed under both approaches using a correlation analysis between the realized parameters and the realized GHG emissions obtained from the Monte Carlo simulation.

Approach \ Equation 3		$E_{fire} =$	A ×	P ×	BD ×	$\Sigma_i(G_{ef,i} \times GWP_i)$
Retrospective	Mean	Results of Monte Carlo simulation	Value of author	Value of author	This study*	This study
	Variance		French et al. 2004	Value of author	This study*	This study
	Probability density function		Normal	Normal	Normal	Normal
Prospective	Mean	Results of Monte Carlo simulation	_	This study	This study	This study
	Variance		_	This study	This study	This study
	Probability density function		_	Log-normal	Normal	Normal

E_{fire} is the amount of GHG emissions (Mg of CO_2-eq), A is the total fire-damaged area (ha), P is the average of depth of burn (m), BD is the average bulk density of peat soil (Mg m^{-3}), G_{ef} is the average emission factor for each gas (kg Mg^{-1}dry matter burnt) and GWP is the global warming potential for each gas (Mg $CO_{2\text{-}eq}$/Mg of gas).*Except for Konecny et al. (2016) who provided a measured bulk density, so that, the value was used instead of the mean estimated from this study.

Figure 1-1. Data organization to quantify GHG emissions according to each approach.

3. Results

3.1 Meta-analyses

The parameter estimates and their standard errors that were obtained from the meta-analyses are given in Table 1-4. The effect of land cover classification ("disturbed" versus "undisturbed") in the meta-analysis of bulk density was found to be non-significant with a p-value of 0.1161 and, consequently, this effect was not kept in the model. The sum of the emission factors for each GHG was estimated at 2,546 ± 75.32 kg Mg^{-1} of CO_2-eq. The contribution of the individual gas is shown in Annex 3. Together, CO and CO_2 amounted to 88 % of the total emissions, CH_4 13% and NO -1 %.

Table 1-4. Parameter estimates and their standard errors obtained from the meta-analyses

Parameter	Estimate	Standard error	Std. deviation of random effects	Std. deviation of residuals
Bulk density (Mg m^{-3})	0.145	0.018	0.040	0.10
Depth of burn (m)	0.228	0.1216	0.250*	0.98*
Emission factors(kg Mg^{-1}d.m)				
CO_2	1,586.06	17.00	21.07	73.79
CH_4	10.51	0.95	0.89	5.158
CO	258.68	15.34	24.40	46.41
NO_x	1.04	0.47	0.78	0.36

*on the log transformed scale

3.2. Estimated GHG emissions

3.2.1 Retrospective approach

Re-estimated GHG emissions with their respective confidence intervals for fire episodes between 1997 and 2015 are shown in Figs. 1-2 and 1-3. The fire episode in 1997 corresponds to the study by Page et al. (2002), the one in 2002 to Limin et al. (2004), the one in 2006 to Ballhorn et al. (2009), the one in 2015 to Simpson et al. (2016) and "Various" corresponds to the study by Konecny et al. (2016), which focused on the average of eight fires from 1997, 2001, 2002, 2004, 2005, 2006, 2009 and 2011.

In Fig. 1-2, the estimated GHG emissions are reported per hectare in order to facilitate their comparison. The fire episode of 1997 contributed most GHGs and displayed the largest confidence intervals. The fire episodes represented as "Various" contributed least and represented less severe fires on average.

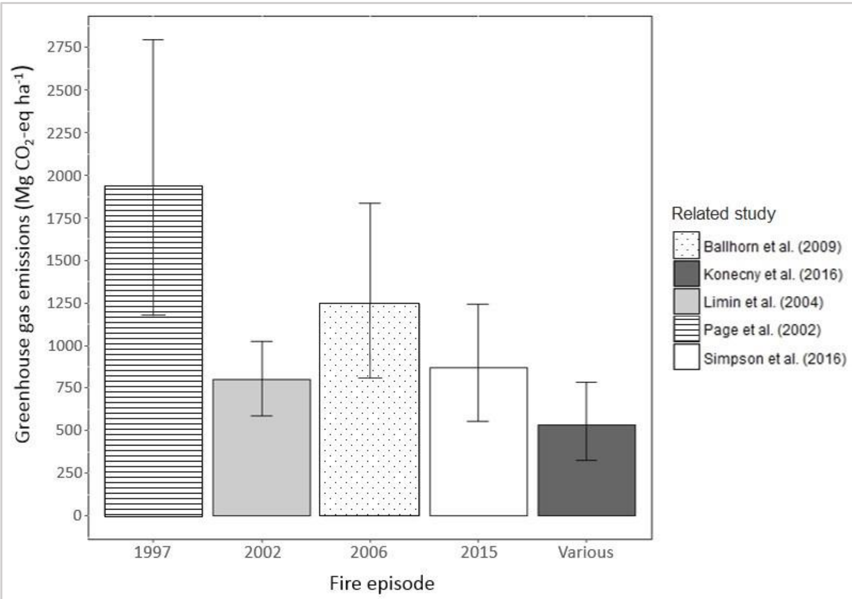


Figure 1-2. Re-estimated greenhouse gas emissions based on the retrospective approach. The whiskers show the 0.95 confidence intervals obtained by Monte Carlo simulation. The labels 1997, 2002, 2006, 2015 and Various refer to the studies of each fire episode in the Table 1-1.

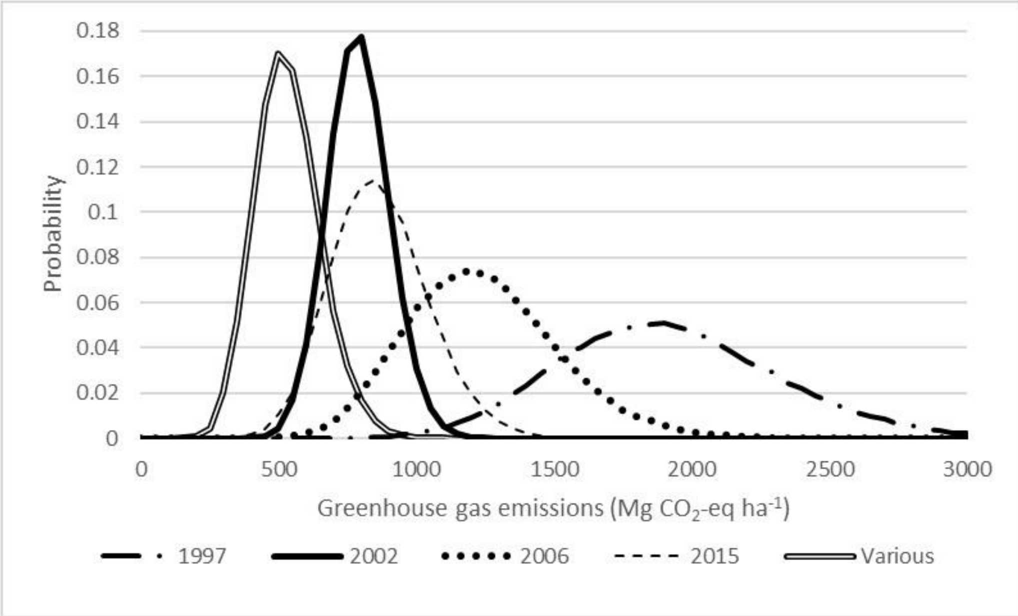


Figure 1-3. Distribution of the greenhouse gas emissions per hectare based on Monte Carlo simulation. The labels 1997, 2002, 2006, 2015 and various refer to the studies of each fire episode in the Table 1-1.

The contribution of each parameter to total variance is shown in Fig. 1-4. For all studies, the bulk density and fire-damaged area were the two major sources of uncertainty, followed by depth of burn and emission factors, for which the contributions were almost negligible in the study by Simpson et al. (2016) and Konecny et al. (2016) (Fig.1-4).

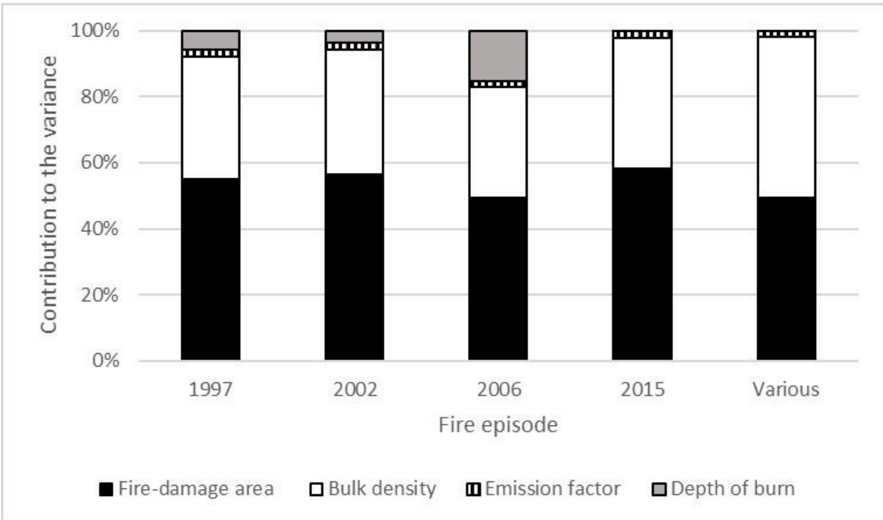


Figure 1-4. Contribution to variance of the different parameters in the re-estimated GHG emissions for the different fire episodes in the retrospective approach. The labels 1997, 2002, 2006, 2015 and various refer to the studies of each fire episode in the Table 1.

3.2.2 Prospective approach

The GHG emissions for a future fire were estimated at 842 Mg ha^{-1} CO_2-eq. on average with a standard deviation of 466 Mg ha^{-1} CO_2-eq. We obtained a 0.95 confidence interval ranging from 267 to 2 024 Mg ha^{-1} CO_2-eq. (Fig. 1-5). The mean predicted GHG emissions were very close to those obtained with the IPCC guidelines (Hiraishi et al., 2014). The largest contribution to variance could be attributed to the depth of burn, with 94.2%, followed by bulk density with 5.5 % and the emission factor with 0.3 %. The difference between the variance estimated by Monte Carlo simulation and that obtained with Goodman's formula (Eq.1-6) did not exceed one percent, with the Monte Carlo variances and standard deviations always being greater (Table 1-5).

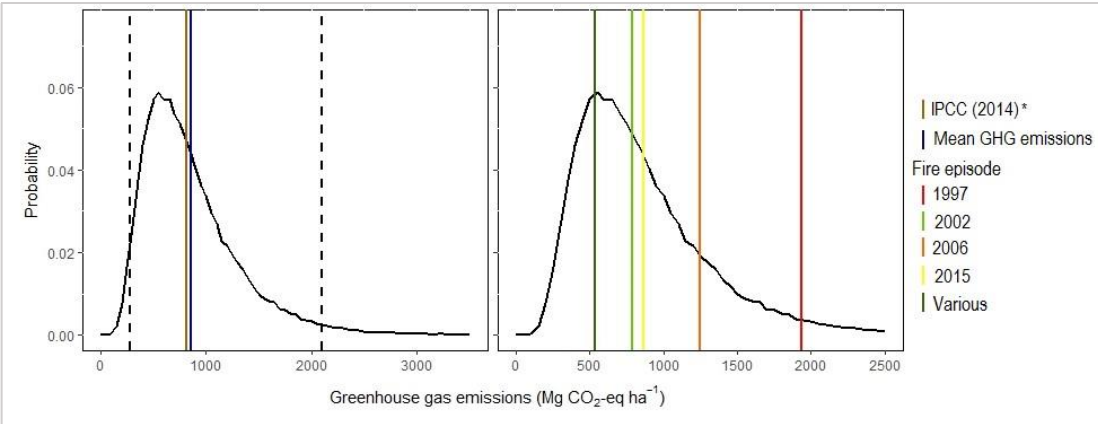


Figure 1-5. Distribution of GHG emissions from peat soil combustion in the prospective approach. Left: Mean GHG emissions estimated in the prospective approach and *mean estimated with default values provided by the IPCC (Hiraishi et al., 2014). The dashed lines represent the limits of the 0.95 confidence interval of the estimated GHG emissions in the prospective approach. Right: Means estimated in the retrospective approach for different fire episodes.

Table 1-5. Comparison of the relative standard deviations (%) estimated by Monte Carlo simulation with those estimated using Goodman's estimator (Eq. 1-6).

Approach	Fire episode	Related study	Monte Carlo simulation	Goodman (1960)
Retrospective approach	1997	Page et al. (2002)	20.5	20.3
	2002	Limin et al. (2004)	20.2	20.1
	2006	Ballhorn et al. (2009)	21.6	21.2
	2015	Simpson et al. (2016)	19.8	19.7
	Various	Konecny et al. (2016)	21.4	21.4
Prospective approach			55.3	54.4

4. Discussion

4.1 Estimating the impact of peatland wildfires on climate change

Two equations were found in the literature to estimate the impact of peatland wildfires on climate change. In this study, we standardized these equations to obtain a new one (Eq. 1-3). Based on this new equation, the emission factors and GWP were used to estimate the amount of GHG emissions in CO_2 equivalent. Considering all GHG instead of carbon emissions only provides a better picture of the real contribution of peatland wildfires to climate change.

In the method proposed by the IPCC for the estimation of GHG emissions from peat soil, it is suggested using a default value of 1 for the combustion factor, assuming that all of the volume of peat is consumed (Hiraishi et al., 2014). Some authors refer to this combustion factor as "combustion completeness", i.e. the fraction of fuel combusted (Akagi et al., 2011; Van der Werf et al., 2010; Van Leeuwen et al., 2014). In the same IPCC guidelines(Hiraishi et al., 2014) , this combustion factor is also defined as "burning efficiency and can be used to characterize smoldering vs. flaming fires". However, the difference between smoldering vs. flaming is usually handled through the "Modified Combustion Efficiency" concept (Akagi et al., 2011; Christian et al., 2003; Levine, 1999; Stockwell et al., 2014, 2016). To avoid confusion, we preferred to estimate the amount of burned peat by means of the depth of burn instead of using a combustion factor as in Eq. 1-2. The effects of combustion incompleteness were then taken into account through the emission factors G_{ef}, which were representative of smoldering conditions (see Table 1-3).

The estimated means of the parameters from the meta-analyses based on mixed models proved more representative than an arithmetic mean, because additional information provided in each study was used. The methodological differences in measurements between studies were account through study random effect applied to emission factors and bulk density. The fire random effect applied to depth of burn, which included the variance between the fire episodes.

Additionally, the information collected to carry out the meta-analysis was selected with specific criteria related to fires. For example, we emphasized that the bulk density used in our study corresponded to the first 85 cm of peat soil depth, because it is a potential depth of burn according to the dataset collected. Another important aspect of our results was the identification of the parameters that most contributed to the total variance of estimated GHG emissions in both approaches.

4.2 Retrospective and prospective approaches

In the retrospective approach, the largest estimated GHG emissions per hectare corresponded to the severe fire episode in 1997 followed by the one in 2006, which was influenced by the drought induced by ENSO in those years (Fig.1-2). This phenomenon also affected other fire episodes, but to a lesser extent (Ballhorn et al., 2009; Page & Hooijer, 2016). The difference between severe and less severe fire episodes is represented in a probability graphic obtained by Monte Carlo simulation (Fig. 1-5). In fact, the fire in 1997 was a very severe fire episode that resulted in a large depth of burn compared to the average found by Konecny et al. (2016). This asymmetrical distribution led us to assume a log-normal distribution for depth of burn instead of a normal distribution. The residuals of the meta-analysis corroborated the log-normal distribution. However, it needs to be stressed that the number of fire episodes remained small in our meta-analysis. Additional data on other fire episodes should confirm whether or not the log-normal distribution is the most appropriate distribution.

In the prospective approach, the estimated GHG emissions were close to the estimated GHG emissions of the less severe fire episodes under the retrospective approach (Fig. 1-5). This estimate was also similar to the GHG emissions estimated using the default values provided by the IPCC. Our results strengthen confidence in the IPCC methodology, both the mean value of emissions and uncertainty are close to those found in this study. However, we managed to determine the amount of uncertainty that stemmed from each parameter and their contribution to the GHG emission variance.

4.3 Contribution of the parameters to GHG emission variance

In the retrospective approach, the largest contribution to variance stemmed from the fire-damaged area and bulk density. It must be stressed that this contribution of the fire-damaged area to variance is based on a default relative error of 15 % found in the literature (French et al., 2004), because none of the authors provided it. The pattern was completely different in the prospective approach, where the largest contribution to variance arose from the depth of burn (93 %). This difference between the retrospective and prospective approaches was due to the fact that the depth of burn was measured in the former approach, whereas the latter approach was based on the average fire. Our meta-analysis on depth of burn indicated great variability from one fire to another. This variability was essentially due to climatic and environmental conditions, which affected the depth of burn much more than the bulk density and emission factors. This result is in line with that of French et al. (2004), who found that the greatest contribution to variance in the estimates of GHG emissions in boreal peatlands also stemmed from the depth of burn.

In the retrospective approach, the contribution of the depth of burn to variance when using the data of both Konecny and Simpson et al. (2016) was negligible. In fact, the variance associated with the estimated depth of burn in the retrospective approach was inversely proportional to the sample size, which in turn depended on the methodology. In this regard, remote sensing is much more efficient that field measurements. It allows for a much larger sample size, as indicated in Table 1-1. In this context, the contribution made by the other parameters to variance were highlighted in the retrospective approach (Fig.1-4).

The relative standard deviations estimated by Monte Carlo simulation was always greater than that estimated using Goodman's formula, but never by more than one percent (Table 1-5). A natural question that arises is which estimate of variance is the best. Goodman's variance is analytically unbiased (see Annex 1). Monte Carlo simulation does not account for the fact that the means of the probability density functions are actually estimated. Consequently, it overestimates variance by a quantity that is dependent on the product of the variances of the parameters, exactly like the uncorrected estimator shown in Eq.1-2 in Annex 1. In Konecny et al. and Simpson et al. (2016), the variance associated with the depth of burn was so small that this product remained very small too and the Monte Carlo variance was very close to that of Goodman.

While Goodman's formula was an unbiased estimator of variance, the distribution of the estimated GHG emissions remained unknown and a distributional assumption had to be made to produce confidence intervals. In this regard, the Monte Carlo method is superior because it provides an empirical distribution from which confidence intervals can be derived using the percentile method (Tibshirani & Efron, 1993). However, the bounds of these confidence intervals should be considered as slightly too wide because the Monte Carlo method overestimates the variance. A significant improvement would be the coupling of these two methods. For example, a correction factor based on Goodman's formula could be applied to the actual GHG emissions in order to correct for the bias in the estimated variance, and the confidence intervals could be based on these corrected realizations. This remains to be developed.

4.4 Limitations

The smoldering behavior of peat combustion can add great uncertainty to estimates of the fire-damaged area. Since the fire-damaged area is usually estimated based on the burn scar, it does not capture the heat of smoldering fires underground, and underestimates the area affected by the fire (Hiraishi et al., 2014; Usup et al., 2004). This is an important aspect to take into account when GHG emissions are estimated in a prospective approach, then extrapolated to a larger area. The same limitation also applies to the estimation of the depth of burn.

The effect of the land cover on bulk density as estimated in the meta-analysis did not show a significant p-value. This may have been due to differences and scarcity in the data we collected: 15 observations for disturbed land cover with a mean of 0.167 Mg $m^{-3}$and only seven observations for undisturbed land cover with a mean of 0.116 Mg m^{-3}. Actually, the correlation between bulk density and land cover or human intervention has been suggested by some authors, as discussed under Bulk density in the Meta-analyses section. With our small sample size, the statistical power of the test remained low and the lack of significance may have been due to the fact that we failed to capture the signal, rather than the absence of an effect.

In the literature, the default value of 0.100 Mg m^{-3} has been used in many studies on GHG emissions following peat combustion (e.g. Ballhorn et al., 2009; Boehm et al., 2001; Limin et al., 2004; Page et al., 2002). Our meta-analysis provided a default bulk density of 0.145 ± 0.018 Mg m^{-3}, which is larger than the best guess value of 0.100 Mg m^{-3}. For now, we cannot confirm that the best guess value leads to an underestimation of GHG emissions, because it still lies close to the lower boundary of the confidence interval of our default value. However, until additional bulk density measurements are made available, our default value should be considered more robust than the best guess, because it was estimated from the existing literature using a state-of-the-art statistical methodology.

In addition to changing across different land covers, bulk density is also known to change across the soil profile (Könönen et al., 2015; Neuzil, 1993; Page et al., 2004). Using average values from the deepest layers can also affect the estimated amount of GHG emissions. For instance, Simpson et al. (2016) based their estimation of carbon losses on a bulk density of 0.106 Mg m^{-3} measured at a depth range of 4.1 to 6.4 m (Warren et al., 2012), although they found an average depth of burn of 0.23 m.

As regards the emission factors of the different GHGs, they were characterized by low variance (Table 1-4) and their combined contribution to the variance of GHG emissions was minor in comparison with the other parameters in both approaches. Consequently, we recommend the value of 2546 ± 75 kg CO_2-eq Mg^{-1} as a reliable default emission factor for CO_2, CO, CH_4 and NO_x. It must be stressed that the emission factors used in this study were obtained under smoldering conditions, as indicated by MCE, and these values could change under flaming conditions.

In this study, we assumed that all the parameters were independent from each other. Nevertheless, there may have been certain correlations between parameters, which were not studied here because the available data did not allow for it. For example, the fire-damaged area and bulk density can be related to the depth of burn through the amount of oxygen available. The large amount of oxygen near the soil surface in forests can increase the likelihood of fire in the dry season compared to agricultural fields. In Central Kalimantan, Ballhorn et al. (2009) found that the fires in peat swamp forests burned deeper than fires on deforested or disturbed peatlands, where bulk density can be higher due to land preparation. This is consistent with other studies in Malaysian and Indonesian peatlands too (Konecny et al., 2016; Okazaki, 1992).

By determining the contribution to variance made by each of the parameters estimated in this study, it was possible to prioritize attention on those making the largest contributions to the uncertainty of GHG emissions due to peatland wildfires. Our results suggest that at least the depth of burn should be measured after each fire, in order to avoid variance due to the great heterogeneity across the different fire episodes. Bulk density was also a significant contributor to the variance of estimated GHG emissions, although its contribution was not as great as that of the depth of burn. The uncertainty associated with bulk density could be reduced by increasing the sample size and re-testing the land cover stratification. The emission factors of the four GHG gases analyzed in this study made a small contribution to variance compared to that of the bulk density and depth of burn. If it is not possible to measure the parameters, or if the aim is to estimate possible avoided emissions in future fires, the estimates in this study (Table 1-4) should be considered as default values. Beyond the need for additional observations, some methodological improvements could reduce the uncertainty of estimated GHG emissions. For instance, coupling of the Monte Carlo and Goodman methods could lead to more reliable confidence intervals.

5. Conclusions

In this study, the GHG emissions from peat combustion and the contribution from parameters to the uncertainty were estimated. Default values of the depth of burn, bulk density of peat soil, and emission factors were obtained for past and future fire episodes. For a future fire, the average GHG emissions were estimated at 842 Mg ha^{-1} CO_2-eq. with a standard deviation of 466 Mg ha^{-1} CO_2-eq. In addition, we determined the main parameters contributing to the uncertainty of this estimation. In retrospective approaches, fire-damaged area and bulk density were the two major sources of uncertainty contributing around 54 % and 39 % respectively. In prospective approaches, depth of burn was the main contributor with 94.2 %. The contribution of emissions factors to these uncertainties for the four gases analyzed here was negligible. Our results show then the importance to focus on depth of burn, fire area damaged and bulk density to decrease the uncertainty in the estimation of GHG emissions from peat combustion in wildfires.

Annexes

Annex 1. Estimating the variance of products

The next developments are inspired by (Goodman, 1960). Let us define two means, i.e. μ_X and μ_Y. Their estimates, i.e. $\hat{\mu}_X$ and $\hat{\mu}_Y$, are actually two random variables with means μ_X and μ_Y and variances $\mathbb{V}(\hat{\mu}_X)$ and $\mathbb{V}(\hat{\mu}_Y)$, respectively. The variance of the product of $\hat{\mu}_X$ by $\hat{\mu}_Y$ is well known for being

$$\mathbb{V}(\hat{\mu}_X\hat{\mu}_Y) = \mu_X^2\mathbb{V}(\hat{\mu}_Y) + \mu_Y^2\mathbb{V}(\hat{\mu}_X) + \mathbb{V}(\hat{\mu}_X)\mathbb{V}(\hat{\mu}_Y) \tag{1}$$

In practice, the means and the variances on the right-hand side of Eq. 1 are unknown. Replacing them by their estimates yields the following estimator of the variance of products:

$$\hat{\mathbb{V}}(\hat{\mu}_X\hat{\mu}_Y) = \hat{\mu}_X^2\hat{\mathbb{V}}(\hat{\mu}_Y) + \hat{\mu}_Y^2\hat{\mathbb{V}}(\hat{\mu}_X) + \hat{\mathbb{V}}(\hat{\mu}_X)\hat{\mathbb{V}}(\hat{\mu}_Y) \tag{2}$$

Under the assumption that $\hat{\mu}_X$ and $\hat{\mu}_Y$ are independent, it can be shown that the expectation of this estimator is

$$\begin{aligned}\mathbb{E}[\hat{\mathbb{V}}(\hat{\mu}_X\hat{\mu}_Y)] &= (\mu_X^2 + \mathbb{V}(\hat{\mu}_X))\mathbb{V}(\hat{\mu}_Y) + (\mu_Y^2 + \mathbb{V}(\hat{\mu}_Y))\mathbb{V}(\hat{\mu}_X) + \mathbb{V}(\hat{\mu}_X)\mathbb{V}(\hat{\mu}_Y) \\ &= \mu_X^2\mathbb{V}(\hat{\mu}_Y) + \mu_Y^2\mathbb{V}(\hat{\mu}_X) + 3\mathbb{V}(\hat{\mu}_X)\mathbb{V}(\hat{\mu}_Y) \end{aligned} \tag{3}$$

The comparison between the expectation shown in Eq. 3 and the true variance shown in Eq. 1 indicates that this estimator has a bias equal to $2\mathbb{V}(\hat{\mu}_X)\mathbb{V}(\hat{\mu}_Y)$.

Goodman (1960) proposed the following corrected estimator

$$\hat{\mathbb{V}}_{\text{GOODMAN}}(\hat{\mu}_X\hat{\mu}_Y) = \hat{\mu}_X^2\hat{\mathbb{V}}(\hat{\mu}_Y) + \hat{\mu}_Y^2\hat{\mathbb{V}}(\hat{\mu}_X) - \hat{\mathbb{V}}(\hat{\mu}_X)\hat{\mathbb{V}}(\hat{\mu}_Y) \tag{4}$$

The expectation of this corrected estimator is

$$\begin{aligned}\mathbb{E}[\hat{\mathbb{V}}_{\text{GOODMAN}}(\hat{\mu}_X\hat{\mu}_Y)] &= (\mu_X^2 + \mathbb{V}(\hat{\mu}_X))\mathbb{V}(\hat{\mu}_Y) + (\mu_Y^2 + \mathbb{V}(\hat{\mu}_Y))\mathbb{V}(\hat{\mu}_X) - \mathbb{V}(\hat{\mu}_X)\mathbb{V}(\hat{\mu}_Y) \\ &= \mu_X^2\mathbb{V}(\hat{\mu}_Y) + \mu_Y^2\mathbb{V}(\hat{\mu}_X) + \mathbb{V}(\hat{\mu}_X)\mathbb{V}(\hat{\mu}_Y) \end{aligned} \tag{5}$$

which is precisely the true variance as shown in Eq. 1.

Annex 2. Extending Goodman's estimator to the product of multiple random variables.

The greenhouse gas (GHG) emissions after wildfires in peatlands can be calculated as (see Eq. 3 in the main paper)

$$\text{E}_{\text{fire}} = \text{A} \times \text{P} \times \text{BD} \times \sum_i \text{G}_{ef,i} \times \text{GWP}_i \times 10 \tag{6}$$

where E_{fire} are the total emissions (Mg of CO_2 eq.), A is the total fire-damaged area (ha), P is the average burned area depth (m), BD is the average bulk density (Mg m^{-3}), $\text{G}_{ef,i}$ are the emission factor of gas i (g kg^{-1} of dry matter burnt) and GWP_i is the global warming potential of gas i (kg CO_2 eq. kg^{-1} of gas).

In practice none of the parameters on the right-hand side of Eq. 6 is known and they are replaced by their estimates. Building on Goodman's estimator, the variance of such a product is then

$$\hat{\mathbb{V}}(\hat{\mathrm{E}}_{\mathrm{fire}}) = 10^2\hat{\mathbb{V}}\left(\hat{\mathrm{A}} \times \hat{\mathrm{P}} \times \widehat{\mathrm{BD}} \times \sum_i \hat{\mathrm{G}}_{ef,i} \times \mathrm{GWP}_i\right)$$
$$= 10^2\left(\hat{\mathrm{A}}^2\hat{\mathbb{V}}(\hat{\mathrm{B}}) + \hat{\mathrm{B}}^2\hat{\mathbb{V}}(\hat{\mathrm{A}}) - \hat{\mathbb{V}}(\hat{\mathrm{A}})\hat{\mathbb{V}}(\hat{\mathrm{B}})\right) \quad (7)$$

where $\hat{\mathrm{B}} = \hat{\mathrm{P}} \times \widehat{\mathrm{BD}} \times \sum_i \hat{\mathrm{G}}_{ef,i} \times \mathrm{GWP}_i$. The estimated variance of $\hat{\mathrm{B}}$ can be further expanded as

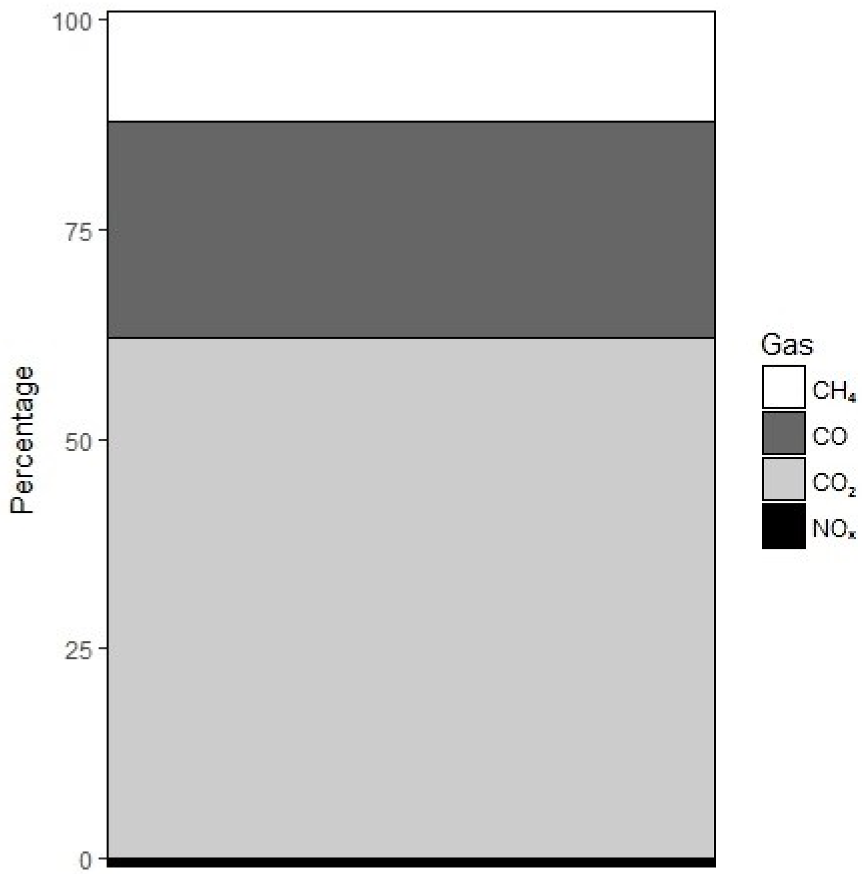
$$\hat{\mathbb{V}}(\hat{\mathrm{B}}) = \hat{\mathbb{V}}\left(\hat{\mathrm{P}} \times \widehat{\mathrm{BD}} \times \sum_i \hat{\mathrm{G}}_{ef,i} \times \mathrm{GWP}_i\right)$$
$$= \hat{\mathrm{P}}^2\hat{\mathbb{V}}(\hat{\mathrm{C}}) + \hat{\mathrm{C}}^2\hat{\mathbb{V}}(\hat{\mathrm{P}}) - \hat{\mathbb{V}}(\hat{\mathrm{P}})\hat{\mathbb{V}}(\hat{\mathrm{C}}) \quad (8)$$

where $\hat{\mathrm{C}} = \widehat{\mathrm{BD}} \times \sum_i \hat{\mathrm{G}}_{ef,i} \times \mathrm{GWP}_i$. Again, the estimated variance of $\hat{\mathrm{C}}$ can be expanded as

$$\hat{\mathbb{V}}(\hat{\mathrm{C}}) = \hat{\mathbb{V}}\left(\widehat{\mathrm{BD}} \times \sum_i \hat{\mathrm{G}}_{ef,i} \times \mathrm{GWP}_i\right)$$
$$= \widehat{\mathrm{BD}}^2\left(\sum_i \mathrm{GWP}_i^2\hat{\mathbb{V}}(\hat{\mathrm{G}}_{ef,i})\right) + \left(\sum_i \hat{\mathrm{G}}_{ef,i} \times \mathrm{GWP}_i\right)^2\hat{\mathbb{V}}(\widehat{\mathrm{BD}})$$
$$- \left(\sum_i \mathrm{GWP}_i^2\hat{\mathbb{V}}(\hat{\mathrm{G}}_{ef,i})\right)\hat{\mathbb{V}}(\widehat{\mathrm{BD}}) \quad (9)$$

Reinserting this expanded variance into Eq. 8 which in turn is reinserted into Eq. 7 yields an unbiased estimator of the variance associated to the estimated GHG emissions.

Annex 3. Contribution of the different gases as a percentage of the total greenhouse gas emissions measured in CO_2-eq.




EXOTIC

Chapter 2
General assessments

Scope of Chapter 2

This chapter provides the basic information and the parameters used throughout this thesis to develop the different scenarios of biomass valorization on peatlands. More specifically, ***Part I*** of the chapter presents the study area, Ogan Komering Ilir (OKI), and the context in which the assessments were carried out. ***Part II*** provides an estimate of the GHG emissions resulting from peat combustion related to fire activity for the whole study area. This estimate was a prerequisite for Chapter 3 in which it represents a "business as usual" scenario for comparison with alternative scenarios of biomass valorization. Finally, in ***Part III*,** an assessment of the distance related to biomass transportation was performed, assuming different factory locations. This assessment was also used to evaluate the impact of biomass transportation in terms of GHG emissions in Chapter 3 and the cost of biomass transportation to the factories in Chapter 4.

PART I. STUDY AREA

1. Ogan Komering Ilir (OKI)

Indonesia is the world's largest archipelago (Cribb & Ford, 2009). It is a developing country with an annual growth rate of the population of 5.3 % between 2000 and 2017 (Felipe et al., 2019). In 2018, the population of the country was estimated at 267.6 million habitants (World Bank, 2018) for a total area of approximately 2 million km². Agriculture is the main occupation of one third of the working population (Felipe et al., 2019).

Our study area is Ogan Komering Ilir (OKI), a regency of Sumatera Selatan province, located in the southern part of Sumatra island (Fig. 2-1). Sumatera Selatan province is one of the 33 provinces of Indonesia, with a total of 8 million inhabitants. Its capital, Palembang, has some 1.6 million inhabitants (National Census, 2015). Given its airport, train station and large-scale port, it is considered as a crossroad between Jakarta and the rest of Sumatra ("IPC Boom Baru") (Samuel, 2015). The main activities in the province are oil extraction south of Palembang, coal and gas, paper pulp, the cultivation of oil palm (*Elaeis sp.)* and rubber trees *(Hevea sp.)* for rubber (Samuel, 2015).

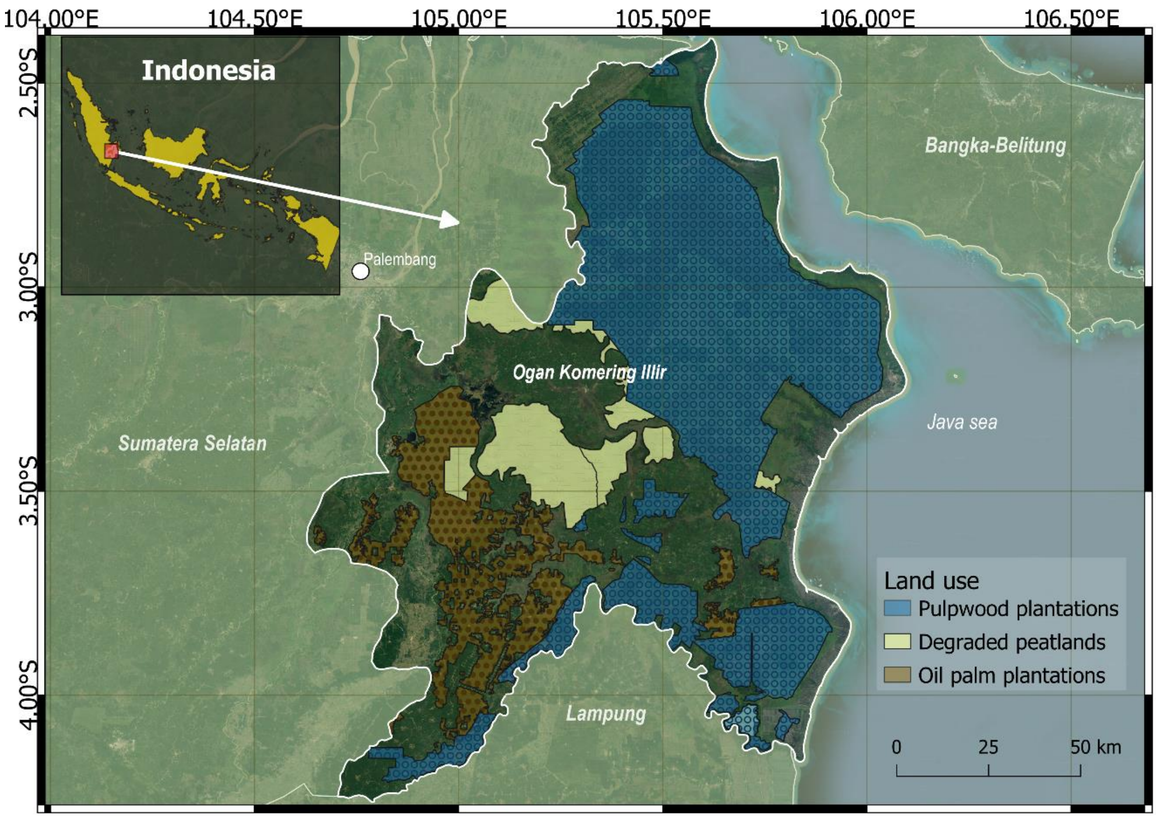


Figure 2-1. Ogan Komering Ilir and the three land uses selected in this study. Data source: World Resources and Google Satellite

OKI has approximately 786,500 inhabitants (National Census, 2015) and is divided into 18 districts. Its area is about 19,000 km², with plantations occupying almost 10,000 km² (World Resources, 2019). The majority of the plantations are industrial plantations of acacia *(Acacia mangium* Willd*)*, rubber and oil palm (Laithier, 2016). Peat soils cover around 49 –56 % of the surface of OKI (Laithier, 2016; World Resources, 2019). Monthly temperatures and precipitations range from 23° C to 31° C and from 105 mm to 364 mm, respectively (Fig. 2-2), for a total annual precipitation of 2640 mm (Data from WorldClim v2).

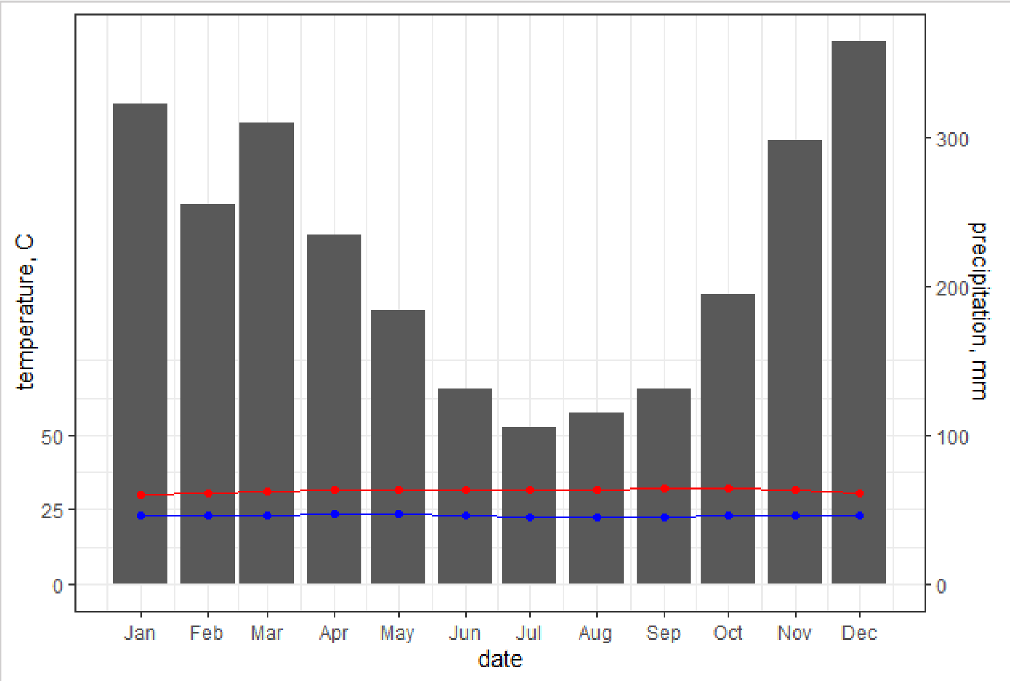


Figure 2-2. Monthly temperatures and precipitations in OKI. The bars correspond to the precipitation; the red and blue lines are the maximum and minimum temperatures, respectively. Data source: *WorldClim v2.*

In this thesis, we focused on the three major land uses on peat soils in OKI: (i) degraded peatlands; (ii) oil palm plantations; and (iii) pulp wood plantations (Fig. 2-3). These three land uses were selected because they represent a large area in OKI, around 50 % of the total surface, and they were affected by fires in recent years. They do not cover all OKI, but the remaining land use is a complex mosaic of degraded peatlands and smallholder agriculture. Their entanglement is beyond our scope here. In addition, these land uses are considered for their potential biomass valorization. A description of these three land uses and their potential biomass valorization is shown in Table 2-1.

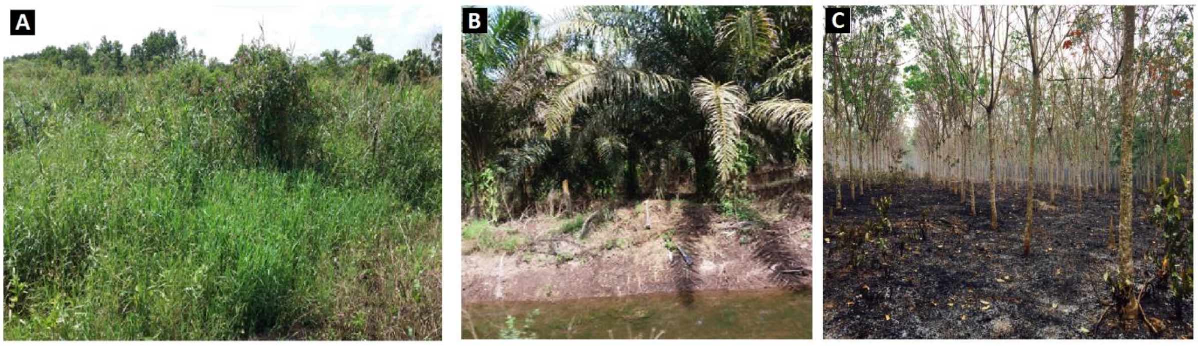


Figure 2-3. Three land uses with potential biomass valorization in OKI. (A) Degraded peatlands; (B) Oil palm plantations; and (C) Pulpwood plantations. Source: The author (A and B) and Mekra Nasriantra (C), resident of TulungSelapan.

Table 2-1. Three land uses on peatlands and their potential biomass valorization.

Land use	Description	Area (ha)[i]	Potential biomass valorization	Biomass composition[ii]
Degraded peatlands	Deforested and unmanaged areas or abandoned plantations, covered by bushes, ferns and grass with average height lower than 2 m	124,000	Bushes and grass	Lignin: 25-55 % Polysaccharides: 30-72 %
Oil palm plantations	Industrial plantations based on 25-year rotations	183,000	Residues of trunks	Lignin: 18-22 % Hemi-cellulose: 25-59 % Alpha cellulose: 19-47 % Moisture: 57-83 %[2]
Pulpwood plantations	Industrial plantations established with a rotation period of 7-8 years	677,000	Logging residues of trunks and branches< 7-8 cm	Lignin: 25-55 % Polysaccharides: 30-72 %

[i] The areas were estimated from World Resources (2019), and verified and rectified whenever possible through satellite image interpretation.
[ii] According to Roda et al. (2015).

PART II. GREENHOUSE GAS EMISSIONS FROM PEAT SOIL COMBUSTION IN OKI

1. Introduction

OKI is one of the areas affected by fires in the Sumatera Selatan province (Laithier, 2016) (Fig. 2-4). Some of these occur in degraded peatlands where fire is used for land clearing, hunting and non-timber forest product collection or caused by accident, without supervision and control, which leads to the expansion of the fire (Sinclair et al., 2020). Fire can also occur in plantations or nearby, where burning is used as a site preparation treatment. Slash and burn for land clearing has been a traditional land preparation method for centuries. It is no longer commonly used, especially not in large industrial plantations due to governmental regulations, NGOs monitoring, and the increased awareness on associated risks notably in peatland areas. Nevertheless, slash and burn is still tolerated for smallholders who do not have the technical means to avoid it. Residues of agricultural activities are burned under supervision until extinction. In drought periods, these prescribed burnings can be difficult to keep under control due to the availability of dry fuel in the form of biomass and peat. Fires in peat soils can burn and expand horizontally and vertically underground for long periods of time as smoldering combustion (Akagi et al., 2011). Belowground burning and fire propagation makes it difficult to identify the actual origin of fires. Hence, some prescribed fires[2] can affect areas by accident beyond the intended extent, including palm plantations or other neighboring plantations. This study does not analyze the origin of fires but rather focuses on analyzing the impact of biomass availability on the severity of the fire impacts and on ways to limit those.

In this part, we estimated the GHG emissions from peat soil combustion for the three aforementioned land use types in the OKI area. In order to obtain a regional level estimate of GHG emissions due to peat soil combustion, we carried out an analysis of fire occurrence in OKI for the period 2002-2018. This estimate is one of the emission sources used in Chapter 3 to define the business as usual scenario. The business as usual scenario is the baseline to measure the impact of the implementation of proposed alternative peatland management scenarios (IPCC, 2018).

[2] Prescribed fires refers to the IPCC terminology. However, they can also be called “controlled fires”.

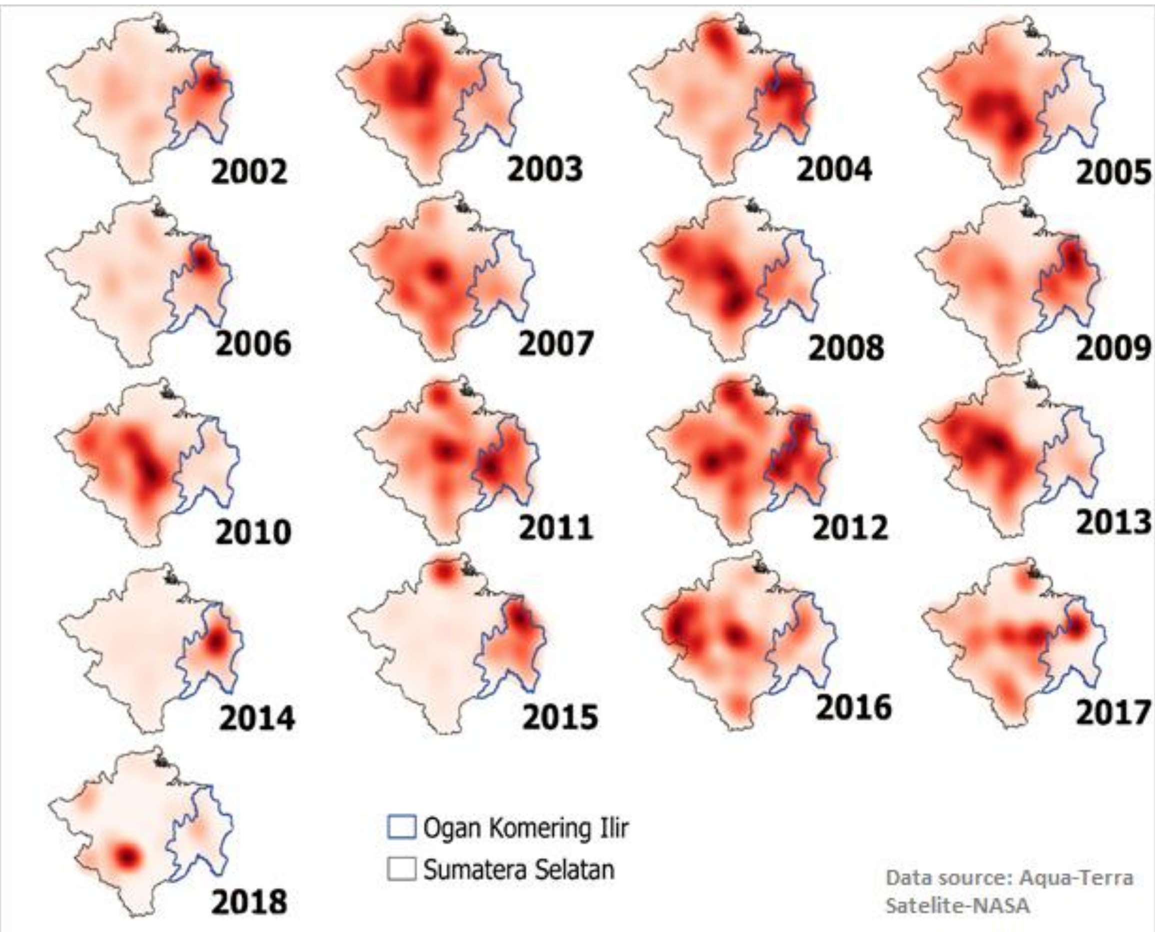


Figure 2-4. Fire distribution in Sumatera Selatan province for the period 2002-2018. Data source: NASA, consulted from 2017 to 2019. The red color indicates fire hot spots. The dark red color delineates the areas with the greatest concentration of fire hot spots.

2. Material and Methods

2.1. Fire occurrence

2.1.1. Data collected

The fire occurrence assessment was performed using vectorial geodata of (1) the administrative division of Sumatera Selatan, (2) the land use in OKI, (3) fire hotspots, and (4) a grid size of 889 m x 891 m per pixel (79.21 ha $pixel^{-1}$), which roughly corresponded to a 30" grid. The geodata of the administrative division were obtained from the Database of Global administrative Areas (GADM, 2018).The geodata of land use were obtained from World Resources International (WRI) and Global forest Watch (GFW)(World Resources, 2019), which were verified and rectified whenever possible through the interpretation of satellite images. Land use maps do not exhaustively cover all the concessions of oil palm and pulpwood plantations. WRI and GFW, identify these different land uses by hand, and improve them regularly. They have an imperfect identification, which leaves out the young industrial plantations that have not, yet grown enough to be clearly discernible, and which leaves out some of the village mosaics of various plantations. Thus, the quality of the calculation of this study depends strongly on the quality of the identification of zones by WRI-GFW. The 2002-2018 period was chosen as the baseline period (IPCC, 2018) according to fire hotspot data availability. The fire hotspots were detected using NASA's Aqua and Terra satellites, and the data were collected from June 2002 to December 2018.

2.1.2. Data analysis

In order to estimate the fire occurrence by land use, the 30" grid was overlaid on the land use layer and the fire activity was assessed in each pixel of the grid. The average number of fire occurrences was calculated as the number of years with at least one hotspot over the 2002-2018 period:

$$\bar{x} = \frac{\sum(F_O \times P_a)}{\sum P_a} \tag{2-1}$$

where $\bar{x}$ is the average number of fire occurrences, F_O is the number of years with fire occurrence, and P_a is the number of pixels affected. All these analyses were run using the dplyr, tidyr and sf packages of R.

2.2. Estimating greenhouse gas emissions from peat soil combustion in OKI

To estimate the amount of GHG emissions by pixel, we assumed that there were two types of fires: (1) wildfires in degraded peatlands, which are the focus of Chapter 1; and (2) prescribed burnings in oil palm and pulpwood plantations where the fires are assumed to be under strict control and presumably extinguished at the appropriate time. In Chapter 1, the mean GHG emissions and their standard deviation following a single wildfire were estimated at 842±466 Mg CO_2-eq ha^{-1}. For prescribed burnings, we assumed that the mean GHG emissions and their standard deviation were 402±200 Mg CO_2-eq ha^{-1} according to Hiraishi (2014). For each land use, the mean annual GHG emissions due to peat soil combustion were estimated as the product of the years with fire occurrence per pixel and the mean GHG emissions of a single fire episode.

Given that not all of the surface of the pixel burned each time a fire occurred, the burned area was estimated from the density of hotspots per pixel (Fig. 2-5). According to a study in a context similar to that of our study area, the burned area per hotspot is 15-16 ha in a degraded peatland in Central Kalimantan. Other authors found 75 ha in a cropland (Smith et al., 2007), and between 100 and 180 ha in boreal forest (Li et al. 2000; Wotawa 2006). All of the aforementioned studies emphasize the fact that the burned area varies according to climatic conditions, vegetation, level of drainage and fuel available on the land. Given the resources needed for such an assessment, it was not carried out in OKI. However, these values are subject to a large degree of uncertainty and can vary across the land uses.

The average number of hotspots per pixel in our study was 2.5 for degraded peatland, 2.1 for oil palm plantations and 4.3 for pulpwood plantations. The burned area was computed as the product of the average of hotspot fires per pixel for each land use, multiplied by 15.5 ha, the mean of burned area per hotspot estimated by Tansey et al. (2008). This estimate of burned area was used because of the similar context of our study area. The burned area obtained per pixel for each land use to estimate the GHG emissions was 38.75 ha, 32.55 ha and 66.65 ha for degraded peatland, oil palm plantations and pulpwood plantations, respectively. The uncertainty of the burned area affects the regional estimate of GHG emissions because it affects the estimated burned area.

However, it does not affect the estimated GHG emissions reported in Chapter 1 of this thesis and those of Hiraishi et al. (2014).

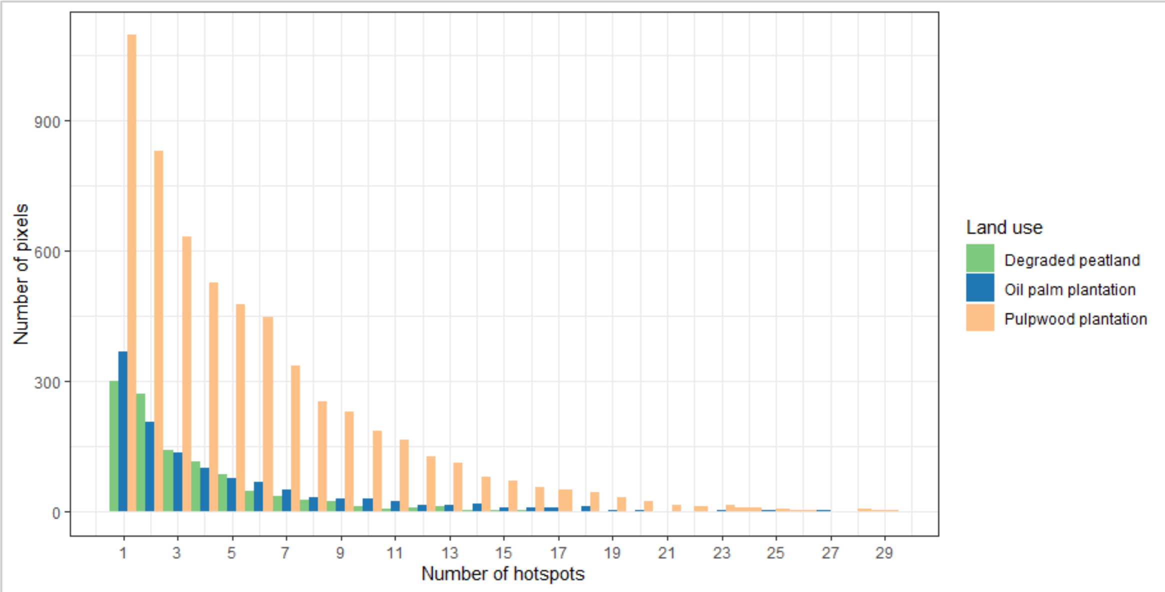


Figure 2-5. Density of hotspot fire per pixel.

2.3. Correction factors of recurrent fires

In the prospective approach (see Chapter 1), the amount of GHG emissions released by peat soil combustion is assumed to be proportional to the depth of burn. A recent study conducted by Konecny et al. (2016) in Central Kalimantan showed that the depth of burn gradually decreases where fires are recurrent. According to this study, the depth of burn in a second fire is 59 % of the one observed after a first fire. After three fires and four or more fires, the depths of burns are 35 % and 12 % of the observed depth of burn after the first fire, respectively. The regional GHG emissions were re-estimated by applying these correction factors based on the number of fires that occurred in each pixel of degraded peatland. Both estimates, with and without correction factors for the depth of burn, were compared. We did not apply any correction factors for recurrent fires in oil palm and pulpwood plantations because it was assumed that these were prescribed burnings under strict control and that the conditions in plantations were different from those in degraded peatlands.

3. Results and discussion

3.1. Fire activity assessment

3.1.1. Fire occurrence

The results shown that the 70 %, 45 % and 76 % of the pixels of degraded peatlands, oil palm and pulpwood plantations, respectively, were affected by fires during the period 2002-2018 (Table 2-2 and Fig. 2-6). The weighted average of years with fires that occurred during the 17 years was 1.45 ±1.37 years for degraded peatlands, 0.98±1.38 years for oil palm plantations and 1.56±1.31 years for pulpwood plantations. Beyond the number of pixels affected by land use, we found that the largest burned area affected per pixel was pulpwood plantations with 84 % of the pixel area affected, followed by degraded peatland with 49 % of the pixel area affected and, finally, oil palm plantations with 41 %. However, no significant difference of fire occurrence was found between land uses due to the large variance of each one.

The frequency of fires occurring within plantation limits may hence be underestimated. On the other hand, fires occurring within plantation may also originate from outside the plantation, which would lead to an overestimation of the frequency of fire occurrences in plantations. Both sources of error are unlikely to compensate for one another.

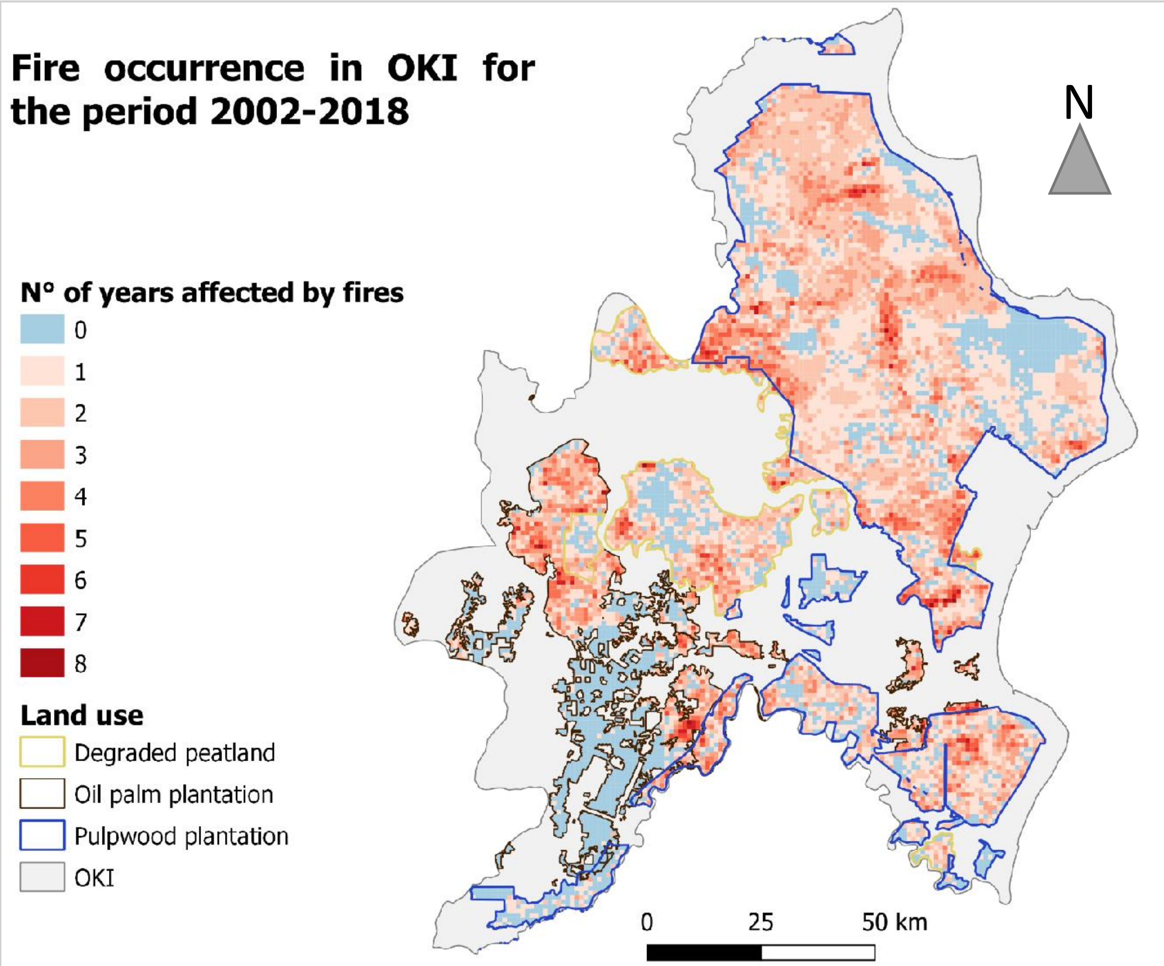


Figure 2-6. Fire occurrence in OKI for the period 2002-2018.

Table 2-2. Number of pixels with fire occurrence in the period 2002-2018.

N° of years with fire occurrence	Degraded peatland	%	Oil palm	%	Pulpwood	%
0	484	30	1539	55	1821	24
1	427	27	476	17	2260	29
2	376	24	347	12	1997	26
3	170	11	238	9	1022	13
4	93	6	117	4	372	5
5	30	2	44	2	151	2
6	16	1	21	1	48	1
7	1	0.06	5	0.18	15	0.20
8	1	0.06	0	0	4	0.05
Total	**1598**	**100**	**2787**	**100**	**7690**	**100**

3.2. Estimated greenhouse gas emissions from peat soil combustion in OKI.

The GHG emissions estimated for the areas affected by fires of the three land uses in OKI during the period 2002-2018 are shown in Table 2-3. Pulpwood plantations were the greatest contributor of GHG emissions among the three land uses, followed by degraded peatlands and oil palm plantations. After applying the correction factors for depth of burn derived from Konecny et al. (2016), the estimate for degraded peatlands decreased to 36,710,505 Mg CO_{2}-eq, a reduction of about 50 %.

Table 2-3. Greenhouse gas emissions from peat combustion in OKI for the period 2002-2018.

Land use	Fire-damaged area (ha/pixel)	Fire-damaged area during 2002-2018 (ha)	GHG emissions (Mg $ha^{-1}yr^{-1}CO_{2}$-eq)	Total GHG emissions during 2002-2018 (Mg CO_{2}-eq)
Degraded peatlands with correction factors	38.75	89,978	24.0	36,710,505
Oil palm plantations	32.55	88,959	23.6	35,761,578
Pulpwood plantations	66.65	799,000	23.6	321,198,080

These correction factors, derived from Konecny et al. (2016), were applied to degraded peatlands affected by wildfires, obtaining a depth of burn of 21 cm in the first fire occurrence. The estimated depth of burn obtained in Chapter 1 for a wildfire in degraded peatland was similar to the estimate obtained by Konecny et al. (2016): 22.8 cm. The fact that both estimates were similar makes it possible to apply these correction factors to degraded peatland land use. However, it is not known if the same results would be obtained using the model of Konecny et al. (2016) for land use types other than degraded peatland. For this reason, the correction factors were not applied to oil palm and pulpwood plantations, which could imply an overestimate of the GHG emissions presented here.

The so-called corrected estimated emissions rely on the assumption that the bulk density remains unaffected by fire. Some studies revealed that the bulk density increases after each fire due to ash accumulation, which, in turn, decreases the availability of oxygen and, consequently, the depth of burn (Ballhorn et al., 2009; Konecny et al., 2016; Sinclair et al., 2020). The fact that the bulk density increases after each fire means that the emissions may not decrease proportionally to the depth of burn due to the increased carbon content. Thus, the use of these correction factors in degraded peatland could lead to an underestimate. It is also not known whether the fire that was considered the first fire by Konecny et al. (2016) is really the first fire. Finally, another uncertainty of these correction factors is the limited field measurements used to validate the results obtained (Wijedasa, 2016).

Despite the different methods used to reduce the uncertainty of the GHG emission estimates, the variability of the parameters always provide an error margin, which should be known. The question is: What is better? To overestimate or to underestimate? Two cases must be considered. The first is the estimate of a baseline scenario and the other is the estimate of the mitigated scenario. In the first case, if the baseline is underestimated, the mitigation measurements will be lower. In the second case, if we overestimate the mitigation scenario impact, it could mean that the evaluated mitigation scenario will not have the expected effect on reducing the impact on climate change.

Regarding the model provided by Konecny et al. (2016), if we know the different parameters involved, the method could be used to reduce the propagation error. If not, the choice to overestimate or to underestimate should be consistent for the baseline and mitigation scenarios.

4. Conclusions

Part II focused on the fire occurrence in OKI for the period 2002-2018. Based on this fire occurrence, we estimated the emissions due to “peat soil combustion” used in Chapter 3 to define the business as usual scenario for OKI.

We found that pulpwood plantations were the greatest contributor of GHG emissions in OKI due to three main reasons: the large surface area of plantations in the study area, the high percentage of pixels with fire occurrence, and the large burned area affected per pixel among the three land uses. However, it is unknown if the fires originated from the plantation or the plantations were affected by accident.

The estimates are subject to a major source of uncertainty. The burned area per pixel is not performed in this study, and it is based on another study developed in a similar context to ours. It is recommended to carry out a burn area assessment in OKI in order to refine the estimate of GHG emissions for the study area.

The correction factors provided by Konecny et al. (2016) applied to degraded peatland land use refer to the depth of burn, the parameter that was the most uncertain, as reported in Chapter 1. The depth of burn decreases after recurrent fires, indicating an overestimate if correction factors are not used. However, if it is not certain how many fires have occurred, the use of these correction factors could underestimate the GHG emissions. In addition, the effect of the increase in bulk density on the depth of burn is unknown. These corrections were not applied to the other land uses because it is not known whether they can be applied to plantations, where the conditions are different. However, they could influence the accuracy of the estimate of GHG emissions, leading to an overestimate if they are not applied.

PART III. BIOMASS TRANSPORTATION TO FACTORIES

1. Introduction

In OKI, both roads and waterways are used to transport freight, the choice of the preferred route depending on weather conditions (Samuel, 2015). In some cases, several means of transport have to be used on the same trip due to poor road conditions. During the dry season, the level of waterways goes down, making the use of freight boats impossible but enabling transportation by road. On the contrary, the wet season favors the transportation on waterways and impedes that on roads.

In this part, a distance assessment was carried out to obtain the minimum, maximum and mean distances for biomass transportation in OKI. In addition, we defined five factory locations that could take the biomass collected in the three land uses under alternative scenarios. The objective was to estimate the influence of the distance of biomass transportation on the total GHG emissions in Chapter 3, and the influence of the distance on transport costs in Chapter 4.

2. Methods

2.1. Definition of factory locations for biomass valorization

The distance assessment of the biomass transportation was carried out in OKI and Palembang (Fig. 2-7). We defined five potential factory locations where we considered that a factory for biomass valorization could be installed:

(1) Asian Pulp & Paper (APP): There is a pulp and paper factory belonging to the APP group. We consider this location as the focal point to sell biomass for the manufacturing of particle panel boards.

(2) Palembang: Palembang is a big city with a huge energy demand, met only by fossil fuel energy at this time. We consider this location to be a potential site of electricity production by heat and co-generation.

(3) Secukai and (4) Pedemaran: These two regions already have some panel board factories that use rubber wood as feedstock. We consider these locations to be potential sites for the valorization of biomass with fiber and particle panel boards.

(5) Sungai Lumpur: This location is the only possible one where liquid biofuel could easily be loaded onto boats or barges and transported at a low cost to any demand point in Indonesia. We consider it to be a potentially ideal site for a bioethanol refinery.

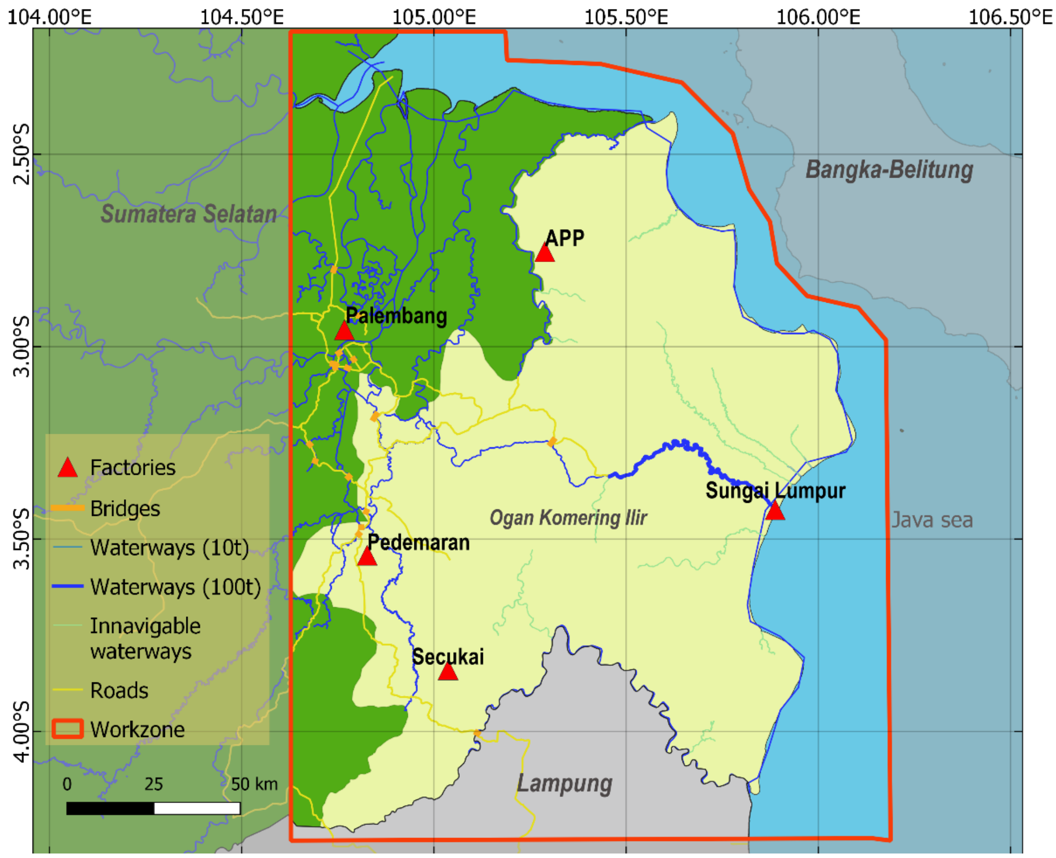


Figure 2-7. Factory locations and vectors for distance assessment. 10t and 100t waterways refers to the capacity of the boat.

2.2. Data sources and analyses

To perform the distance assessment of biomass transportation, we obtained geodata related to roads and waterways from recent studies in the same area (Laithier, 2016; Samuel, 2015). The work zone was defined as a MASK for limiting raster operations in the zone of interest (see Table 2-4 and Fig. 2-7). This area includes OKI, the ocean and the surroundings of Palembang.

Table 2-4. Description of the work zone area

Number of rows	3,187
Number of columns	3,188
Number of pixels	10,160,156
Area of the pixel	3,968m^2 = 63 m x 63 m
Total surface	4,032,405 ha

The rivers were classified according to the transit capacity as "Waterways (10t)" for the small rivers navigable for 10t-capacity boats, "Waterways (100t)" for big rivers navigable for 100t-capacity boats, and "unnavigable waterways" taken into account not for biomass transport but as obstacles in the calculation of distances from one point to another. Bridges make it possible to avoid gaps in road calculations when crossed by a river.

To estimate the distance per pixel assigned to the raster maps, values of the friction cost of the study of Desprès (2015) were assigned to each pixel. The friction cost is a coefficient in kilometers to calculate the real distance according to the state of the routes. In this case, a friction cost of 0.07 km per pixel was used for waterways and roads, and 0.14 km per pixel for off-roads. The friction cost for off-roads is more than double that of the pixel due to the tortuosity of the roads (Desprès, 2015). For unnavigable waterways, a null value was assigned. The vectors of the different routes were eventually converted into rasters and each pixel was assigned the friction value that corresponded to that type of route. Consecutively, the raster maps were overlaid and the distances from any point to the nearest road, waterway and road and waterways together were calculated (Fig. 2-8). The distance from any point to a road and a waterway were computed together in some cases due to the weather conditions or to the fact that the path to the final destination requires the use of both types of routes. Finally, the distance from any off-road point and from roads and waterways to each factory were calculated.

The main tools used were r.mapcalc, r.patch and r.cost of GRASS GIS software.

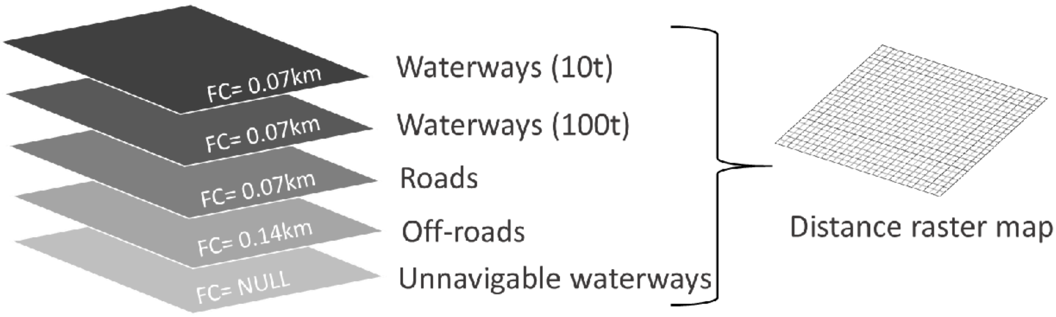


Figure 2-8. Distance map creation process. FC= Friction cost.

3. Results and discussion

3.1. Distances from roads and waterways

The waterways provided greater access to the study area than roads. The average distance from any point to the nearest waterway was 49 km (min=0, max=233) whereas the average distance to the nearest road was 122 km (min=0, max=347) (Fig. 2-9).

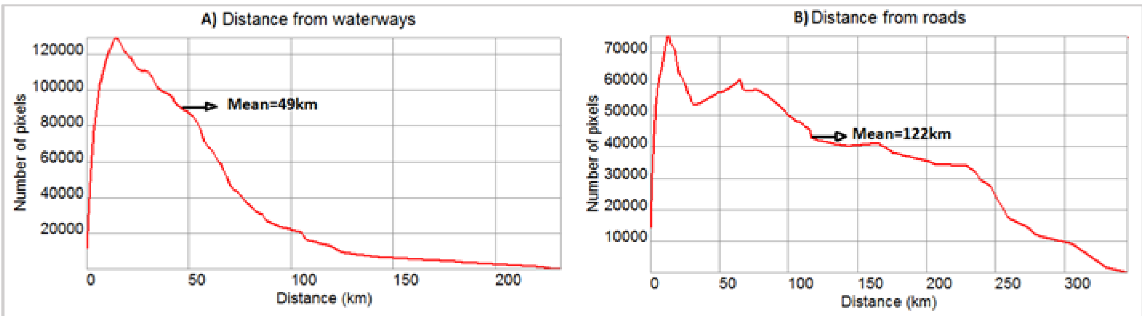


Figure 2-9. Distance from roads and waterways to any point in OKI.

Although the waterways provided a greater access to all of the locations in the study area, it must be stressed that they are not available throughout the year (Fig. 2-10) because of weather conditions or the fact that the use of both routes is necessary due to the path of the final destination. Thus, the distance from roads and waterways together was obtained. The average distance to the nearest road or waterway in the study area was 23 km (min= 0, max= 133) (Fig 2-11).

Figure 2-10. Left: Freight truck freight stranded because of poor road conditions. Road from Palembang to Tulung Selatan. Right: Tulung Selatan port, boat freight of 10t with Hevea sp latex. April 2017.

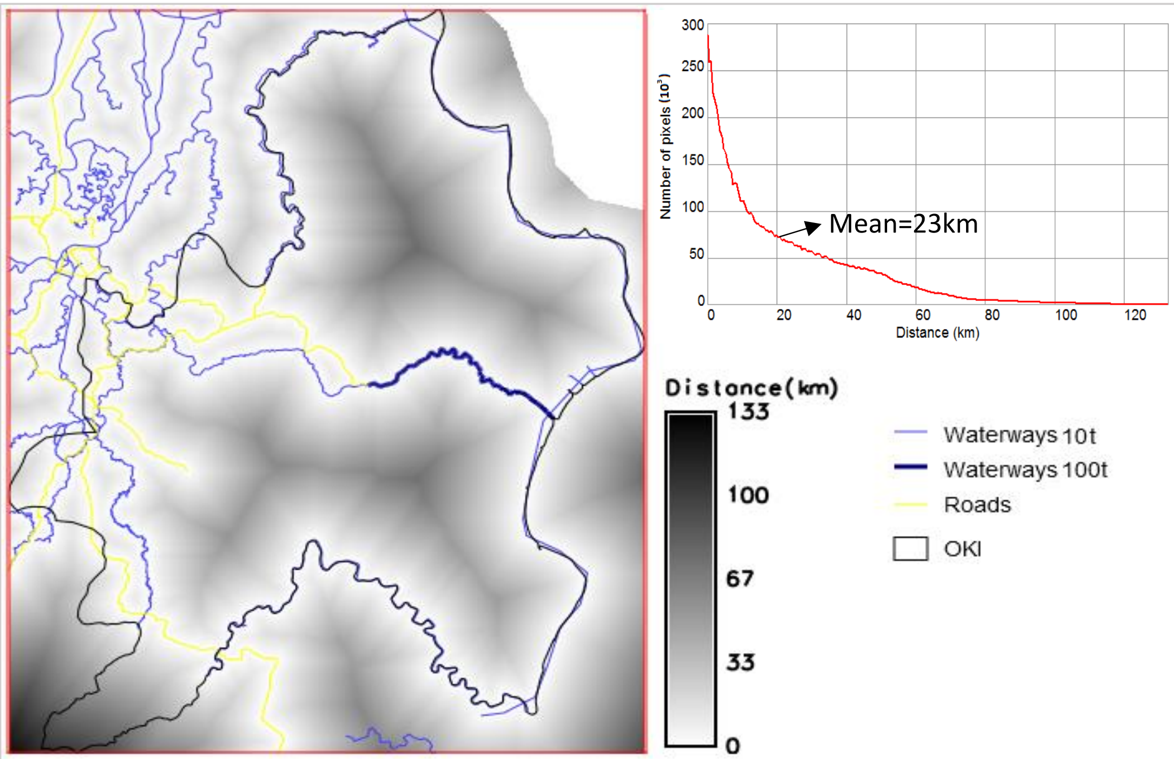


Figure 2-11. Distance from any point to roads and waterways in OKI.

3.2. Distance from factory locations

The average distance to the five factory locations from any point of the off-road were similar (Table 2-5. Distance of the five factories from any point of the off-road). We noted that Palembang, Pedemaran and Secukai all have access to both types of routes, which allows the greater accessibility of biomass transport throughout the year. The APP and Sungai Lumpur locations were limited to waterways, which is important to take into account for logistical reasons. The distance to access a road from the factories is about 0-9 km.

The successive areas of 100 km computed here made it possible to identify the most distant areas of each factory location that would be the least suitable for biomass valorization (Fig. 2-12). The distribution of the degraded peatland area is similar between factory locations. Regarding oil palm plantations, almost 100 % of the area is contained in the first 200 km from Secukai and Pedemaran. For pulpwood plantations, about 80 % of the area is within the first 200 km of Sunga Lumpur. These successive areas were evaluated using different criteria such as biomass concentration, fire occurrence and transportation cost. These criteria are evaluated in Chapter 4.

Table 2-5. Distance of the five factories from any point of the off-road.

	Distance (km)			
	Min	Max	Mean	sd
Palembang	0	482	207	103
APP	0	452	204	103
Pedemaran	0	423	203	93
Secukai	0	433	207	99
Sungai Lumpur	0	424	203	93

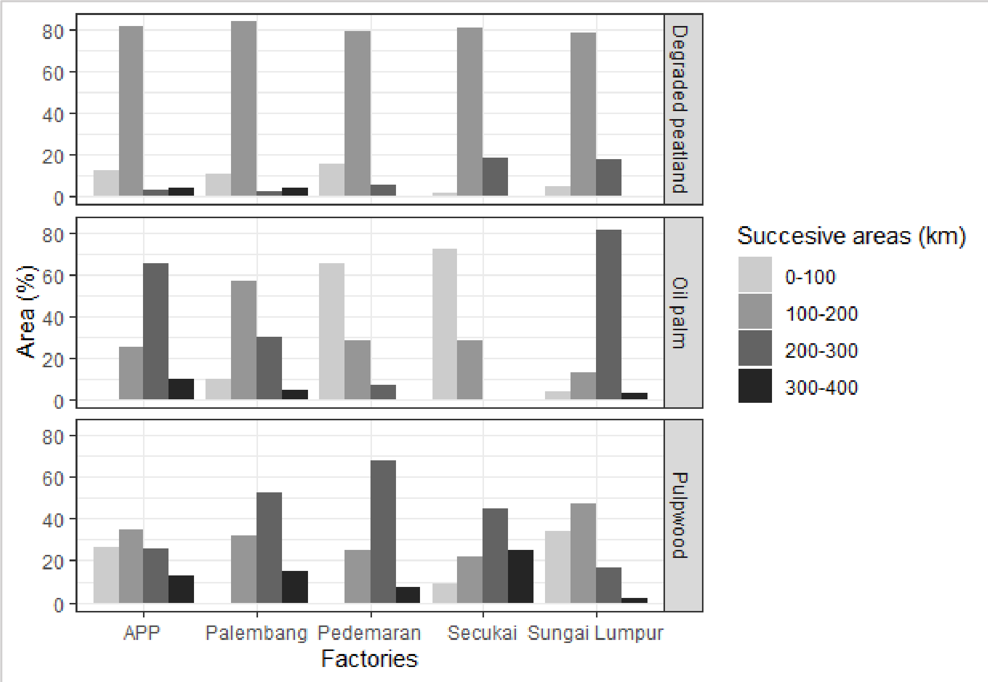


Figure 2-12. Distribution of the surface area of each land use in the successive areas of 100 km from each factory location.

4. Conclusion

The distance assessment made it possible to identify the nearest and farthest points of roads, waterways and factory locations. The waterways give the widest access to the study zone. However, the entire length of the waterways and roads is not accessible throughout the year. For this reason, the distance from the five factory locations was obtained considering the two types of routes together. This may add an extra cost due to the transfer of the biomass from one transportation network to another, which is considered in Chapter 4. However, the study was carried out considering the real context of the study area. The minimum, maximum and mean distances to transport the biomass from any off-road point to the five factory locations evaluated were similar. This assessment made it possible to identify the most distant areas, which are evaluated in detail in the next chapters using different indicators.

Annexes

Data and R script of Part II is found in Dataverse CIRAD as “Fire occurrence in OKI”.

Chapter 3
Life cycle greenhouse gas emissions of biomass valorization in OKI

Scope of Chapter 3

In this chapter, the life cycle greenhouse gas emissions of different land use management scenarios were estimated. To this end, the emission source “Peat soil combustion” and the fire occurrence obtained in ***Chapters 1*** and ***2*** were used to define the “Business as usual” scenarios, then compared with scenarios in which biomass valorization was implemented to decrease fires for land clearing.

1. Introduction

Land clearing practices that use fires to clear biomass are common in peatlands in Ogan Komering Ilir (OKI). This type of land preparation increases the risk of fires spreading to the surrounding areas and contributes significantly to climate change due to carbon loss (Farmer et al., 2011). When biomass burns in peatlands, a proportion of peat soil is also burned, increasing the GHG emissions from fires. In this chapter, several mitigation scenarios are analyzed in order to compare their global contribution to climate change in terms of CO_2-eq with business as usual scenarios. The comparison of mitigation scenarios with business as usual helps to determine whether there is additionality when implementing mitigation scenarios in OKI as an alternative to current land management practices. In this context, the additionality is GHG emissions that can be avoided by implementing mitigation scenarios (IPCC, 2018).

For this purpose, three types of biomass corresponding to the three land uses analyzed in this study (see Chapter 2, Table 2-1) were considered for bioethanol production, combined heat and power generation and panel manufacturing. Bioenergy production was considered as a potential end use for biomass valorization, since OKI is an area with limited access to electricity. It is estimated that around 30 % of households in Sumatera Selatan do not have access to electricity (Asian Development Bank, 2016). In addition, encouraging biomass use for bioenergy production should reduce the use of fossil fuels. Panel manufacturing was also considered because it is an important economic activity in the study area, where factories are already installed for this purpose.

2. Methodology

2.1. Life cycle assessment

Life cycle assessment (LCA) is a methodology used in this study to compare the greenhouse gas (GHG) emissions from different peatland management scenarios. It assesses the potential environmental impacts of a given production system throughout its life cycle, considering all inputs and outputs (ISO, 2006). The main function in this LCA is peatland management. The selected functional unit is then 1 ha of peatland managed over 1 year (1 ha yr). According to the scope of the study, among the different criteria considered in the LCA, the criterion chosen was “Climate change”. The LCA software used was SimaPro 9.0.0.48, with the impact assessment method “IPCC 2013 GWP 100a” developed by the Intergovernmental Panel on Climate Change. This indicator provides the impact in CO_2 equivalent (CO_2-eq).

The assessment was performed for the three land uses studied in this thesis: degraded peatlands, oil palm plantations and pulpwood plantations (see Chapter 2). For each land use, we analyzed five land management scenarios (Fig.3-1).

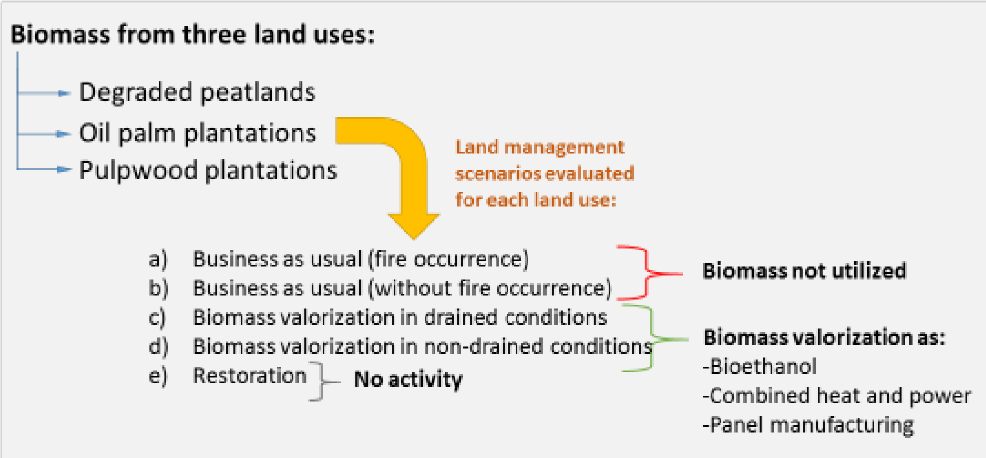


Figure 3-1. Description of the land uses and scenarios considered for the life cycle assessment of GHG emissions.

According to the organization shown in Fig. 3-1, the impact of each scenario was evaluated by defining different emission sources for each scenario (Table 3-1). The emission sources are described in detail below (Section 2.3) and are: Greenhouse gas fluxes from organic soil, C sequestration in aboveground biomass and residues, Peat soil combustion due to fires, Biomass valorization processes, and Substitution from biomass valorization.

Table 3-1. Organization of the peatland management scenarios evaluated. In yellow, the emission source evaluated for each scenario.

Scenarios	Business as usual		Biomass valorization						Restoration
	Fire occurrence	No fire occurrence	Drained	Non-drained	Drained	Non-drained	Drained	Non-drained	Non-drained
Type of biomass valorization / Emission sources	Not utilized		Bioethanol production		Combined heat and power		Panel manufacturing		No activity
Greenhouse gas fluxes from organic soil									
C sequestration in aboveground biomass and residues									
Peat soil combustion due to fires		-	-	-	-	-	-	-	-
Biomass valorization processes	-	-							-
Substitution from biomass valorization	-	-							-

2.2. Description of scenarios

Five scenarios were defined for each land use in order to compare the impact of different peatland management systems on climate change.

The scenario descriptions are as follows:

a) "Business as usual (fire occurrence) and b) Business as usual (without fire occurrence)" (BAU): These scenarios are defined as the baseline to measure the changes that could occur in comparison with the following land management scenarios evaluated here. BAU scenarios were based on current land management using fires and drainage. The areas with and without fire occurrence were differentiated so as to estimate the corresponding impact. The impact of drainage was taken into account for both BAU scenarios for the three land uses, since all of these areas are considered as drained. For the areas affected by fires, the fire occurrence was calculated based on the period 2002-2018 (see Chapter 2, Part II). The fire occurrence obtained for the affected areas was 2.08 years for degraded peatlands, 2.19 years for oil palm plantations and 2.4 years for pulpwood plantations.

c) "Biomass valorization in drained conditions" and d) "Biomass valorization in non-drained conditions": Both scenarios assumed the conversion from current land management practices to a biomass valorization system to prevent the use of fire. In scenario *c*, biomass valorization was analyzed assuming drained conditions, typically around -80 cm for oil palm and -70 cm for pulpwood plantations (Afriyanti et al., 2019; Evans et al., 2019; Evers et al., 2016). The drainage of degraded peatlands is usually indirect, being affected by that of the surrounding lands, and a drainage level of -30 cm was thus assumed.

Scenario *d* was analyzed for degraded peatlands, assuming non-drained conditions, meaning that the water table is between 10 cm below and 10 cm above ground. This scenario is based on the concept of paludiculture. Paludiculture is a biomass cultivation practice in wet or rewetted peatlands that maintains the natural conditions of peatland, enabling peat formation from accumulated biomass. In paludiculture, only the part of net primary production that is not necessary for peat formation is harvested, meaning mostly the plants but not their roots (Wichtmann & Joosten, 2007).

This scenario is not evaluated for oil palm and pulpwood plantations, since these crops cannot be developed under non-drained conditions. In the case of degraded peatlands, paludiculture systems can be considered as a viable alternative. A sensitivity analysis of different levels of drainage was performed and is described in Section 2.4.

e) "Peatland restoration": This scenario is considered for degraded peatlands. It was assumed that the water table is raised in peatlands that were previously drained for forestry, agriculture or other human-related activities in order to re-establish the water-saturated conditions (Wilson et al., 2016). In this case, it was assumed that there was no activity, since the biomass was not utilized for any purpose, in order to enable natural vegetation regeneration to begin.

2.3. Life cycle inventory

The life cycle inventories of these scenarios were based on data from reviews or estimations from meta-analysis reviews performed, which are detailed below for each emission source. The scope of the reviews was tropical peatland, specifically in South Sumatra.

The emission source descriptions used in each scenario are as follows (Table 3-1):

Greenhouse gas fluxes from organic soil: Under natural conditions, the mean water table level is close to the soil surface, with seasonal fluctuations, presenting conditions of water saturation and low oxygen for most of the year (Hiraishi et al., 2014). Carbon is then mostly emitted as CH_4 as a product of biomass decomposition in anaerobic conditions (Hooijer et al., 2006, 2010; IPCC, 2006). When the water table falls due to drainage or strong climate phenomena such as El Niño, the carbon stored in peat soil is oxidized and released into the atmosphere under aerobic conditions as CO_2.

The emission factors used are those from the 2013 Wetlands Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Hiraishi et al., 2014). These guidelines provide the emission factors for peatlands for different land use categories and climate regions, based on flux data for each of the gain and loss terms of the mass balance (Table 3-2). These emission factors assume a drainage level of 30 cm below the surface. However, the literature reports that the drainage level is usually 80 cm below the surface for oil palm plantations and 70 cm for pulpwood plantations (Afriyanti et al., 2019; Evans et al., 2019; Evers et al., 2016; Verwer et al., 2008). Thus, a sensitivity analysis was specifically carried out to estimate the effect of the drainage level on GHG emissions, from 30 cm as provided by the IPCC, to 80 cm below the surface for oil palm plantations and 70 cm for pulpwood plantations (see Section 2.5). For degraded peatlands, the IPCC default value is used since drainage is indirect and varies according to the surroundings plantations.

Table 3-2. Emission factors for drained and non-drained peatlands according to the IPCC 2013 Wetlands Supplement (2014) (standard deviation in brackets).

IPCC land use category	CO_2-C (t ha^{-1} yr^{-1})	CH_4 (kg ha^{-1}yr^{-1})	N_2O-N (kg ha^{-1}yr^{-1})	Corresponding land use in this study	Related scenarios[1]
Cleared Forest Land (shrub land), drained	5.3(±2)	4.9(±2.6)	2.4(±1.1)	Degraded peatland	a-b-c
Rewetted peatland or paludiculture management	0	41(±17)	NA	Degraded peatland-Pulpwood-Oil palm	d-e
Plantations, drained, short rotations, e.g. acacia	20(±4)	2.7(±3.6)	3.77(NA)	Pulpwood	a-b-c
Oil palm plantations	11(±6)	0	1.2(NA)	Oil palm	a-b-c

[1)]a and b) “Business as usual” scenarios; c) “Biomass valorization in drained conditions”; d) “Biomass valorization in non-drained conditions” and e) “Peatland restoration”.

C sequestration in aboveground biomass and residues: To estimate the carbon that will be released into the atmosphere due to the valorization of biomass, a review of carbon sequestration in biomass was performed (Table 3-3). For degraded peatlands, the carbon sequestered per year in aboveground biomass during regeneration was used. For biomass from oil palm and pulpwood plantations, the carbon sequestration in residues at the end of the rotation was used and then divided by the rotation time to obtain the values of carbon sequestered per year (see Chapter 2, Table 2-1 for more details).

Table 3-3. Sources of carbon sequestered in biomass (standard deviation in brackets).

Land use	C sequestered in waste (t $ha^{-1} yr^{-1}$)	Reference	Observation
Degraded peatlands	2.15(±1)	(Basuki et al., 2016; Chave, 2015; Poorter et al., 2016; Requena Suarez et al., 2019)	
Oil palm plantations	2.32(NA)	(Roda et al., 2015)	4.64 t ha^{-1} yr^{-1} of dry matter assuming 50 % carbon content
Pulpwood plantations	2.7(±1.5)	(Nurwahyudi, 2001; Okimori et al., 2003)	5.4 t ha^{-1} yr^{-1} of dry matter assuming 50 % carbon content

Peat soil combustion due to fires: This emission source was estimated in Chapters 1 and 2, where the GHG emissions from peat combustion during fire episodes were obtained. Two types of fires were considered: wildfires occurring in degraded peatlands and prescribed fires occurring in plantations. The mean annual GHG emissions from peat soil combustion were estimated by multiplying the fire occurrence in the affected areas for each land use by the corresponding amount of GHG emissions from peat combustion, whether prescribed fires or wildfires, and dividing by 17 years (baseline period). For degraded peatland, we obtained an amount of 50 Mg CO_2-eq $ha^{-1}yr^{-1}$, 52 Mg CO_2-eq $ha^{-1}yr^{-1}$ for oil palm plantations and 48 Mg CO_2-eq $ha^{-1}yr^{-1}$ for pulpwood plantations.

Biomass valorization processes, including bioethanol production, combined heat and power generation, and panel manufacturing: The impact of biomass valorization processes was adapted from the *ecoinvent* database (Bauer, 2007; Werner et al., 2007).

Biomass transportation was included in this emission source, considering an average distance of 200 km. This average distance was obtained from the distance assessment carried out in Chapter 2 - Part III, for which biomass transportation to five factory locations is assumed: APP, Palembang, Secukai, Pedemaran and Sungai Lumpur. A sensitivity analysis was carried out to evaluate the impact of this average distance on this emission source, using the minimum and maximum distances found in the distance assessment (see Section 2.5).

Substitution from biomass valorization, including production and use of kerosene, combined heat and power from coal, and panel manufacturing from dedicated plantations: The end products of biomass valorization are assumed to substitute reference products. The reference products are then considered as avoided products: fossil kerosene substituted by bioethanol, combined heat and power generation from coal substituted by generation from biomass, and panel manufacturing from biomass waste. The impact of these reference processes was evaluated from the ecoinvent database (Bauer, 2007; Edwards et al., 2014; Werner et al., 2007). The value obtained is accounted as negative since it represents avoided emissions due to substitution. Kerosene and ethanol were considered equivalent on an energy basis.

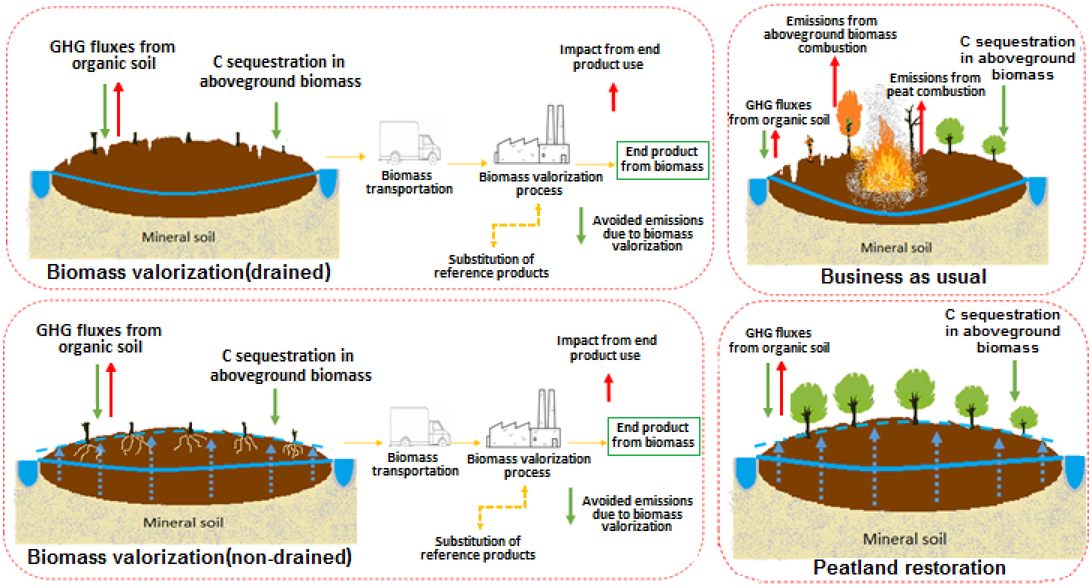


Figure 3-2. Representation of compared scenarios and the respective emission sources evaluated in each scenario. Red arrows represent emissions and green arrows represent carbon sequestration.

2.4. Uncertainties

A Monte Carlo simulation was carried out with 50 000 realizations using the SimaPro software to obtain the uncertainties for each scenario. The same approach was then used to obtain the probability that the impacts of one scenario remains greater or lower than those of the others, despite their respective uncertainties. These comparisons between scenarios were applied only for cases where the uncertainties were overlapping (Fig. 3-3).

For these comparisons, when known, the standard deviation of the parameters of the different emission sources was processed with the SimaPro software along with the uncertainties provided by the ecoinvent database. For the “Peat soil combustion” in wildfires emission source, the uncertainties were calculated in Chapter 1. For the other emission sources, the uncertainties were taken from each reference (see related Tables in Section 2.3).

2.5. Sensitivity analyses

Two sensitivity analyses were carried out:

1) Distance from the different factory locations: The impact of biomass transportation is included in the emission source "Biomass valorization processes". The mean distance used was 200 km, which was similar for the five factories. To estimate the influence of different distances for biomass transportation, this mean was replaced by the minimum and maximum distances, 50 km and 500 km respectively (see Chapter 2 - Part III).

2) Drainage level: The emission factors shown in Table 3-2 were used to estimate the impact of the emission source "Greenhouse gas fluxes from organic soil". As explained previously, the values from the 2013 IPCC Guidelines assume a drainage level of 30 cm below the surface. To estimate the impact of different levels of drainage on the GHG assessments, a sensitivity analysis was carried out. The different situations considered are given in Table 3-4.

Table 3-4. Main recommendations regarding the drainage level for different land uses

Land use	Drainage level (cm)	Observation	Reference
Oil palm plantations	80	Current level of drainage used	Afriyanti et al. (2019), Evers et al. (2016) and Verwer et al., (2008)
Pulpwood plantations	70	Current level of drainage used	Evans et al. (2019)
Oil palm plantations	30	Minimum level of drainage that can be managed	Afriyanti et al. (2019) and Evers et al. (2016)
Pulpwood plantations	40	Minimum level of drainage that can be managed	Evans et al. (2019)
Oil palm plantations	50	Roundtable on Sustainable Palm Oil (RSPO) criteria	Parish et al. (2019)
Degraded peatlands	30	IPCC default value	Hiraishi et al., (2014)
Oil palm plantations	30	IPCC default value	Hiraishi et al., (2014)
Pulpwood plantations	30	IPCC default value	Hiraishi et al., (2014)
All	40	Government recommendation	Evans et al. (2019)

The impact of the variability of drainage levels on GHG emissions was estimated by means of two studies. The first is a study by Couwenberg et al. (2010), who found that for each additional 10 cm of drainage level up to 50 cm below the surface, the CO_2 flux increased by 9.0 t ha^{-1} yr^{-1} (R^2=0.75). This value is the result of a meta-analysis based on gas fluxes from tropical peat soils in Southeast Asia and related subsidence data.

The second study found a similar value of 9.1 t ha^{-1} yr^{-1} of CO_2 for each additional 10 cm of drainage level below the surface up to 1 m. It is based on experimental measurements of CO_2 fluxes in relation to water depth and long-term monitoring of peat soil subsidence, obtaining a linear relationship of R^2=0.71 (Hooijer et al., 2010). This study was carried out in drained peatlands occupied by croplands and shrublands (or recently cleared and burned) in Indonesia, Malaysia, Brunei and Papua New Guinea, using data on the thickness of peat soil, the carbon content and the drainage level.

Methane emissions were not taken into account in these studies, since they occur in high water levels, up to approximately 20 cm below ground (Couwenberg et al., 2010).

The sensitivity analysis was carried out using the mean of both studies, 9 t ha^{-1} yr^{-1} of CO_2 for each 10 cm added to the drainage level, assuming a maximum drainage level of 100 cm. This additional amount obtained from these studies was added to the total amount obtained for the "Greenhouse gas fluxes from organic soil" source, assuming the same emission factors for other GHGs such as CH_4.

2.6. The GHG emissions balance at OKI

The objective of the GHG emissions balance was to estimate the total amount of GHGs emitted yearly for each land use studied in OKI in order to implement mitigation scenarios as an alternative type of land management. A general BAU scenario was computed by adding both BAU scenarios, with and without fire occurrence (Eq.3-1), for each land use. Next, the impact of the biomass valorization scenarios was computed for the total of each land use in OKI (Eq.3-2) and then compared with the general BAU scenario.

$$BAU_{OKI,land\ use\ i,D\ or\ ND} = (A_{F,i} \times BAU_{F,D\ or\ ND} + A_{NF,i} \times BAU_{NF,D\ or\ ND}) \qquad (3\text{-}1)$$

where $BAU_{OKI,\ land\ use\ i,\ D\ or\ ND}$ is the GHG emissions of business as usual scenarios for the three land uses, in drained and non-drained conditions separately at the OKI scale in Mg CO_2-eq ha^{-1} yr^{-1}, A_F is the area affected by fires in ha, BAU_F is the GHG emissions estimated for the business as usual scenario with fire occurrence in Mg CO_2-eq ha^{-1} yr^{-1}, A_{NF} is the area unaffected by fires in ha, and BAU_{NF} is the GHG emissions estimated for the business as usual scenario without fire occurrence in Mg CO_2-eq ha^{-1} yr^{-1}. A_F and A_{NF} were obtained in Chapter 2.

$$LM_{OKI,land\ use\ i,D\ or\ ND} = E_{D\ or\ ND} \times A \qquad (3\text{-}2)$$

where $LM_{OKI,\ land\ use\ i,\ D\ or\ ND}$ is the GHG emissions of each land management scenario for the three land uses, in drained and non-drained conditions separately at the OKI scale in Mg CO_2-eq ha^{-1} yr^{-1}, E is the GHG emissions estimated for each land management scenario in Mg CO_2-eq ha^{-1} yr^{-1}, and A is the total surface area for each land use.

For the scenarios in drained conditions, the corrected value of the CO_2 emission factor obtained in the sensitivity analysis of drainage levels was used: 30 cm below ground for degraded peatlands, 80 cm below ground for oil palm plantations, and 70 cm below ground for pulpwood plantations.

3. Results

3.1. GHG emissions of land management scenarios

The GHG emissions evaluated for the BAU scenario with fire occurrence in degraded peatlands, oil palm plantations and pulpwood plantations were respectively 70.60±30, 139.40±31 and 159±27

Mg CO_2- eq ha^{-1} yr^{-1} (Fig. 3.3). The GHG emissions evaluated for BAU without fire occurrence were 18.45±12, 85.08±21 and 108.3±15 Mg CO_2-eq ha^{-1} yr^{-1} for degraded peatlands, oil palm plantations and pulpwood plantations respectively. Both of the BAU scenarios were compared below with the biomass valorization scenarios for each land use.

Regarding the restoration scenario, the GHG emissions estimated were the same for the three land uses, - 0.90 Mg CO_2-eq ha^{-1} yr^{-1}. This scenario assumed the reconversion of the land to natural peatland.

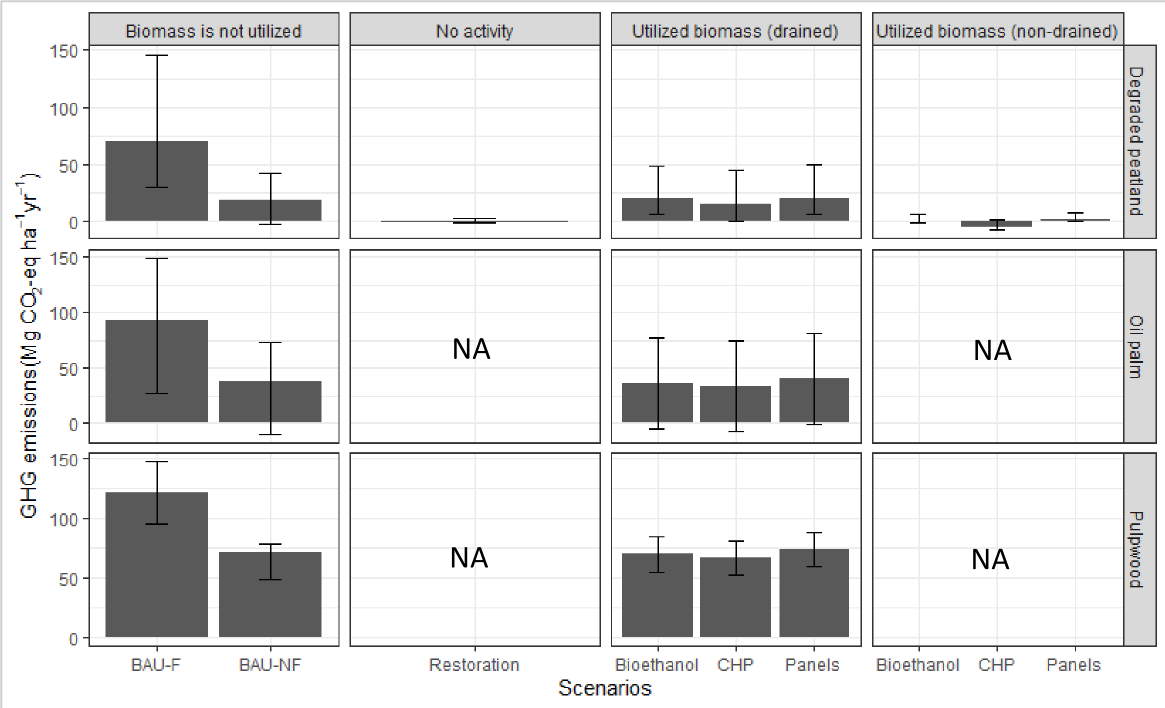


Figure 3-3. Life cycle GHG emissions of land management scenarios for the three land uses, in CO_2-eq (Mg ha^{-1} yr^{-1}). BAU-F = Business as usual with fire occurrence, BAU-NF = Business as usual without fire occurrence, and CHP = Combined heat and power generation.

3.1.1. Degraded peatlands

Regarding the biomass valorization scenarios in drained and non-drained conditions separately, the impacts of the three types of biomass valorization are similar. In all cases, biomass valorization could avoid around 74 % of GHG emissions in drained conditions and 99 % in non-drained conditions compared with the BAU with fire occurrence scenario (Fig. 3-4). On the contrary, the impacts of the biomass valorization scenarios in drained conditions are similar to the BAU without fire occurrence scenario for the three types of valorization, while scenarios in non-drained conditions and restoration presented a smaller impact than both of the BAU scenarios. Biomass valorization for combined heat and power generation had the smallest impact of all scenarios, followed by the restoration scenario.

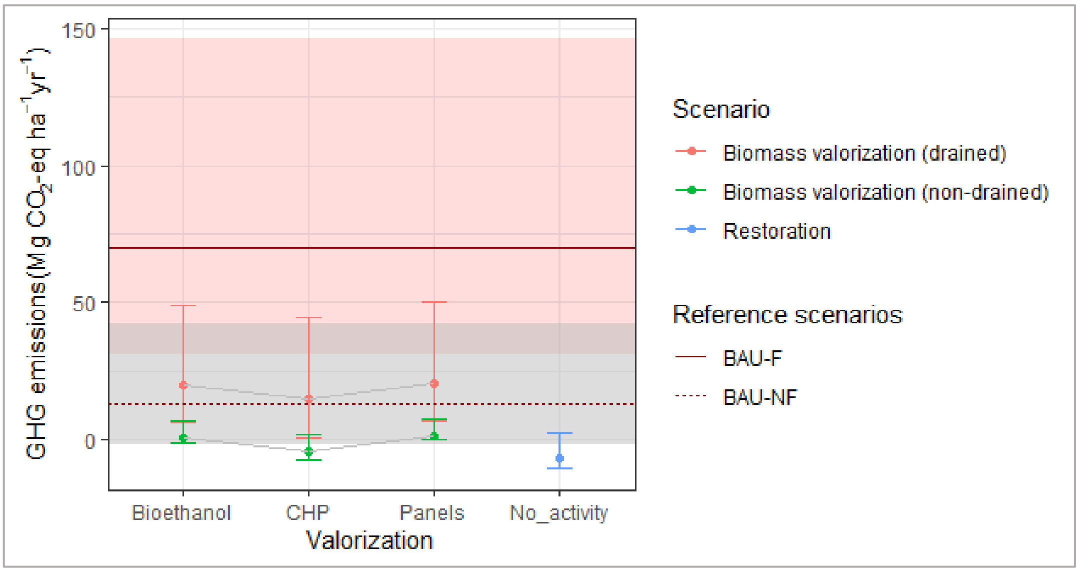


Figure 3-4. Greenhouse gas emissions of the different land management scenarios compared with the reference scenarios in degraded peatlands. BAU-F = Business as usual with fire occurrence, BAU-NF = Business as usual without fire occurrence, and CHP = Combined heat and power generation. The error bars and shaded areas of the reference scenarios are the confidence interval at 95 %.

Fig. 3-5 shows the contribution of each emission source to the overall GHG emissions. We can observe that in the BAU with fire occurrence scenario, the main contributing emission source is peat soil combustion.

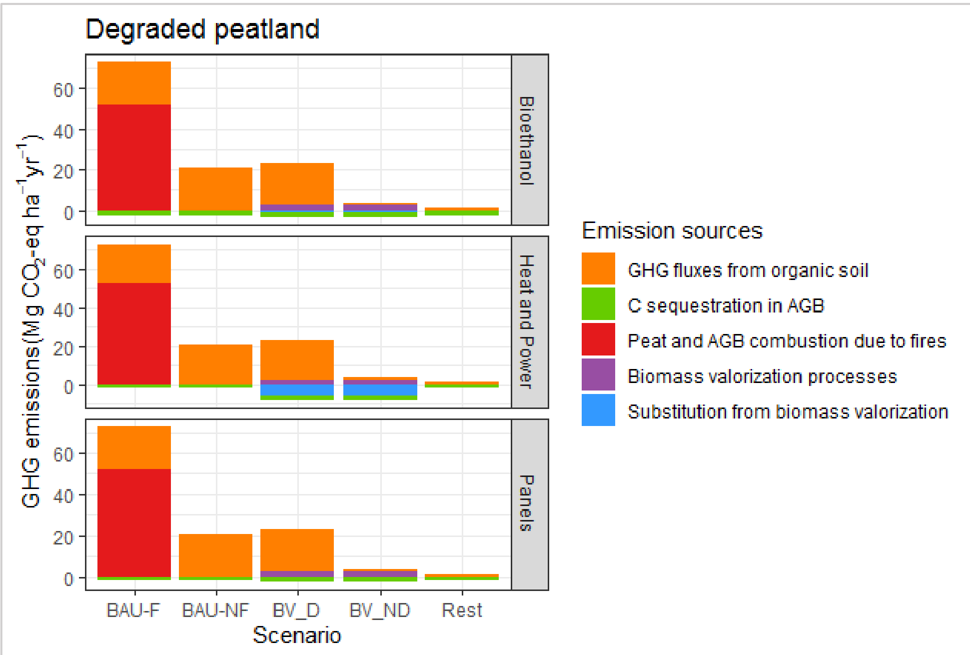


Figure 3-5. Detailed life cycle GHG emissions of the different land management scenarios. BAU-F = Business as usual with fire occurrence, BAU-NF = Business as usual without fire occurrence, BV_D = Biomass valorization in drained conditions, and BV_ND = Biomass valorization in non-drained conditions.

For biomass valorization scenarios in drained conditions, the main contributing emission source is GHG fluxes from organic soil. For biomass valorization scenarios in non-drained conditions, the main contributing emission source was the impact of biomass valorization. The restoration scenario presents a small impact from GHG fluxes from organic soil and the carbon stock in biomass produced a negative net amount of emissions.

3.1.2. Oil palm plantations

Similar to the case of degraded peatlands, the impacts of the three types of biomass valorization are similar. In all cases, biomass valorization could avoid around 60 % of GHG emissions in drained conditions compared to the BAU with fire occurrence scenario (Fig. 3-5). On the contrary, the impacts of the biomass valorization scenarios in drained conditions are similar to the BAU without fire occurrence scenario for the three types of valorization. Biomass valorization for combined heat and power generation had the smallest impact of all scenarios.

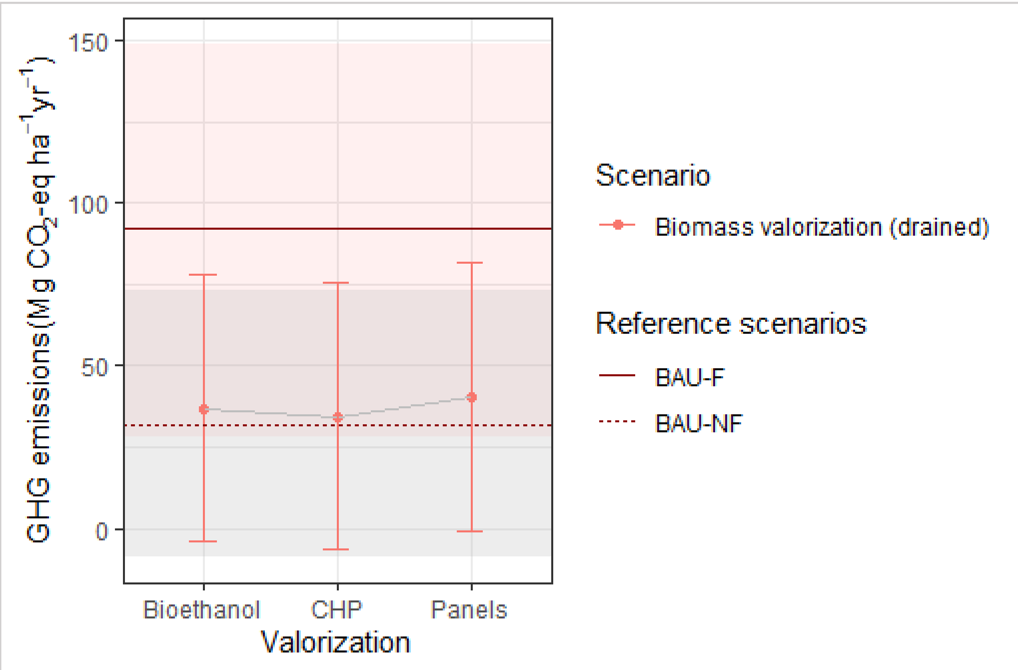


Figure 3-6. Greenhouse gas emissions of the different land management scenarios compared with the reference scenarios in oil palm plantations. BAU-F = Business as usual with fire occurrence, BAU-NF = Business as usual without fire occurrence, and CHP = Combined heat and power generation. The error bars and shaded areas of the reference scenarios are the confidence interval at 95 %.

We can observe in Fig. 3-7 that in the BAU scenarios and the scenarios in drained conditions, the main contributing emission sources are GHG fluxes from organic soil and peat soil combustion, with 80.40 and 52.0 Mg CO_2-eq ha^{-1} yr^{-1} respectively.

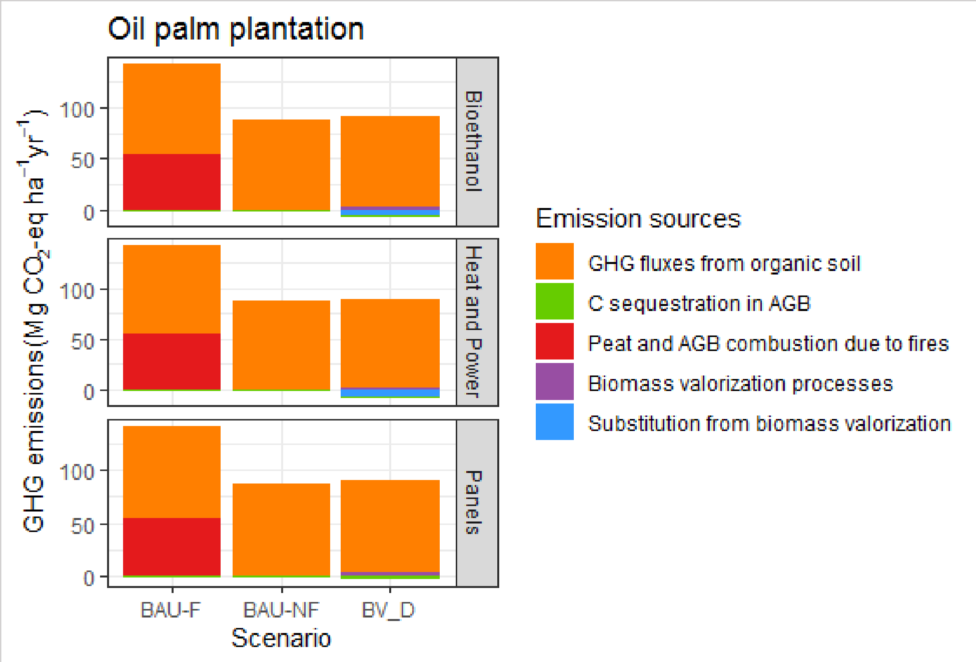


Figure 3-7. Detailed life cycle GHGs of the different land management scenarios. BAU-F = Business as usual with fire occurrence, BAU-NF = Business as usual without fire occurrence, BV_D = Biomass valorization in drained conditions.

3.1.3. Pulpwood plantations

In pulpwood plantations, biomass valorization could avoid around 40 % of GHG emissions in drained conditions compared with the BAU with fire occurrence scenario (Fig. 3-8).

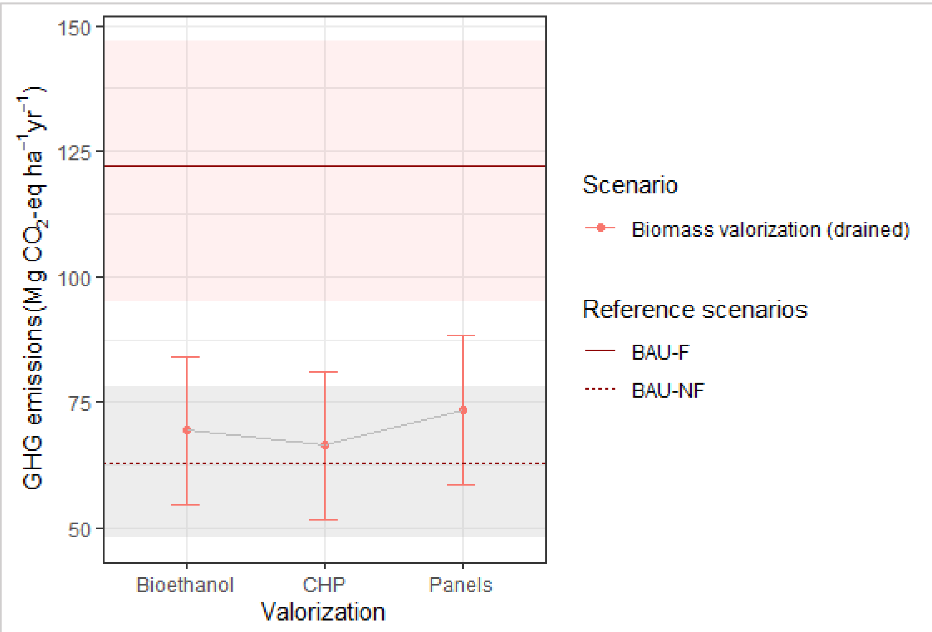


Figure 3-8. Greenhouse gas emissions of different land management scenarios compared with the reference scenarios in pulpwood plantations. BAU-F = Business as usual with fire occurrence, BAU-NF = Business as usual without fire occurrence, and CHP = Combined heat and power generation. The error bars and shaded areas of the reference scenarios are the confidence interval at 95 %.

On the contrary, the impact of the biomass valorization scenarios in drained conditions are similar to the BAU without fire occurrence scenario for the three types of valorization

Fig. 3-9 shows the contribution of each emission source to the overall GHG impacts. We can observe that in the BAU scenarios and the scenarios in drained conditions, the main contributing emission source is GHG fluxes from organic soil with 111 Mg CO_2-eq ha^{-1} yr^{-1}, followed by peat soil combustion with 48.0 Mg CO_2-eq ha^{-1} yr^{-1}.

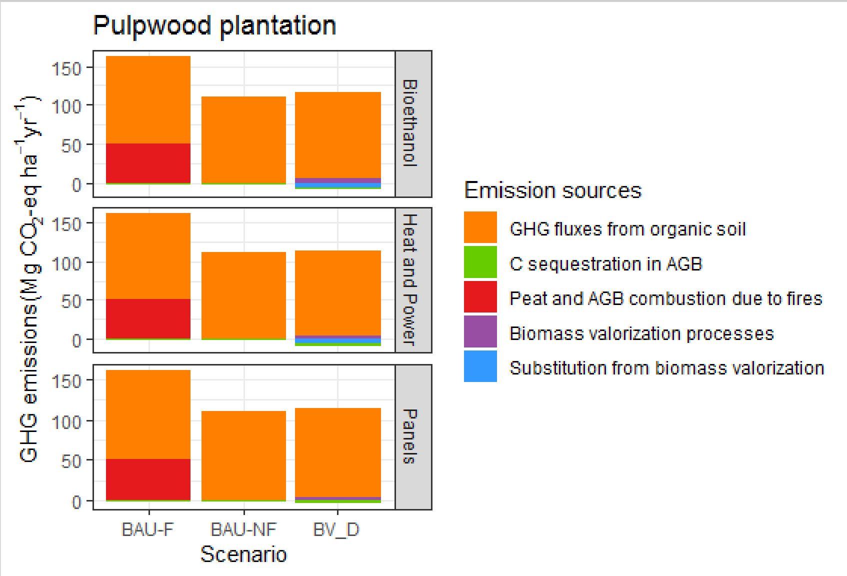


Figure 3-9. Life cycle GHG emissions of the different land management scenarios. BAU-F = Business as usual with fire occurrence, BAU-NF = Business as usual without fire occurrence, BV_D = Biomass valorization in drained conditions.

3.2. Sensitivity analyses

1) Distance from the different factory locations: The sensitivity analysis of biomass transportation for the three land uses showed that the amount of GHGs estimated above with the mean of 200 km (Fig. 3-10) did not differ significantly from the biomass transportation distances tested, at 50 km and 500 km.

Indeed, the contribution of the impact of the biomass valorization processes was around 10 % of the total impact of the biomass valorization scenarios, and biomass transportation represented around 20 % of this emission source. Consequently, the biomass transportation distances in OKI do not significantly affect the overall GHG emissions.

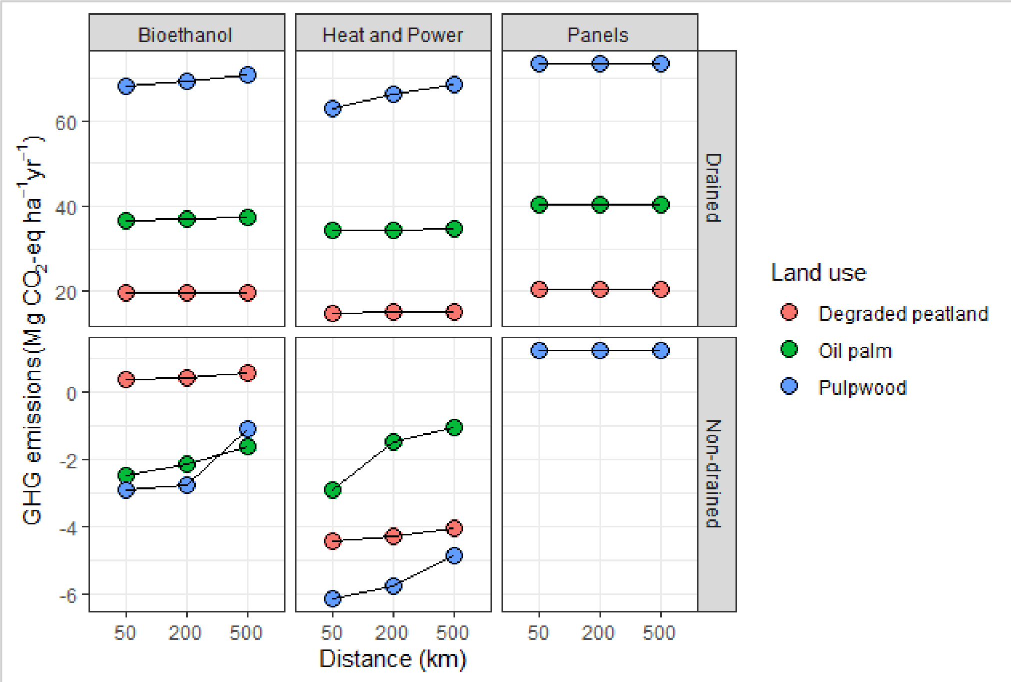


Figure 3-10. Results of the sensitivity analysis for biomass transportation distances.

2) <u>Drainage level:</u> This sensitivity analysis showed a significant influence of the drainage level on GHG emissions. Considering the current drainage level of 80 cm for oil palm plantations and 70 cm for pulpwood plantations instead of the IPCC default value of 30 cm increased the GHG emissions by 47 and 37.6 Mg CO_2 ha^{-1} yr^{-1} respectively (Fig. 10 and 11).

In the case of degraded peatland, since the drainage level is subject to the conditions of the surrounding lands, the current level is assumed the same as the initial estimation of 30 cm below ground.

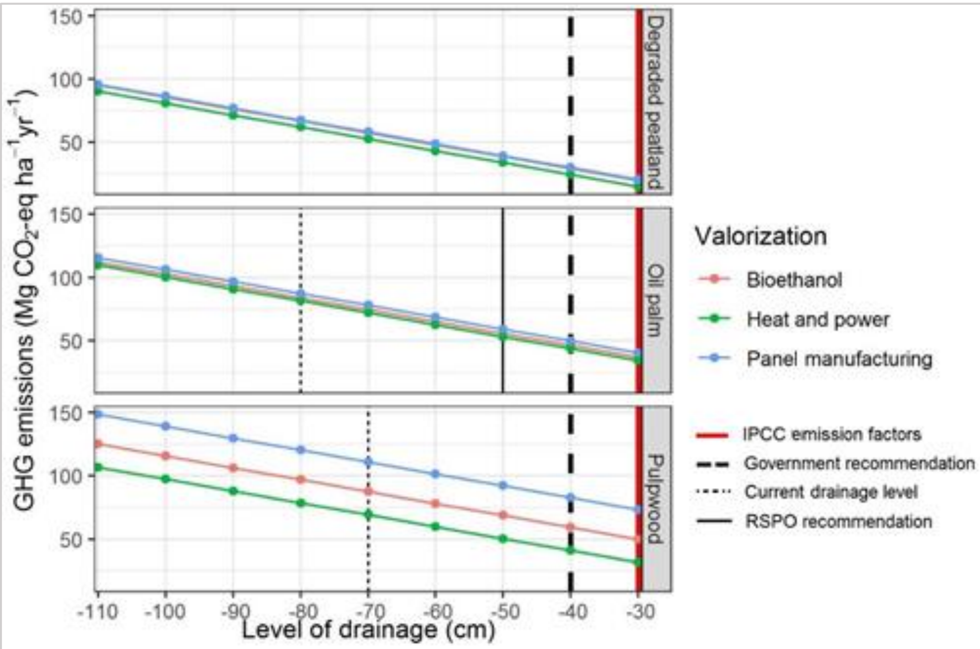


Figure 3-11. Results of the sensitivity analysis for the drainage level.

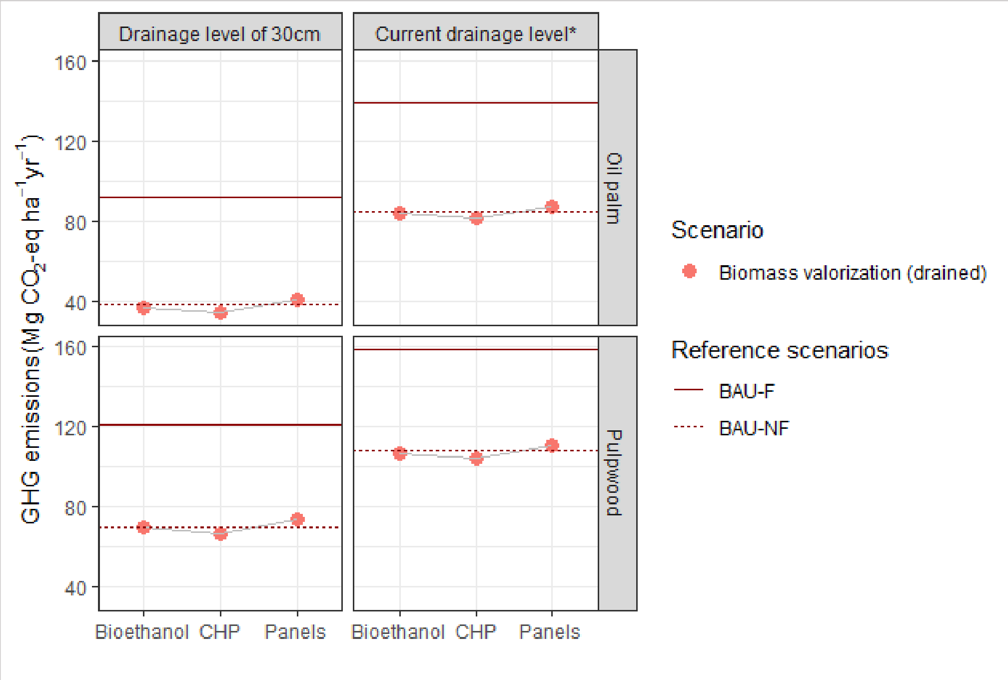


Figure 3-12. Comparison of the GHG emissions of biomass valorization scenarios in drained conditions between the default values or current values of drainage levels.

3.3. Uncertainties

The comparisons between scenarios were carried out only for cases where the uncertainties were overlapping. The uncertainties obtained for the different land management scenarios are often considerable, with overlapping between the scenarios evaluated in degraded peatlands. However, the certainty that the impact of a scenario is greater or lower than another, despite the uncertainty found in each scenario is shown in Table 3-5. For all of the scenarios, we confirmed the difference between scenarios with a certainty of more than 95 %.

Table 3-5. Comparison of uncertainties between scenarios

Land use	Type of valorization	A) Scenario with more emissions	B) Scenario with fewer emissions	Certainty of A >= B (%)
Degraded peatlands	Bioethanol	Non-drained	Restoration	100
		Drained	Non-drained	99
		Drained	BAU-NF	100
	Combined heat and power	Non-drained	Restoration	100
		Drained	Non-drained	99
		Drained	BAU-NF	100
	Panel manufacturing	Non-drained	Restoration	100
		Drained	Non-drained	99
		Drained	BAU-NF	100

3.4. The GHG emissions balance in OKI

The GHG emissions balances in OKI were estimated taking into account the correction of the CO_2 emission factor obtained from the drainage level sensitivity analysis as shown in Table 3-6. Fig. 3-13 shows the global impact of each land management scenario in drained and in non-drained conditions for degraded peatlands, compared with a combination of both BAU scenarios, taking into account the areas with and without fire occurrence.

Table 3-6. Correction of the CO_2 emission factor of drainage levels for scenarios in drained conditions

	Default values		Corrected values	
	Emission factor for CO_2-C (t ha^{-1} yr^{-1})	Drainage level below the surface (cm)	Emission factor for CO_2-C (t ha^{-1} yr^{-1})	Drainage level below the surface (cm)
Degraded peatland	5.3	30	Not applied	-
Oil palm	11	30	23.8	80
Pulpwood	20	30	30.3	70

At the OKI regional level, the impact of biomass valorization in drained conditions could reduce GHG emissions by 10 % in degraded peatlands, by 2 % in oil palm plantations and by 4 % in pulpwood plantations. The differences between the three land uses can be explained by the drainage level, which is lowest for degraded peatlands among the three land uses, followed by oil palm and then pulpwood plantations. However, the 30 cm drainage level assumed for degraded peatlands is uncertain because the drainage level can vary depending on the surrounding lands.

In non-drained conditions, the impacts of biomass valorization scenarios are lower than the impact of BAU. This is because the main emission sources, i.e. peat soil combustion and GHG fluxes from organic soil, could be avoided, whereas in drained conditions only emissions from peat soil combustion could be avoided.

Among the three types of biomass valorization, combined heat and power is the scenario with the lowest impact for the three land uses. The restoration scenario was assumed only for degraded peatlands, since the objective is not to change the type of land use, as discussed below.

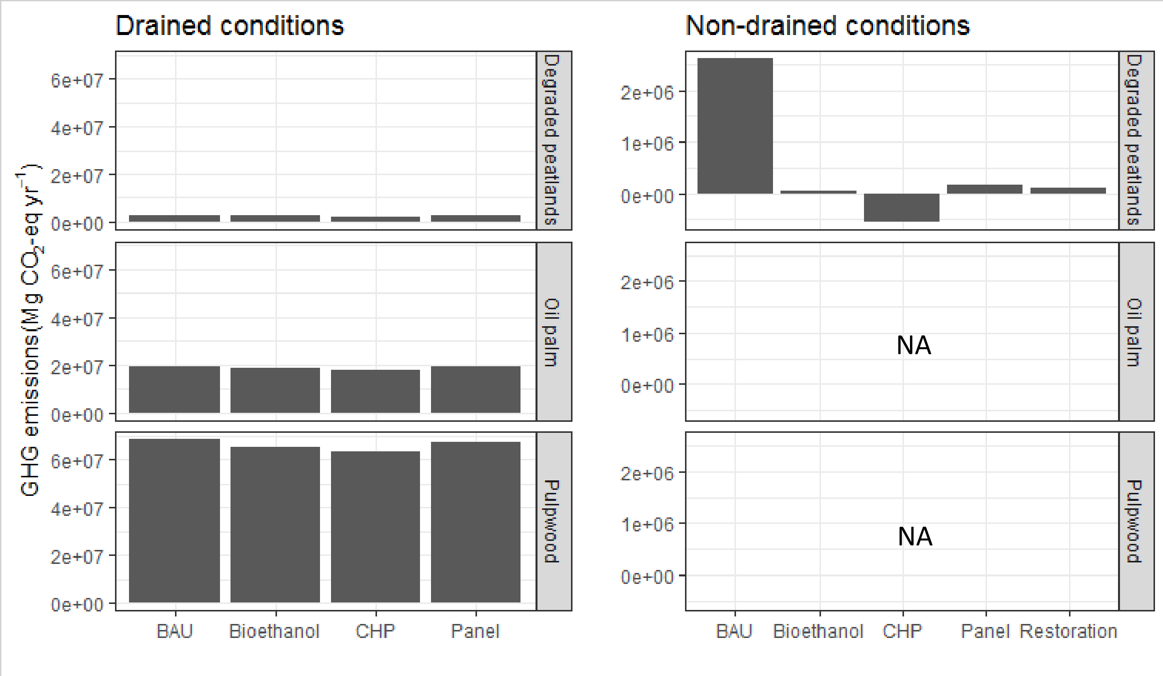


Figure 3-13. The GHG emission balance in OKI for biomass valorization scenarios in drained and non-drained conditions. BAU = Business as usual scenario taking into account areas with and without fire occurrence, and CHP = Combined heat and power generation.

4. Discussion

4.1. The impact of land management scenarios and their implementation in OKI

From the land management scenarios considered, we obtained the impact of each one for a functional unit of 1 ha of peatland managed for 1 year, which enabled us to compare them. We then assessed the impact these scenarios could have when implemented at the OKI regional level.

Regarding land management scenarios, the BAU scenarios represent the current land management situation using drainage and fire in peatlands in OKI. We confirmed that BAU with fire occurrence was in all cases the scenario that produced the most GHG emissions. The main emission source for BAU with fire occurrence scenarios was “Peat soil and combustion” for degraded peatlands and “GHG fluxes from organic soil” for oil palm plantations and pulpwood plantations. In the BAU without fire occurrence and biomass valorization scenarios, the main emission source was “GHG fluxes from organic soil”.

The scenarios in non-drained conditions evaluated in degraded peatlands presented the lowest impact. This result can be explained by the low drainage level, leading to waterlogged and anaerobic conditions, which enable carbon accumulation in peat soil due to the inhibition of biomass decomposition (Page et al., 2004; Ritzema & Wösten, 2006). On the contrary, when the peatland is drained, CO_2 emissions increase because of greater oxygen availability, which enables rapid biomass decomposition, inducing dead matter loss as CO_2 (Bragazza et al., 2009; Hoyos-Santillan et al., 2015). This is congruent with the study by Evans et al. (2019) in Sumatra, which found that in *Acacia* plantations and peatland forests, the main predictor of subsidence is the drainage level, losing around 4.2 cm yr^{-1} of peat soil as gas fluxes.

GHG emissions from biomass valorization scenarios in non-drained conditions were close to those in the “restoration” scenario. The scenarios in non-drained conditions were not evaluated for oil palm and pulpwood plantations because that would be difficult to implement since these crops cannot be cultivated in non-drained conditions.

Regarding the impact of each type of biomass valorization, the impact of panel manufacturing is higher than that of bioethanol production and combined heat and power generation. Since, in the latter two, the benefit of replacing fossil fuels with bioenergy is greater than that of replacing wood panels with biomass waste panels.

At the OKI regional level, we obtained that the impact of implementing biomass valorization scenarios in drained conditions decreased by 4 % compared with the BAU. In absolute numbers, this represents a considerable amount of GHG emissions, about 3.7^5 Mg CO_2 ha^{-1} yr^{-1}. Almost all other GHG emissions not avoided by biomass valorization correspond to the emissions from drainage.

This reduction of GHG emissions relies on the assumption that all the fires in this areas are due to biomass combustion for fertilizing or land clearing. If a proportion of these fires are accidental or other reason, the reduction of GHG emissions can be overestimated.

Another important aspect that was overlooked in this study is this one: if the biomass that is usually burned for fertilizing the fields, is harvested for other uses, the fertility might be affected over time. It might then be necessary to add synthetic fertilizers to maintain the fertility. This impact of additional fertilization was not considered in this study.

4.2. Paludiculture as a model for implementing biomass valorization scenarios

Biomass valorization scenarios in non-drained conditions are an example of paludiculture systems, in which plantations can be managed by waterlogging. The scenarios in non-drained conditions reduce GHG emissions and benefit peat formation due to the dead matter not decomposed as CO_2 gases. The non-decomposed dead matter will be injected as peat into the catotelm layer (Parish et al., 2008).

This system is already used in temperate peatlands, but it is a new practice in tropical peatlands (Giesen, 2013; Wichtmann & Joosten, 2007). A social assessment was carried out in Malaysia to explore stakeholders' views on the paludiculture system (Middelberg et al., 2019). The results showed that a paludiculture system is more feasible for smallholders because they do not use heavy machinery. However, the smallholders surveyed who are currently palm oil producers would not exchange oil palm for another crop under the paludiculture system because it would not give them the same benefits as oil. This means that paludiculture could be an interesting system to implement in areas not yet used, such as degraded peatlands.

Degraded peatlands are not currently used for any specific economic activity, but are nevertheless affected by fires and drainage. Giesen (2013) and Middelberg (2019) identified different species for timber, medicine, food and other uses that can grow in non-drained conditions, and provided their economic potential. In addition to reducing GHG emissions from peat oxidation, land managed with paludiculture systems could also prevent the expansion of fires from the surrounding areas by acting as a wet buffer zone.

4.3. Sensitivity analyses

The sensitivity analysis on the distance of biomass transportation showed that the factory location was not an important factor in terms of GHG emissions. The determination of the most convenient locations for factories will therefore be considered according to economic and logistic aspects in the next chapter.

Regarding the sensitivity analysis on the drainage level, we found a significant increase in GHG emissions when the emission factors provided by the IPCC, assuming a 30 cm drainage level, were adjusted to consider the current drainage levels of oil palm and pulpwood plantations as reported in the literature, at 80 cm and 70 cm respectively. Some of the oil palm plantations in OKI are managed under the RSPO, which recommends a drainage level of -50 cm, but it was not possible to determine the location of these plantations in the study area.

5. Conclusions

The greenhouse gas emissions of the five land management scenarios, including the BAU scenarios, were estimated. Moving from current practices that use fires to clear land to biomass valorization could make it possible to avoid between 2 and 10 % of current GHG emissions from peatland management in OKI.

The results showed that the main emission sources for all scenarios were “Greenhouse gas fluxes from organic soil” and “Peat soil combustion”. This means that the effect of land management (drainage/fire) is more important than the type of biomass valorization analyzed in this study.

The scenarios in non-drained conditions significantly reduce GHG emissions in comparison with business as usual, since they reduce the gas fluxes from peat oxidation and enable carbon sequestration in peat soil. However, the scenarios in non-drained conditions are considered only for degraded peatlands, because waterlogged conditions are not suitable for oil palm and pulpwood crops.

Previous studies have shown that the drainage levels in oil palm and pulpwood plantations can be reduced up to a certain level while maintaining productivity. These results should then be used for current production systems in order to reduce GHG emissions from drainage, since this study has shown that this is a key factor for GHG emissions.

Biomass valorization can be an option to reduce haze from fires, which has an impact on climate change, but also causes other problems, such as health issues due to fine particulate matter ($PM_{2.5}$) or economic losses associated with the haze from land management using fires.

Finally, paludiculture systems may be an option to be implemented in degraded peatlands in order to provide a use that could be more productive for the owners than the current land use management. Previous studies have identified different profitable species suited to waterlogged conditions. Thus, socio-economic studies should be carried out to introduce these new production systems and species. Paludiculture has the potential to create economic activities in peatlands that have a lower impact than the current land management systems.

Annexes

Annex 3-1. Detailed life cycle GHG emissions of land management scenarios in degraded peatlands, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

			Bioethanol production		Combined heat and power		Panel manufacturing		
Emission source	Business as usual (with fire occurrence)	Business as usual (without fire occurrence)	Biomass valorization (drained)	Biomass valorization (non-drained)	Biomass valorization (drained)	Biomass valorization (non-drained)	Biomass valorization (drained)	Biomass valorization (non-drained)	Restoration
Greenhouse gas fluxes from organic soil	20.60	20.60	20.60	1.25	20.60	1.25	20.60	1.25	1.25
C sequestration in aboveground biomass	-2.15	-2.15	-2.15	-2.15	-2.15	-2.15	-2.15	-2.15	-2.15
Peat combustion due to fires	50.00		-	-	-	-	-	-	-
Aboveground biomass combustion due to fires	2.15		-	-	-	-	-	-	-
Production and use of kerosene	-	-	-1.16	-1.16	-	-	-	-	-
Bioethanol production and use	-	-	2.51	2.51	-	-	-	-	-
Biomass transport and energy generation	-	-	-	-	2.23	2.23	-	-	-
Production and use of coal for electricity generation	-	-	-	-	-2.08	-2.08	-	-	-
Production and use of coal for heat generation	-	-	-	-	-3.55	-3.55	-	-	-
Particle board manufacturing with solid wood	-	-	-	-	-	-	-0.31	-0.31	-
Particle board manufacturing with waste biomass	-	-	-	-	-	-	2.46	2.46	-
Total*	**70.60 ±30**	**18.45 ±12**	**19.80 ±11**	**0.45**	**15.05**	**-4.30 ±3**	**20.60 ±11**	**1.25 ±3**	**-0.90 ±2**

*At 30 cm below ground drainage level

Annex 3-2. Detailed life cycle GHG emissions of land management scenarios in oil palm plantation, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

	Business as usual		Biomass valorization		
Emission source	With fire	Without fire	Bioethanol	Combined heat and power	Panel manufacturing
-Greenhouse gas fluxes from organic soil	40.4	40.4	40.4	40.4	40.4
-C sequestration in aboveground biomass	-2.32	-2.32	-2.32	-2.32	-2.32
-Peat combustion due to fires	52	-	-	-	-
-Aboveground biomass combustion due to fires	2.32	-	-	-	-
-Production and use of kerosene	-	-	-5.04	-	-
-Bioethanol production and use	-	-	3.87	-	-
-Biomass transport and energy generation	-	-	-	2.4	-
-Production and use of coal for electricity generation	-	-	-	-2.24	-
-Production and use of coal for heat generation	-	-	-	-3.83	-
-Particle board manufacturing with solid wood	-	-	-	-	-0.313
-Particle board manufacturing with waste biomass	-	-	-	-	2.63
Total (at 30 cm below ground drainage level)	**92.4 ±31**	**38.1 ±21**	**36.9 ±21**	**34.4 ±21**	**40.4 ±21**
Total (at 80 cm below ground drainage level)*	**139.4**	**85.1**	**83.9**	**81.4**	**87.4**

*The increase of 47 t CO2 eq correspond to the adjust of drainage level to 80cm obtained from the sensibility analyses

Annex 3-3. Detailed life cycle GHG emissions of land management scenarios in pulpwood plantation, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

	Business as usual				
Emission source	**With fire**	**Without fire**	**Bioethanol**	**Combined heat and power**	**Panel manufacturing**
-Greenhouse gas fluxes from organic soil	73.4	73.4	73.4	73.4	73.4
-C sequestration in aboveground biomass	-2.7	-2.7	-2.7	-2.7	-2.7
-Peat combustion due to fires	48	-	-	-	-
-Aboveground biomass combustion due to fires	2.7	-	-	-	-
-Production and use of kerosene	-	-	-5.8	-	-
-Bioethanol production and use	-	-	4.51	-	-
-Biomass transport and energy generation	-	-	-	2.79	-
-Production and use of coal for electricity generation	-	-	-	-2.61	-
-Production and use of coal for heat generation	-	-	-	-4.46	-
-Particle board manufacturing with solid wood	-	-	-	-	-0.294
-Particle board manufacturing with waste biomass	-	-	-	-	3.01
Total (at 30 cm below ground drainage level)	**121.4 ±26**	**70.7 ±15**	**69.4 ±14.7**	**66.4 ±14.7**	**73.4 ±14.8**
Total (at 70 cm below ground drainage level)*	**159**	**108.3**	**107.01**	**104.02**	**111.016**

*The increase of 37.6 t CO2 eq correspond to the adjust of drainage level to 70 cm obtained from the sensibility analyses

Annex 3-4. Sensitivity analysis on different biomass transportation distances from degraded peatlands to factories evaluated in biomass valorization scenarios, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

Biomass valorization	Scenario	50 km	200 km	500 km
Bioethanol production	Drained conditions	19.7	19.8	19.9
	Non-drained conditions	0.38	0.45	0.59
Combined heat and power generation	Drained conditions	14.9	15.05	15.3
	Non-drained conditions	-4.44	-4.30	-4.03
Panel manufacturing*	Drained conditions	20.6	20.6	20.6
	Non-drained conditions	1.25	1.25	1.25

Annex 3-5. Sensitivity analysis on different biomass transportation distances from oil palm plantations to factories evaluated in biomass valorization in drained conditions, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

Biomass valorization	50 km	200 km	500 km
Bioethanol production	36.6	36.9	37.5
Combined heat and power generation	34.2	34.41	34.7
	-4.89	-1.45	-4.45
Panel manufacturing*	40.4	40.4	40.4
	1.25	1.25	1.25

Annex 3-6. Sensitivity analysis on different biomass transportation distances from pulpwood plantations to factories evaluated in biomass valorization in drained conditions, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

Biomass valorization	50 km	200 km	500 km
Bioethanol production	67.0	69.4	73.0
	-24.2	-2.74	-18.1
Combined heat and power generation	64.8	66.42	68.0
	-6.01	-5.73	-4.44
Panel manufacturing*	73.4	73.42	73.4
	1.25	1.27	1.25

Annex 3-7. Sensitivity analysis on drainage level for scenarios in drained conditions in degraded peatlands, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

Drainage level (cm)	Business as usual (with fire occurrence)	Business as usual (without fire occurrence)	Bioethanol production	Combined heat and power	Panel manufacturing
-30	70.60	18.45	19.80	15.05	20.60
-40	80.00	27.85	29.20	24.45	30.00
-50	89.40	37.25	38.60	33.85	39.40
-60	98.80	46.65	48.00	43.25	48.80
-70	108.20	56.05	57.40	52.65	58.20
-80	117.60	65.45	66.80	62.05	67.60
-90	127.00	74.85	76.20	71.45	77.00
-100	136.40	84.25	85.60	80.85	86.40

Annex 3-8. Sensitivity analysis on drainage level for scenarios in drained conditions in oil palm plantation, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

Drainage level (cm)	Business as usual (with fire occurrence)	Business as usual (without fire occurrence)	Bioethanol production	Combined heat and power	Panel manufacturing
-30	92.40	38.08	36.91	34.41	40.40
-40	101.80	47.48	46.31	43.81	49.80
-50	111.20	56.88	55.71	53.21	59.20
-60	120.60	66.28	65.11	62.61	68.60
-70	130.00	75.68	74.51	72.01	78.00
-80	139.40	85.08	83.91	81.41	87.40
-90	148.80	94.48	93.31	90.81	96.80
-100	158.20	103.88	102.71	100.21	106.20

Annex 3-9. Sensitivity analysis on drainage level for scenarios in drained conditions in pulpwood plantation, in CO_2-eq. (Mg ha^{-1} yr^{-1}).

Drainage level (cm)	Business as usual (with fire occurrence)	Business as usual (without fire occurrence)	Bioethanol production	Combined heat and power	Panel manufacturing
-30	121.40	70.70	69.41	66.42	73.42
-40	130.80	80.10	78.81	75.82	82.82
-50	140.20	89.50	88.21	85.22	92.22
-60	149.60	98.90	97.61	94.62	101.62
-70	159.00	108.30	107.01	104.02	111.02
-80	168.40	117.70	116.41	113.42	120.42
-90	177.80	127.10	125.81	122.82	129.82
-100	187.20	136.50	135.21	132.22	139.22

Annex 3-10. GHG emission balance of the BAU scenario in OKI.

Land use	A_F (ha yr^{-1})	BAU_F GHG emissions (Mg CO_2-eq ha^{-1} yr^{-1})	A_{NF} (ha yr^{-1})	BAU_{NF} GHG emissions (Mg CO_2-eq ha^{-1} yr^{-1})	BAU OKI (Mg CO_2-eq yr^{-1})
Degraded peatlands	5,293	71	118,729	18	2,564,227
Oil palm plantations	5,233	139	177,370	85	15,805,886
Pulpwood plantations	47,000	159	625,497	108	75,214,325
Total					**93,584,438**

BAU OKI is the total greenhouse gas emissions of business as usual scenarios in OKI, A_F is the area affected by fires, BAU_F is the GHG emissions estimated for the Business as usual scenario with fire occurrence, A_{NF} is the area without fire occurrence, and BAU_{NF} is the GHG emissions estimated for the Business as usual scenario without fire occurrence.

Annex 3-11. GHG emissions balances of the land management scenarios for the three land uses studied in OKI.

Land use	BV drained (Mg CO_2-eq ha^{-1} yr^{-1})	BV non-drained (Mg CO_2-eq ha^{-1} yr^{-1})	A (ha)	BV drained Total land use (Mg CO_2-eq yr^{-1})	BV non-drained Total land use (Mg CO_2-eq yr^{-1})	Restoration[i] Total land use (Mg CO_2-eq yr^{-1})
Biomass valorization for bioethanol production						
Degraded peatlands	19.8	0.5	124,022	2,455,636	55,810	-111619.8
Oil palm	83.9	NA	182,603	15,322,181	NA	NA
Pulpwood	107.0	NA	672,497	71,963,904	NA	NA
Biomass valorization for combined heat and power						
Degraded peatlands	15.1	-4.3	124,022	1,866,531	-533,295	NA
Oil palm	81.4	NA	182,603	14,866,039	NA	NA
Pulpwood	104.0	NA	672,497	69,953,137	NA	NA
Biomass valorization for panel manufacturing						
Degraded peatlands	20.6	1.3	124,022	2,554,853	155,028	NA
Oil palm	87.4	NA	182,603	15,959,464	NA	NA
Pulpwood	111.0	NA	672,497	74,660,616	NA	NA

BV is the greenhouse gas emissions of the biomass valorization scenarios, V is the GHG emissions estimated for biomass valorization scenarios in drained and non-drained conditions and A is the total area of each land use.
[i] The restoration scenario is the same for the three land uses and biomass valorization types (-0.9 Mg CO_2-eq yr^{-1}).

Chapter 4
Socio-economic assessment of emission mitigation scenarios in OKI

Scope of Chapter 4

In Chapter 4, we assessed the socio-economic factors of the three main land uses studied in this work for the OKI district. We focused on the factors that are critical for fire mitigation through biomass valorization. We compared different strategies towards the potential reduction of GHG emissions and costs, for the three main land uses. Our main parameters were fire occurrence, potential biomass and transportation costs.

1. Introduction

The results obtained in Chapter 3 suggest the concept of implementing different land management scenarios instead of burning biomass on peatlands, in order to mitigate GHG emissions. The socio-economic and political aspects are key to developing these scenarios. The Indonesian government plans to increase renewable energy production from 30.9 GWh in 2017 to around 100 GWh in 2025 (PwC Indonesia, 2018). Despite such an ambitious program, PwC Indonesia (2018) reported that existing fuel subsidies, low electricity tariffs, complex regulations, legal uncertainties, logistical challenges and extensive cheap coal resources were all slowing advances in renewable investments and were not making full use of the high Indonesian feedstock capacity.

The Indonesian government also created the Indonesian Peatland Restoration Agency (Badan Restorasi Gambut (BRG)) with the objective of reducing GHG emissions from peat fires. Its mission is to restore more than 2 million ha of peat ecosystems in seven provinces, including Sumatera Selatan Province (Dohong, 2017; Hansson & Dargusch, 2017). However, the budget available for peatland restoration is still not enough to restore the 2 million ha.

In this chapter, we analyze the biomass procurement costs for the different land management scenarios evaluated in Chapter 3. We specifically take into account the limitations that are necessary to ensure peat formation. The objective of this chapter is to draw the boundaries of what is feasible and what is not, and where. The criteria for implementing land management scenarios are assessed based on the intensity of fires, biomass accessibility for potential industries, and cost.

2. Methods

All of the cost calculations are based on the GIS distance calculations already presented in detail in Chapter 2. The algorithm for these distance calculations measures the shortest off-road distance of any pixel to the nearest road or to the nearest navigable waterway. It then measures the distance from the road or waterway to the potential factory location. In order to simplify the analysis and comparison of scenarios, the map pixels are divided into successive 100 km zones, starting from each potential factory location (Fig 4.1).

2.1. Cost factors

We present some costs for implementing the mitigation land management scenarios evaluated in Chapter 3.

2.1.1. Transportation cost of biomass for valorization

We computed the transportation costs with an algorithm referring to the distance maps and to modal rasters. These rasters qualify the modes of transport, and the relevant pixels contain the relevant costs per ton and per distance (Table 4-1). Ong (in prep.) calibrated theses costs in Indonesian Rupiah (IDR), after a survey in OKI. The calibration provides average transportation costs for boats and trucks, according to the most common capacities observed. The algorithm first cumulates the off-road transportation cost from every pixel to the nearest transportation network, be it a road or a waterway. The non-navigable waterways are computed as obstacles, except where bridges exist. The algorithm then cumulates the costs following the transportation network to the target potential factory. The model is a generic model developed for the Southeast Asia region and it was calibrated with specific data from the study area. The details of this multimodal algorithm were taken from Roda (2011). We used the tools r.mapcalc and r.cost to implement the algorithm in the GRASS software.

Table 4-1. Transport costs assigned to the relevant pixels.

Raster qualified by transportation mode	Transportation cost (IDR/ton/km)
Waterways (10t)	434
Waterways (100t)	2,513
Roads	1,177
Off-road	1,000

2.1.2. Cost of biomass for valorization

We carried out a review of the market price of the biomass residues for the three land uses. The most recent values found for the market cost at the factory were US$ 18.3/t for degraded peatlands resulting from land clearing operations (Pirard et al., al 2017), US$ 19/t for residues of lignocellulosic biomass from pulpwood plantations (Simangunsong et al., 2019), and US$ 17.6/t for residues from oil palm plantations (Duque et al., 2015).

These values represent a real market equilibrium for the price at which biomass resources can be sold in Indonesia, with the assumption that this market equilibrium reflects the price the local workforce and services are asking to collect similar lignocellulosic biomass. We use the lowest and highest limits of the three values, US$ 17.6/t and US$ 19/t, as a benchmark to assess the maximum realistic distance of supply in each case, with an error margin. Based on the experience of Jean-Marc Roda, my tutor, we defined the hypothesis that 50 % of this cost is transportation costs and the other 50 % is collection and remuneration costs for local workers.

Under this hypothesis and the aforementioned raster cost, we computed the areas which the cost is acceptable for the market price and, consequently, for the local population.

2.1.3. Peatland restoration cost

For areas where it is not possible, to consider biomass valorization scenarios due to the fact that the cost higher than the acceptable cost margin restoration scenarios and incentive payments were considered.

For the peatland restoration scenario, the cost evaluated is estimated by Hansson and Dargusch (2017) based on the cost of the Indonesian Peatland Restoration Agency (BRG), which included hydrological restoration and assisted revegetation for a cost of US$ 1,866 ha^{-1} for the first year. We added to this cost an incentive payment to owners for environmental services ensuring peatland protection for the first and following years of US$ 230 $ha^{-1}yr^{-1}$ (Lapeyre et al., 2015).

The incentive payment is an alternative that it is not considered in the scenarios evaluated in Chapter 3, but it is used by an NGO in South Sumatra (FFA, 2016) and evaluated in some works (Lapeyre et al., 2015). We thus considered it as an option for areas where biomass valorization scenarios are not economically viable for the market. The incentive payment consists in paying owners to avoid the use of fire for land preparation or any other activity that may lead to peat soil combustion and haze production. Avoiding fires would mean emissions would only result from the gas fluxes from organic soil. The incentive cost assumed is US$ 230 $ha^{-1}yr^{-1}$ (Lapeyre et al., 2015).

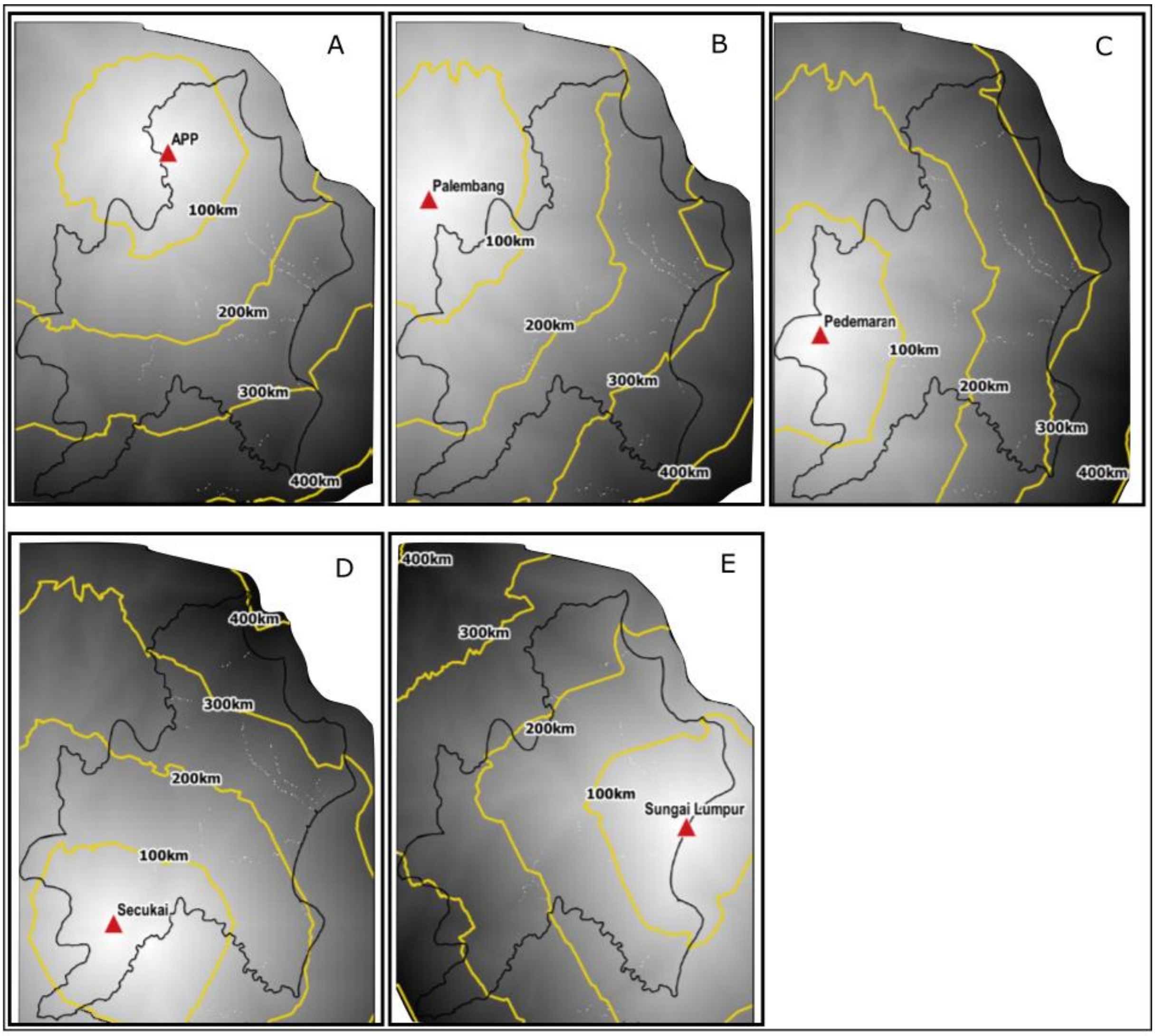


Figure 4-1. Successive distance zones for each factory for biomass transportation

2.2. Technical factors

2.2.1. Area and potential biomass available

The area of each distance zone was computed for each of the land uses (see Chapter 2, Part III). We calculated the potential biomass quantity by multiplying the hectares by the average yield of lignocellulosic biomass residues per hectare for each land use. The yields of potential biomass that can be utilized were the same as those assumed in the other chapters: 4.30 t ha yr^{-1} for degraded peatlands, 4.64 t ha yr^{-1} for oil palm plantations, and 5.4 t ha yr^{-1} for pulpwood plantations. For each potential factory, we assessed the quantities of biomass available, according to the distance, and we discussed the implications.

2.2.2. Occurrence of fires

Since fire occurrences could influence the interpretation of the analysis, they are also quantified for the successive distance zones. In Chapter 2, the fire occurrence was computed for the period 2002-2018 for each land use, obtaining a weighted average of 1.45±1.37 years for degraded peatlands, 0.98±1.38 for oil palm plantations, and 1.56±1.31 for pulpwood plantations. There is no significant difference between the land uses. In this section, we examined whether this result is similarly valid when considering successive distance zones.

2.3. How to compare emission mitigation scenarios in OKI?

We evaluated the implementation of the mitigation scenarios obtained in Chapter 3 using the three different criteria presented below. For each criterion, we evaluated the GHG emissions that can be reduced at the OKI regional level, based on the cost and technical factors mentioned above. These mitigation scenarios include biomass valorization scenarios and the restoration scenario. In the cases where biomass valorization scenarios were considered, the impact of the type of biomass valorization used was the average of the three types of biomass valorization evaluated in Chapter 3, since their impacts are similar to one another.

Considering that in Chapter 3 we evaluated biomass valorization scenarios in drained and non-drained conditions, the scenarios in non-drained conditions are evaluated only for degraded peatlands due to the difficulty of growing oil palm and pulpwood plantations in waterlogged conditions. Similarly, the restoration scenario was also evaluated only for degraded peatlands. The restoration scenario is not proposed for oil palm and pulpwood plantations because the objective was to propose practices to reduce emissions from the current land use and not to assume any land use change. The fact that degraded peatlands do not have an established land use enables us to evaluate them for different scenarios, including scenarios in non-drained conditions and restoration.

2.3.1. Criteria:

1) The first criterion is fire occurrence, based on the idea that mitigation land management scenarios should be implemented as a priority in the zones where fire occurrence is the highest.

2) The second criterion is cold/neutral industrial economics, based on the idea that the best mitigation scenarios should be applied where the greatest amount of biomass can be utilized for the lowest possible average cost. This would ensure maximal mitigation effects, higher margins to remunerate local actors in biomass collection and transportation, and higher margins to ensure sustainability in the long term.

3) The third criterion is the principle of parsimony, recognizing that not all biomass can be utilized at a cost that would ensure fairness for local populations. This is where socio-economics come in: there is already a market for biomass in Indonesia, and at first sight, we can consider the observed price as a negotiated equilibrium. It may not be the best equilibrium in theory, but it represents what emerges given the scarcity or abundance of the local workforce and transportation services, and given the current factory costs. In this work, we consider the Indonesian market for biomass

as a benchmark of the maximum supply cost that would be reasonably feasible. Any biomass beyond this benchmark is considered as non-valuable given the current socio-economic conditions in Indonesia.

3. Results

3.1. First criterion: where do fires occur the most frequently?

We evaluated fire occurrence in the 100 km successive zones from the five potential factory locations (Annex 4-1).We then compared the fire occurrence in each successive zone with the fire occurrence for each land use obtained in Chapter 2. We found no significant differences according to the three main land uses or to the distance zones, due to the high variance. For this reason, we did not use this criterion when evaluating the implementation of mitigation scenarios.

Fig. 4-12 presents an example that takes as a reference the APP factory location. In degraded peatlands, we observed that the fire occurrence increased mostly between 200-300 km from APP. This increment is by 0.53 years greater than the average fire occurrence for the whole land use. In oil palm plantations, the fire occurrence increased by 0.9 years between 100-200 km from APP. For pulpwood plantations, the fire occurrence increased mostly in the area between 0-100 km from APP, by 0.38 years.

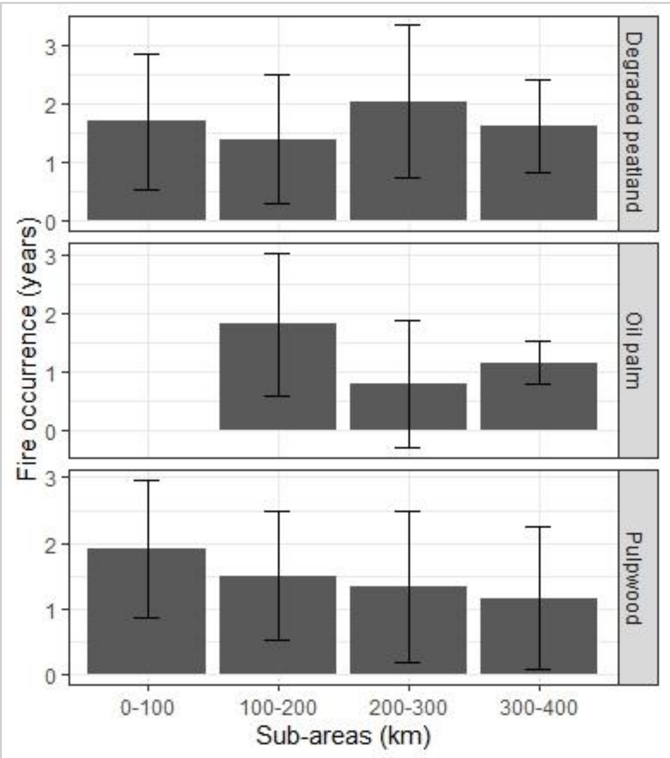


Figure 4-2. Fire occurrence in successive distance zones from APP as the factory location reference.

3.2. Second criterion: what is the biomass availability and its cost?

3.2.1. Biomass availability

First, we looked at the biomass available within each 100 km zone from each potential industrial location in order to determine whether or not the area is homogeneous in each of them. We found heterogeneity throughout each zone in terms of the available biomass.

Fig. 4-3 shows the distribution of biomass availability according to the successive distance zones, and for each potential industrial location. The areas with most potential biomass available obtained were the first 200 km for Pedemaran for degraded peatlands, the first 200 km for Secukai for oil palm plantations, and the first 200 km for Sungai Lumpur for pulpwood plantations. These areas represent about 80 - 97 % of each land use, leaving out only the most distant areas that can increase the transportation cost for a small area.

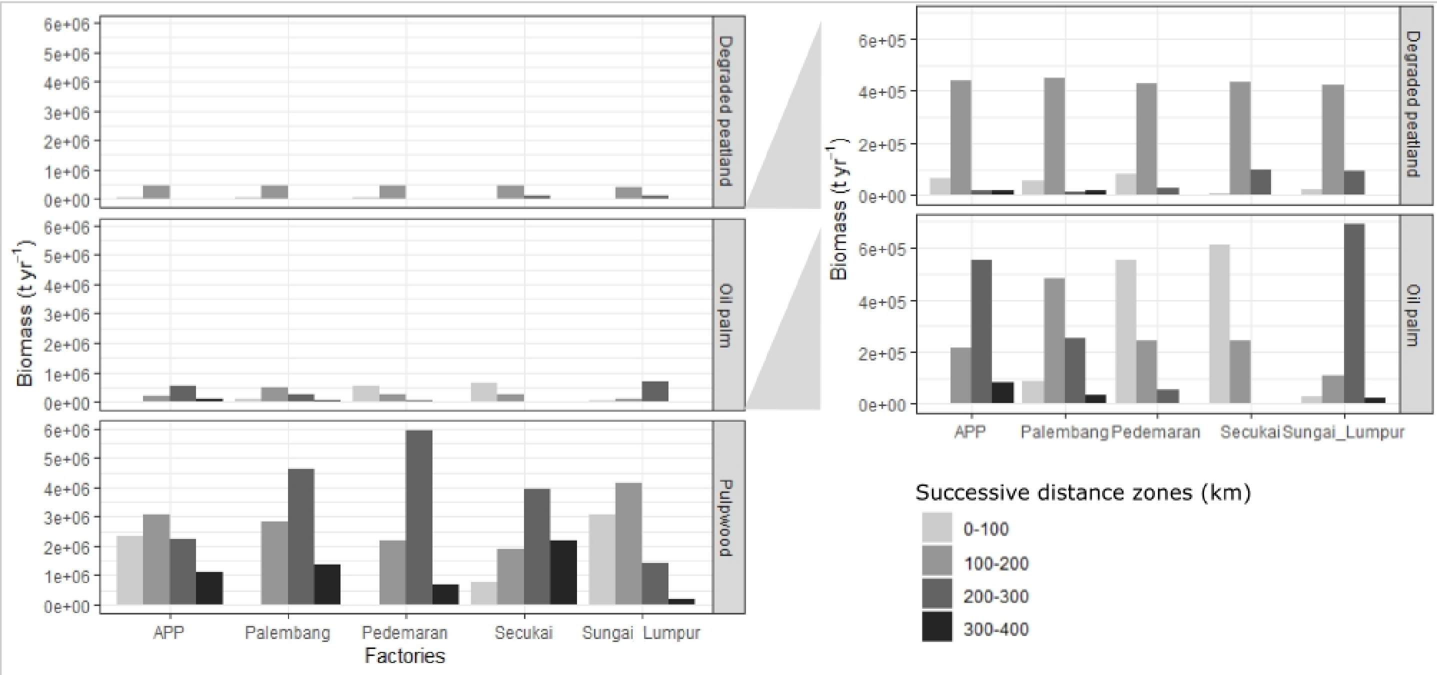


Figure 4-3. Biomass distribution for different land uses and different potential industry locations

3.2.2 Transportation cost

Within the limit of 200 km from the areas with most biomass available shown above, we obtained that the average cost of biomass transportation is approximately US$ 4 and US$ 6 per ton of biomass (Table 4-2). We found that this ratio of 200 km contains the highest biomass available at a price that does not exceed the price accepted by the market.

There is no great difference in costs between factory locations or between land uses. However, we can observe that the cheapest location is Sungai Lumpur and that it has high coverage of pulpwood plantation areas. The transportation cost was obtained using waterways and roads for the same journey. This means that, for a single way, there could be an extra cost for changes in the type of transport (see Chapter 2). The cost of moving biomass from one type of transport to another was not explicitly taken into account in this study, and is included in the average cost of each mode of transport.

Table 4-2. Transportation cost in the selected 200 km zones from each factory.

	Transportation cost (IDR/t)			Transportation cost (US$/t)[i]		
	min	max	average	min	max	average
Degraded peatlands						
Pedemaran	50,085	110,535	80,310	4	8	6
Oil palm plantations						
Secukai	15,271	116,350	65,810	1	8	5
Pulpwood plantations						
Sungai Lumpur	9,468	91,297	50,383	1	7	4

[i] Exchange USD= 13808 IDR

3.2.3. Impact of biomass valorization scenarios

Regarding the GHG emissions avoided by implementing biomass valorization in these areas (Fig. 4- 4), we obtained that the implementation of biomass valorization scenarios in drained conditions in degraded peatlands reduces GHG emissions by approximately 8 % compared with the total BAU of degraded peatlands in OKI. In non-drained conditions, this reduction is about 100 % and even enables carbon sequestration. In oil palm plantations, biomass valorization scenarios could reduce GHG emissions by approximately 3 % compared with the total BAU of oil palm plantations in OKI. Finally, biomass valorization in pulpwood plantations reduces GHGs by approximately 4 % compared with BAU for this land use. In total, the GHG emissions reduction made possible by implementing biomass valorization scenarios in the selected areas for the three land uses could be 4 % compared with the total BAU in OKI.

Within a ratio of 200 km from the potential factory locations mentioned above, the cost of reducing 1 t of GHG emissions in degraded peatlands is US$ 23, US$ 16 in oil palm plantations and US$ 10 in pulpwood plantations.

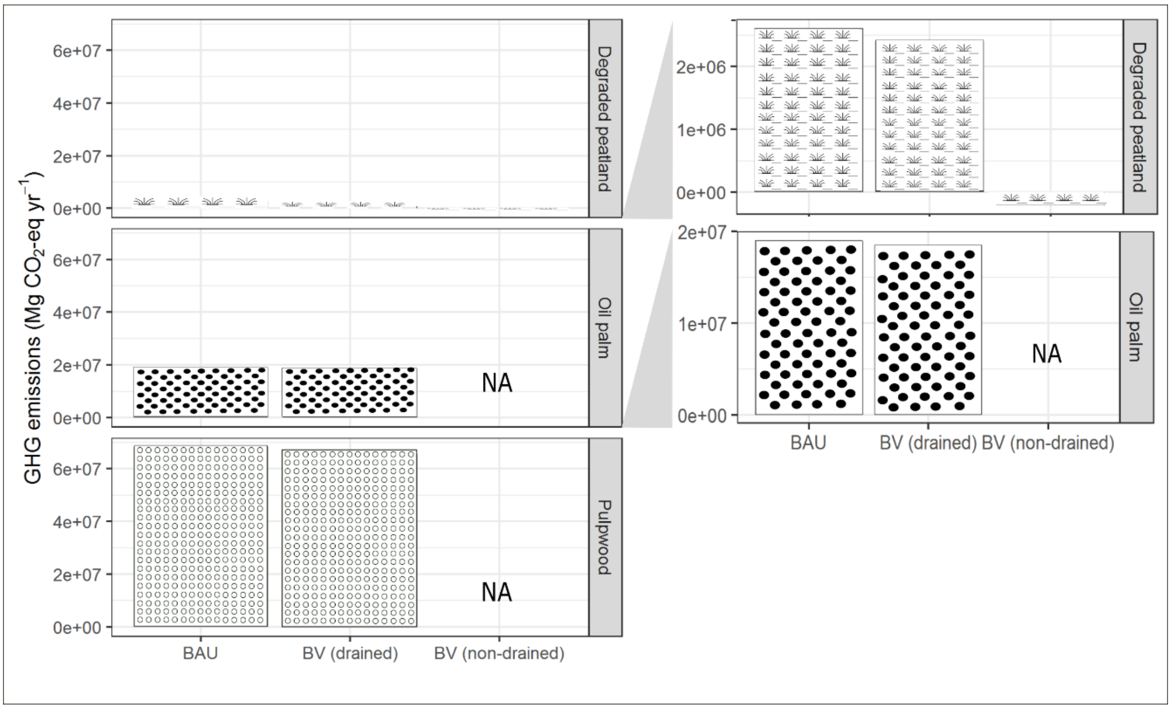


Figure 4-4. Scenarios considered for biomass valorization in OKI for the areas with most available biomass. BAU is the business as usual scenario for each land use obtained in Chapter 3, and BV is biomass valorization.

3.3. Third criterion: where can biomass make a difference to local populations?

In the last paragraph, we evaluated the most suitable areas for biomass valorization for industry, considering the biomass available and the cost within a ratio of 200 km from the factory locations. Here, we evaluated the most suitable areas for the local population to sell biomass to industry.

The acceptable payment to the local population for a ton is between US$ 8.8 and US$ 9.5. This is the accepted remuneration for the local population and for industry based on the hypothesis defined in Section 2.1. To ensure this price, we computed the area limits within which it is possible to maintain this price.

In Fig. 4-5, the white areas correspond to the areas where the biomass market works for both the local population and industry. This means that in these areas, we can obtain a reduction in GHG emissions by implementing biomass valorization instead of burning it, simply by boosting this market. The red areas correspond to the areas where the biomass cost is higher than the margin that the industry is willing to pay, and consequently the local population will not make a profit. In these areas, alternatives to biomass valorization should be considered in order to reduce GHG emissions.

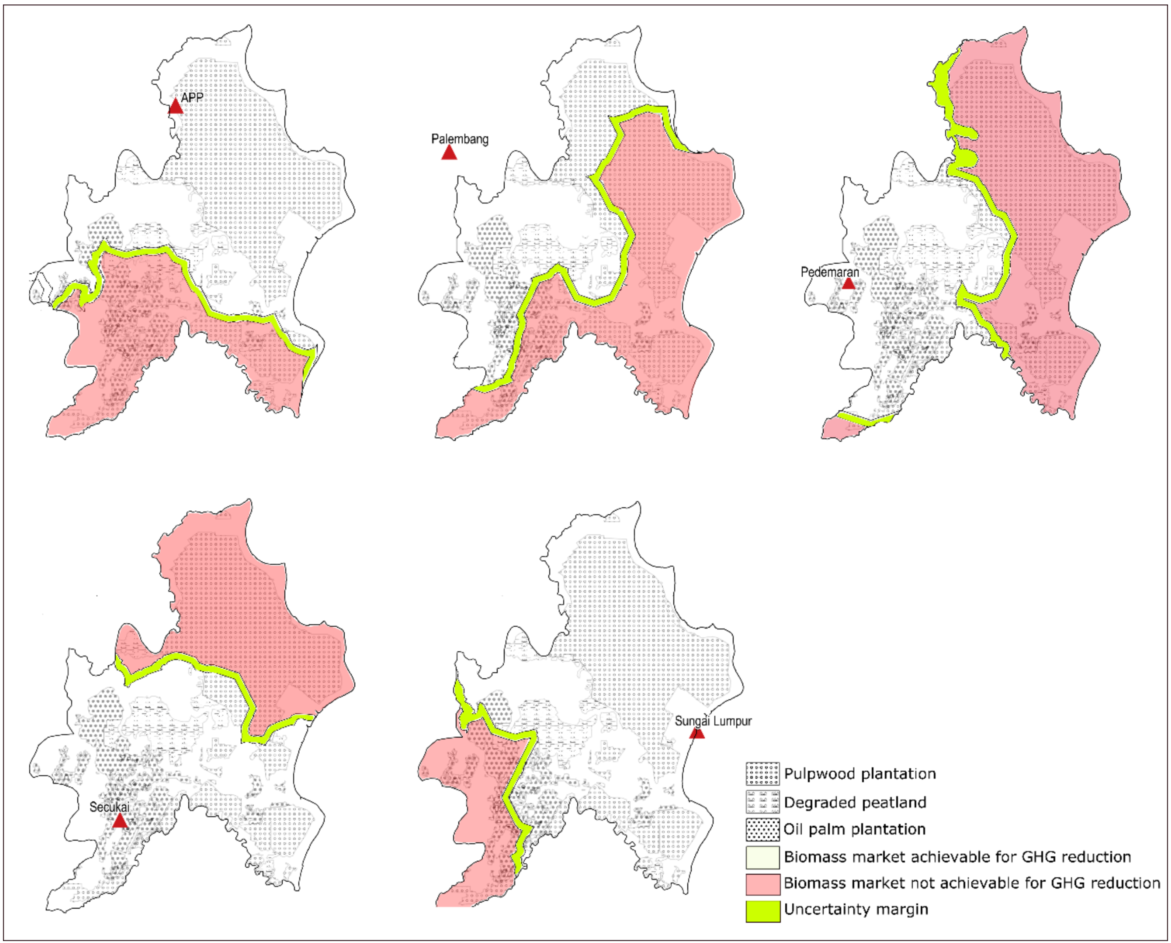


Figure 4-5. Area classification by acceptable biomass cost for the local population based on the third criteria.

We can observe that the locations of Secukai, Pedemaran and Palembang cover a large area of degraded peatlands. We can also observe that the APP and Sungai Lumpur locations cover almost all of the pulpwood plantations and Secukai covers all of the oil palm plantations. The areas obtained from criterion 2 are within these areas. This congruence is positive, since this means that the areas with most biomass available are within an area where the biomass market is suitable.

Beginning with these congruent areas, Pedemaran for degraded peatland, Secukai for oil palm and Sungai Lumpur for pulpwood plantations, we computed the amount of biomass contained in the areas where the biomass market is viable and the GHG emissions that can be avoided by implementing biomass valorization scenarios. We obtained that biomass valorization in the white areas reduces GHG emissions by approximately 4 - 6 % compared with BAU in OKI (Table 4-3). The rest of the biomass contained in the red areas cannot be utilized by industry.

Among the five potential factory locations, Sungai Lumpur and APP cover about 85 % of the three land uses where the biomass market is viable. This indicates that these locations may be interesting for factory installation. In addition, these locations have access to the sea, which is to be considered for exporting the end products to neighboring countries.

Table 4-3. GHG emission reductions and costs of implementing biomass valorization in the biomass market viable for GHG emission reductions.

	Reduction of GHG emissions[i]	Market cost for industry		Remuneration of local population		Market cost of reducing 1 t of GHG emissions	Government cost of reducing 1 t of GHG emissions
		(US$/t)	(US$/total biomass)	(US$/t)	(US$/total biomass)	(US$)	(US$)
Degraded peatlands							
Pedemaran	4 %	18.3	9,239,858	9.2	4,619,929	38	0
Oil palm plantations							
Secukai	6 %	19	16,098,242	9.5	8,049,121	4	0
Pulpwood plantations							
Sungai Lumpur	4 %	17.6	11,509,313	8.8	5,754,656	4	0

[i] Compared with BAU for the corresponding land use

For the biomass contained in the areas where the biomass market is non viable (red zones), we evaluated alternative options. For degraded peatlands, we evaluated the implementation of the restoration scenario. For oil palm and pulpwood plantations, we evaluated the incentive payments for not using fires in land preparation. The cost of implementing these scenarios must be funded by the government or any other organization interested in reducing the impact of peatlands on climate change.

Implementing the restoration scenario in degraded peatlands enables a 100 % reduction in GHG emissions compared with BAU for degraded peatlands and also enables carbon sequestration. The cost of reducing 1 t of GHG emissions is approximately US$ 100 for the first year. This cost includes hydrological restoration, assisted revegetation and incentive payments for not using fire. For the following years, only the cost of incentive payments would be maintained, which represents 10 % of the cost of the first year.

Regarding incentive payments for not using fire in land preparation considered for the red areas of oil palm and pulpwood plantations, the reduction in GHG emissions is around 2 % compared with the BAU for this land use. The cost for the government of reducing 1 t of GHG emissions is US$ 4.

4. Discussion

The three criteria evaluated provide a broad perspective on the GHG emissions that could be reduced by implementing mitigation scenarios in OKI, the areas where the biomass market is or is non viable for reducing GHG emissions, and the cost per ton of GHG emissions reduced.

The first criterion, fire occurrence, was not taken into account as an indicator for implementing mitigation scenarios due to the high variability throughout the successive 100 km zones. This variability is due to the distance of infrastructure, population centers, the dynamics of each land use, and other factors. It would be particularly interesting to explore it in further studies.

From the second criterion, we obtained one factory location for each land use that contained the highest biomass available within a ratio of 200 km. This information made it possible to avoid the furthest areas with a smaller amount of biomass available. However, from the third criterion, we observed that the suitable market areas for biomass valorization are broader than these 200 km zones. In these suitable market areas, GHG emissions could be reduced simply by boosting the biomass valorization market. In addition, identifying these areas is key to determining the best factory location, because they are the optimal zones for the price that the industry is willing to pay and in which the local population obtains acceptable remuneration. Sungai Lumpur followed by APP are considered as potential locations among the five locations evaluated, since they cover a large area where the biomass market is viable, enabling GHG emission reductions.

In order to reduce the use of fire, the local populations need to obtain an incentive to motivate them to stop using fires. In the areas where the biomass market is viable, the local population will obtain additional income from utilizing biomass. Outside this area, as shown in Fig. 4-5 in red, the biomass market is non viable, but the government can invest in incentives or peatland restoration.

The hypothesis raised in the third criteria, which assumes that 50 % of the biomass price found in the literature is the collection and remuneration cost for the local population and the other 50 % is the transportation cost, can vary depending on the context of each area evaluated. However, it is a first approach to gain a perspective on the potential areas where the biomass market is viable, reducing the use of fires in OKI.

4.1. What is the best strategy for the government?

Government resources are limited. The use of these resources in inappropriate areas can mean they are wasted. Boosting the biomass market in the viable areas identified in this study can reduce GHG emissions without government investments in these areas (Table 4-4). The biomass market could reduce annual GHG emissions in OKI by around 4 - 6 %. Government resources could focus on the areas where this market is non viable. These areas represent approximately 15 % of the study area and the cost for the government to reduce 1 t of GHG emissions is between US$ 4 and US$ 100.

Identifying these areas can help the government and other organizations to focus their resources in priority areas where the biomass market is non viable. For example, in Riau, the NGO “Free Fires Alliance” (FFA) created a program “No Burn Village Rewards” that pays industry members at the end of the dry season, IDR 100,000 for a burned area smaller than 1 ha and IDR 50,000 for a burned area smaller than 10 ha, in the form of infrastructure so as to avoid any corruption issues (FFA, 2016). This program is working successfully so far, with approximately six industry members associated with it (FFA, 2016; Jakarta globe, 2019). This experiment by the FFA is aimed at industries. It means that all of these industries can stimulate the biomass market, simultaneously reducing GHG emissions from biomass combustion. This action can provide additional income for the local population and NGOs can invest their resources in areas where options to reduce the use of fires are limited.

Table 4-4. Comparison of the criteria evaluated for implementing different mitigation scenarios in OKI.

Criteria	Description	GHG emission reduction[i]	Cost for the market to reduce 1 t of GHGs (US$)	Cost for the government for reduce 1 t to GHGs (US$)
1. Fire occurrence	Does not apply because there are no significant differences between areas	NA	NA	NA
2. Biomass availability	Biomass valorization in a ratio area of 200 km	4 %	US$ 23 in degraded peatlands US$ 16 in oil palm plantations US$ 10 in pulpwood plantations	0
3. a) Acceptable market cost for local population and industry	Biomass valorization in the areas where the cost of biomass is acceptable for the local population and for industry	5 %	US$ 38 in degraded peatlands US$ 4 in oil palm plantations	0
b) Unacceptable market cost	Peatland restoration and incentive payments for the areas where the cost of biomass is not acceptable for the local population and for industry	100 % for implementing the restoration scenario in degraded peatland 2 % for incentive payments in oil palm and pulpwood plantations	0	US$ 100 in degraded peatlands US$ 4 in oil palm plantations and pulpwood plantations

[i] GHG emission reductions compared to the total BAU in OKI

4.2. Alternatives for areas where the biomass market is non viable

For areas where the biomass market is non viable, we suggest peatland restoration or incentive payments in the case of plantations. Peatland restoration is a government objective that can be considered for degraded peatlands, as shown in this study. Another option is to consider the implementation of paludiculture systems in degraded peatlands. Paludiculture systems are an example of biomass valorization in non-drained conditions. Paludiculture systems consider the crops of species that are suited to waterlogged conditions. In this case, drainage is unnecessary, thereby avoiding emissions from drainage, reducing the risk of fire and providing buffer zones from fire expansion. This system also fosters the implementation of polyculture systems to promote timber, food and non-timber forest products.

5. Conclusion

Using different tools and criteria such as SIG, mitigation scenarios and socio-economic aspects, we identified the areas where the impact of fires can be reduced by boosting the biomass market. We refined the areas where the biomass market can be developed, providing benefits for the government, local populations, potential industries and the environment.

Among the five potential factory locations, we determined that APP and Sungai Lumpur are good options for installing a biomass valorization factory. Both locations cover around 80 % of each of the three land uses evaluated.

The land management scenarios evaluated here can provide additional income for the local population, taking advantage of the biomass residues that are currently burned on peatland. At the same time, they are an alternative means of reducing GHG emissions from fires. The mitigation scenarios presented here are an option to encourage local populations to not use fires for land clearing and which should not become a barrier to economic growth.

An important factor that it is not analyzed in this study is the cost of damage from the recurrent use of fires. This is an aspect to be examined in future studies, since this damage means considerable costs for the government, which the biomass market could avoid.

Annexes

Annex 4-1. Fire occurrence for each succesive zone based on the base period 2002-2018, in years

Factory location	Successive area	Degraded peatlands Weighted average	Degraded peatlands Weighted sd	Oil palm Weighted average	Oil palm Weighted sd	Pulpwood Weighted average	Pulpwood Weighted sd
APP	0-100 km	1.77	1.41	1.83	1.51	1.92	1.26
	100-200 km	1.40	1.34	0.80	1.26	1.51	1.19
	200-300 km	2.21	1.59	0.20	0.70	1.34	1.39
	300-400 km	0.86	1.00	na	na	1.16	1.32
Palembang	0-100 km	1.62	1.54	1.66	1.44	1.78	1.23
	100-200 km	1.43	1.33	0.92	1.31	1.45	1.34
	200-300 km	1.75	1.72	0.71	1.27	1.28	1.28
	300-400 km	0.80	0.99	1.74	1.63	Na	na
Pedemaran	0-100 km	1.29	1.33	0.93	1.34	1.36	1.36
	100-200 km	1.46	1.36	0.84	1.32	1.65	1.29
	200-300 km	2.29	1.76	1.63	1.56	0.95	1.03
	300-400 km	na	na	na	na	Na	na
Secukai	0-100 km	1.18	0.85	0.67	1.19	0.96	1.22
	100-200 km	1.37	1.31	1.79	1.50	1.51	1.43
	200-300 km	1.82	1.57	na	na	1.62	1.29
	300-400 km	na	na	na	na	1.60	1.20
Sungai Lumpur	0-100 km	1.63	1.55	1.67	1.66	1.54	1.37
	100-200 km	1.47	1.39	1.40	1.41	1.53	1.29
	200-300 km	1.27	1.24	0.86	1.33	1.21	1.42
	300-400 km	na	na	0.44	0.82	0.29	0.56

Chapter 5
Synthesis and conclusions

1. Introduction

Southeast Asia is a region currently affected by fires. These fires are used for land clearing, hunting and land tenure, or are caused by accidents. The issue of fires has become a concern for the region due to transboundary haze, affecting the local and neighboring populations. The government and different NGOs are working to find alternatives to end the use of fires. Policies and regulations at the regional and local levels, incentives, land preparation techniques without fire and peatland restoration are the main actions. These actions have led to a reduction in fires in recent years. However, fire alerts continue every year, affecting large peatland areas. In this thesis, we estimated the impact of the use of fire in peatlands and some alternative land management systems, such as mitigation scenarios, to reduce the use of fire. This analysis was performed through a case study in OKI, South Sumatra. The first objective of this thesis, "*Determine the greenhouse gas emissions associated with current fires in agricultural and forest areas in tropical peatlands*", enabled us to estimate the impact of wildfires in peatlands and to determine the parameters that are the main contributors to uncertainty. Through the second objective, "*Quantify avoided emissions from peat soil combustion and evaluate the sustainability of alternative scenarios based on the use of aboveground biomass for bioenergy production and other types of land management*", we estimated the business as usual scenario and evaluated the impact of different mitigation scenarios as alternatives to the use of fire. Finally, from the third objective, *"Identify socio-economic and political determinants to promote the implementation of different types of land use management in OKI"*, we evaluated the environmental and socio-economic impacts of implementing these land management scenarios in OKI.

This study enabled us to obtain a broad perspective on fire activity and its impact in OKI, the most affected peatland areas and the areas most suited to implementing alternative types of land management, such as mitigation scenarios to reduce the use of fire for land clearing.

2. Impact of peatland fires in Southeast Asia

In recent years, different studies have been conducted to estimate GHG emissions from peatland fires in Southeast Asia. Most of these studies estimated carbon loss from the extreme fires of 1997-98, 2005-06 and 2015, almost all of which occurred during severe dry seasons affected by the El Niño phenomenon. These studies reflect the considerable uncertainty of these estimates. In total, 70 % of the emissions estimated come from the peat soil burned and the rest from the aboveground biomass burned.

We proposed a general equation to estimate the GHG emissions from peat soil combustion in fires in order to obtain its impact in terms of CO_2-eq. The estimate in CO_2-eq made it possible to consider the combined global warming potential of different GHGs in the atmosphere. Through a meta-analysis, we obtained default values for the parameters involved in this estimate. These meta-analyses consider data from fires during severe and non-severe dry seasons. Using these default values and the aforementioned general equation, we obtained an amount of 842 Mg ha^{-1} CO_2-eq with a standard deviation of 466 Mg ha^{-1} CO_2-eq for a single fire. The depth of burn was the main contributor to the uncertainty at 94.2 %, followed by the bulk density at 5.5 %. The contribution of emissions factors to these uncertainties for the four gases analyzed was negligible. Given that the depth of burn presented the highest variability among the data collected, we obtained that if it is possible to measure in situ the depth of burn in situ instead of using a default value, the contribution of this parameter to the uncertainty falls significantly to 25 %. In this case, the fire-damaged area and bulk density were the two main sources of uncertainty, contributing around 54 % and 39 % respectively. The contribution of each parameter to variance, as estimated in this study, made it possible to prioritize efforts towards uncertainty reduction. Combining Monte Carlo simulation and an analytical expression of variance, as was the case in this study, could be a promising way of obtaining more reliable confidence intervals.

3. Fire activity in OKI and its impact

From a fire occurrence assessment performed in OKI for the period 2002-2018, we obtained that on average, degraded peatlands were affected by fires 1.45±1.37 years during the 17 years evaluated, 0.98±1.38 years for oil palm plantations, and 1.56±1.31 years for pulpwood plantations, at a 95 % confidence interval. The land use most affected by fires was pulpwood plantations, where 76 % of the pixels presented fire occurrence, followed by degraded peatlands with 70 % of pixels with fire occurrence, and oil palm plantations with 45 %. Beyond the number of pixels affected by land use, we obtained that the largest burned area affected by fires was pulpwood plantations, with 84 % of the pixel area affected, followed by degraded peatlands with 49 % of the pixel area affected, and oil palm plantations with 41 %.

Based on the fire occurrence obtained for each land use, the total GHG emissions from peat soil combustion estimated for this period were $37x10^6$ Mg CO_2-eq for degraded peatlands, $36x10^6$ Mg CO_2-eq for oil palm plantations, and $321x10^6$ Mg CO_2-eq for pulpwood plantations. Correction factors were applied to the estimate of degraded peatlands when consecutive fires occurred for this land use. This correction relates to the depth of burn, the parameter with the highest uncertainty, as reported in Chapter 1. The changes occurred in the bulk density of peat soil after each fire, playing an important role in the depth of burn of the next fire occurring, and indicating an overestimation if the correction factors are not used. However, if it is not certain how many fires have occurred, the use of these correction factors could underestimate GHG emissions. This correction was not applied to the other land uses because of a lack of field data for these cases. It could lead to an overestimation of GHG emissions for oil palm and pulpwood plantations.

For a more reliable estimate of GHG emissions in OKI, we recommend that future works perform a study regarding the fire-damaged area and depth of burn in fires. The fire-damaged area is usually estimated based on the burn scar , a process that does not capture the heat of smoldering fires underground, and underestimates the area affected by fires. In addition, the fire-damaged area by pixel estimated in Chapter 2 is based on another study carried out in a similar context to our study area. However, it would be useful to perform a specific study in our study area to corroborate the fire-damaged area obtained here. Regarding the depth of burn, our results suggest that it should at least be measured after every fire, in order to avoid variance due to the considerable heterogeneity across the different fire episodes.

4. Impact of alternative peatland management scenarios

We evaluated the impact of biomass valorization scenarios in drained and non-drained conditions and another scenario assuming peatland restoration. The scenarios in non-drained conditions and restoration were considered for degraded peatlands. For oil palm and pulpwood plantations, non-drained conditions are not suitable for adequate growth. These scenarios were compared with two BAU scenarios: areas with fire occurrence and areas without fire occurrence.

For biomass valorization scenarios, we evaluated bioethanol production, combined heat and power generation and panel manufacturing. The GHG emissions from the three types of biomass valorization were similar. The impact of the restoration scenario was the same for the three land uses, enabling net carbon sequestration. The emission source that contributed the most to the impact in oil palm and pulpwood plantations was gas fluxes from organic soils due to drainage, followed by peat soil combustion. For degraded peatlands, the main contributor was peat soil combustion because the drainage level was considered lower than in plantations.

Comparing biomass valorization in drained conditions with BAU scenarios, we obtained that biomass valorization could avoid between 50-60 t ha^{-1} yr^{-1} of CO_2-eq in areas with fire occurrence. At the regional level, utilizing biomass could reduce GHG emissions by about 2 - 10 %.

Regarding biomass valorization scenarios in non-drained conditions, these enabled a GHG emissions reduction of approximately 100 % compared with BAU. These scenarios refer to degraded peatlands, where it could be possible to reduce the drainage level because this land use does not have an established use. For this land use, paludiculture systems are an interesting option that could be more productive for the owners than the actual land use management. Paludiculture is a practice that uses species adapted to waterlogged conditions and harvests only the part of net primary production that is not necessary for peat formation. Recent studies list potential species for paludiculture systems that produce latex, pulp, fruit, wood and other similar uses to the species planted in drained conditions. Paludiculture has the potential to create economic activities in peatlands that have a lower impact than the current land management.

5. Socio-economic criteria for implementing mitigation scenarios in OKI

Defining the areas where the biomass market is or is non viable makes it possible to prioritize the suitable areas for implementing biomass valorization and to focus government investment in peatland restoration or incentive payments on those areas where the biomass market is non viable. Moreover, the biomass market could create additional income for the local population. Boosting the biomass market in the viable areas identified in this study could reduce GHG emissions from fires by about 4 - 6 %.

For the areas where a biomass market is non viable, we recommend investing resources from the government or other interested organizations in reducing fires, through peatland restoration or incentive payments. This means that the local people who cannot benefit from the biomass market could benefit from incentive payments or peatland restoration.

Having determined the most appropriate areas in which to implement each scenario, efforts should be focused on ensuring organization between the local population, government and industry in order to make the implementation of land management scenarios possible.

To be realistic about the implementation of mitigation scenarios in the areas where the biomass market is non viable, peatland restoration should be considered for degraded peatlands. Incentive payments should be considered for plantations, to enable the current economic activity to continue. The mitigation scenarios presented here are an option to encourage the local population to not use fire for land clearing, and should not become a barrier to economic growth.

6. Conclusion and perspectives for future work

The major issue that motivated this thesis was that of the fires currently affecting Indonesian peatlands. This environmental issue is closely connected to socio-economic factors. This thesis provides a broad perspective on the environmental and socio-economic aspects of land management in OKI and the implementation of mitigation scenarios.

The thesis led us to three main conclusions:

1) Mitigating an environmental issue can be compatible with the economic activity in an area, creating additional income for the population,

2) Considerable biomass potential in OKI, which could create new economic activity, is currently being wasted, and,

3) The resources the government or other organizations invest in reducing the use of fires could be better used by organizing and prioritizing areas, while benefiting the local population.

Having demonstrated these findings, the next step is to put them into practice. To do so, I consider that the next studies to be carried out are divided into three main areas, as follows:

1) Error propagation for more accurate estimates: To obtain more reliable estimates of GHG emission reductions achieved by implementing mitigation scenarios, we should take into account the error propagation for both mitigation scenarios and business as usual. Business as usual is the benchmark to evaluate GHG emission reductions achieved by implementing mitigation scenarios. For future works, I recommend measuring in situ the depth of burn and bulk density as priority parameters, and taking into account fire recurrence. This measurement will avoid the variance between sites caused by using default values. The fire-damaged area should also be modeled considering residual smoldering combustion and not only the scar that it is visible in satellite images. The estimates of these parameters must be measured for each type of land use due to the different land preparation for each one.

It is also important to validate the fire occurrence estimated in this study by comparing with the data from other sources, such as for example, Sentinel 3. In addition to this, it would be worth performing an exhaustive analysis of the fire origin in each land use.

2) Environmental impacts: In this study, we evaluated mitigation scenarios to reduce the impact of fires. We demonstrated that the drainage level has a considerable impact in terms of GHG emissions, similar to or greater than that of fires. We suggested evaluating mitigation scenarios by taking into account practices aimed at lowering the drainage level. We described a first approach to GHG emission reductions through biomass valorization in non-drained conditions. These scenarios represent paludiculture systems. Some studies list potential species to use in these systems, but I did not find any documented experiments. One of these studies found that producers are not willing to exchange their current crops for species that are not well known, and for this reason I recommend evaluating this system in degraded peatlands where no species are currently produced. For the current crops such as oil palm or pulpwood, one of the options to consider is the adaptation of these species to a lower drainage level. I also recommend studying how the reduction of fires can avoid impacts on issues other than GHG emissions, such as impacts on air, water, biodiversity, and health, among others.

3) Socio-economic aspects: In this study, we evaluated three types of biomass valorization. However, these types of biomass valorization should also be evaluated in terms of opportunities, capital costs and income for the local population.

To boost the biomass market in OKI, we recommend performing a study of the main stakeholders that could be involved, in particular the municipal government, the local population, potential industries and a neutral body to help organize these stakeholders. I underline the main objective of developing a biomass market in OKI: reducing the impact of fires in peatlands and generating additional income for the local population. For these reasons, I recommend including a neutral body to coordinate the organization of stakeholders so as to avoid industry benefiting more than the local population.

A study of the carbon market to boost the biomass market should be performed. To do so, it is necessary to focus on the accurate estimates mentioned in the first point in order to demonstrate the additionality of mitigation scenarios. Finally, the cost for the government of the fires occurring every year should be evaluated, since it could be avoided and invested in incentive payments and peatland restoration.

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Résumé substantiel

Introduction

Trois pour cent de la masse terrestre totale est couverte de tourbières, elles se trouvent principalement dans les régions boréales (83%) et tempérées (4%). Sur ces trois pour cent, les tourbières tropicales représentent 12,7 %, l'Amérique du Sud détenant la plus grande superficie de tourbières tropicales (46 %), suivie par l'Asie (36 %) et l'Afrique (18 %). Les tourbières tropicales joue un rôle important en tant que réservoir de carbone, stockant environ 350 000 TgC. Dans la partie sud-est de l'Asie, le carbone stocké dans les tourbières est estimé à environ 68 500 Tg de carbone.

Le changement d'utilisation des terres au cours des dernières décennies et les pratiques de gestion des terres, dans les plantations forestières et agricoles, ont causé une perte importante de carbone. Dans les tourbières, la préparation des terres pour l'agriculture ou les plantations de bois à pâte nécessite être drainé et des feux afin de créer les conditions adéquates pour des utilisations agricoles plus intensives. Le nettoyage des champs par le feu est une pratique traditionnelle utilisée par les agriculteurs migrants, les entreprises privées et les agences gouvernementales. Les feux de tourbières sont généralement caractérisés par une combustion qui couve (en anglais « Residual smoldering combustion » - RSC). RSC implique un processus lent et persistant, largement responsable de l'expansion des feux. Ce type de combustion peut continuer à se développer sous terre, verticalement jusqu'à ce qu'il atteigne la nappe phréatique, ou horizontalement sous la forme de RSC après des feux de surface. Les derniers incendies dans les tourbières indonésiennes ont libéré une grande quantité de gaz à effet de serre (GES) dans l'atmosphère. Ces incendies affectent également l'économie et la santé humaine des habitants de l'Indonésie et des pays voisins. Parmi les plus importants, on peut citer les incendies survenus en 1997-98, 2006 et 2015, lors du phénomène El Niño - Oscillation australe.

Face à ce problème d'incendies de tourbe, qui touche l'Indonésie et les pays voisins, le gouvernement a adopté des politiques, des réglementations, des innovations techniques, des développements en matière de surveillance des incendies et des incitations à une meilleure gestion des terres. Cependant, malgré ces mesures, les incendies se poursuivent dans la région. Les principales raisons de la persistance des incendies sont la non-application des politiques et des réglementations, le manque d'incitations, le manque de connaissances techniques et d'informations sur la préparation des terres à l'absence de feux et à cause des aspects culturels (par exemple, l'utilisation du feu pour des raisons traditionnelles).

Dans cette thèse, nous avons évalué différents scénarios de gestion des terres comme une option pour réduire les incendies, en convertissant la biomasse aérienne en bioénergie ou autres bioproduits au lieu de la brûler et, en même temps, en créant des incitations pour la population.

Les trois principaux objectifs de la thèse sont : i) Déterminer les émissions de gaz à effet de serre associées aux incendies actuels des zones agricoles et forestières sur les tourbières tropicales ; ii) Quantifier les émissions évitées provenant de la combustion de la tourbe et évaluer la durabilité des scénarios alternatifs basés sur l'utilisation de la biomasse aérienne pour la production de bioénergie et autres sous-produits ; et iii) Identifier les déterminants socio-économiques et politiques pour promouvoir l'utilisation de la biomasse sur les tourbières pour la production de bioénergie. J'ai développé ces objectifs à travers quatre chapitres qui correspondent chacun à un objectif, sauf pour le chapitre 2 qui correspond aux évaluations générales utilisées pour effectuer les analyses des autres chapitres.

Aperçu de la thèse

Mon projet de thèse est développé en quatre chapitres principaux. Dans le ***Chapitre 1***, nous nous sommes concentrés sur le principal problème qui a motivé cette thèse : les incendies dans les tourbières tropicales. Ce chapitre donne une perspective de la situation actuelle dans les tourbières d'Asie du Sud-Est et une estimation des émissions de GES des tourbières brûlées lors des incendies en termes de CO_2 équivalent ha^{-1}.

Étant donné que les incendies sont un problème local mais ont un impact à plus grande échelle, c'est-à-dire une brume transfrontalière vers l'Asie du Sud-Est et un impact direct sur le changement climatique, nous avons analysé à partir du Chapitre 2, différents scénarios de gestion des terres à travers un cas d'étude à Ogan Komering Ilir (OKI). Le ***Chapitre 2*** fournit les informations de base et les paramètres utilisés tout au long du rapport pour développer les différents scénarios de gestion des terres sur les tourbières en OKI. Plus précisément, il présente la zone d'étude, une estimation des émissions de GES résultant de la combustion de la tourbe liée à l'activité du feu pour l'ensemble de la zone d'étude et une évaluation de la distance liée au transport de la biomasse a été réalisée. Dans le ***Chapitre 3***, nous avons analysé différents scénarios de gestion de l'utilisation des terres où la valorisation potentielle de la biomasse est analysée comme alternative au nettoyage des tourbières par des incendies, et leur impact a été estimé. Enfin, au ***Chapitre 4***, nous avons évalué la mise en œuvre des scénarios de gestion des terres en OKI. Une analyse intégrant les résultats obtenus dans les derniers chapitres avec une évaluation économique a été réalisée.

Chapitre 1. Estimation des émissions de gaz à effet de serre provenant de la combustion de la tourbe lors des incendies dans les tourbières indonésiennes, et leur incertitude

1. Introduction

Les incendies dans les tourbières indonésiennes peuvent avoir un impact important sur le changement climatique en raison de la grande quantité de gaz à effet de serre (GES) qu'ils libèrent dans l'atmosphère. Dans les tourbières, la préparation des terres pour l'agriculture ou les plantations de bois à pâte nécessite un drainage afin de créer les conditions adéquates pour des utilisations agricoles plus intensives (Farmer et al., 2011). Environ 70 % des émissions totales de carbone à la suite d'incendies de tourbières proviennent de la combustion des sols tourbeux, tandis que les 30 % restants proviennent de la combustion de biomasse en surface (Page et al., 2002 ; Van der Werf et al., 2010). L'impact des incendies de tourbières en termes d'émissions de carbone a été abordé dans de nombreuses études (Ballhorn et al., 2009 ; Konecny et al., 2016 ; Page et al., 2002 ; Van der Werf et al., 2010). Bien que les estimations des émissions de carbone varient considérablement selon les différents épisodes d'incendie, ces études présentent une constante : les estimations sont toutes sujettes à de grandes incertitudes. Il existe en fait de nombreux paramètres impliqués dans l'estimation des émissions de carbone et l'incertitude entourant chacun d'entre eux n'est pas bien connue.

Dans ce chapitre, nous avons effectué une analyse documentaire sur les émissions de GES provenant des feux de tourbières en Asie du Sud-Est, ainsi qu'une méta-analyse sur les paramètres utilisés pour estimer leur impact sur le changement climatique en termes de CO_2 équivalent. En outre, nous avons proposé une équation générale pour estimer les émissions de GES des incendies de tourbières.

2. Méthodes

Dans la littérature, l'impact des feux de tourbières sur le changement climatique est estimé à l'aide de deux indicateurs : les émissions de GES et la perte de carbone. Nous avons normalisé les deux méthodes afin d'obtenir une estimation plus complète de l'impact des feux de tourbières sur le changement climatique comme suit :

$$\mathrm{E_{fire}} = \mathrm{A} \times \mathrm{P} \times \mathrm{BD} \times \sum_i (\mathrm{G_{ef,i}} \times \mathrm{GWP_i}) \times 10 \qquad (1)$$

où E_{fire} est la quantité d'émissions de GES (Mg de CO_2 équivalent), A est la superficie totale endommagée par le feu (ha), P est la profondeur moyenne de combustion (m), BD est la densité apparente moyenne du sol tourbeux (Mg m^{-3}), Gef est le facteur d'émission moyen pour chaque gaz (kg Mg^{-1} matière sèche brûlée) et GWP est le potentiel de réchauffement climatique pour chaque gaz (Mg de CO_2 équivalent /Mg de gaz). Toutes les estimations des émissions de GES dans cette étude ont été obtenues en utilisant l'équation 1.

Nous avons rassemblé des études relatives à la profondeur de combustion des récents épisodes d'incendies, à la densité apparente des sols de tourbe et aux facteurs d'émission de CO_2, CO, CH_4 et NO_x à partir de la littérature existante. Les donnes rassemblées ont été analysés en utilisant une approche de méta-analyse.

Avant d'obtenir une estimation des émissions de GES et de l'incertitude liée à cette estimation, deux approches ont été envisagées. La première était une approche "rétrospective". Elle suppose que l'incendie a déjà passé et que certains paramètres ont déjà été mesurés ou estimés pour cet incendie particulier. La seconde approche était une approche prospective. Elle consistait à faire des projections des émissions futures par la combustion de la tourbe. Cette approche s'applique également à l'estimation des émissions de GES après un incendie pour lequel aucune mesure n'aurait été prise. Enfin, la contribution de chaque paramètre à la variance des émissions de GES estimées a été évaluée.

3. Résultats

Les émissions de GES d'un seul épisode d'incendie ont été estimées à 842 Mg ha^{-1} CO_2-eq avec un écart-type de 466 Mg ha^{-1} CO_2-eq. Le paramètre contribuant le plus à la variance était la profondeur brûlée, à 94,2 %, suivi de la densité apparente du sol, à 5,5 %, et des facteurs d'émission, à 0,3 %. Nos estimations des émissions de GES étaient proches de la quantité estimée à partir des valeurs par défaut fournies par le GIEC, ce qui renforce la confiance dans la méthodologie du GIEC. Lorsque la profondeur brûlée a été évaluée par télédétection, le paramètre qui a le plus contribué à la variance est devenu la zone endommagée par le feu, suivie par la profondeur brûlée. La contribution de chaque paramètre à la variance, telle qu'elle a été estimée dans cette étude, a permis de hiérarchiser les efforts de réduction de l'incertitude. La combinaison de la simulation de Monte Carlo et d'une expression analytique de la variance pourrait être un moyen prometteur d'obtenir des intervalles de confiance plus fiables.

4. Conclusion

Dans cette étude, les émissions de GES provenant de la combustion de la tourbe et la contribution des paramètres à l'incertitude ont été estimées. Les valeurs par défaut de la profondeur de combustion, de la densité apparente du sol tourbeux et des facteurs d'émission ont été obtenues pour les épisodes d'incendie passés et futurs. Pour un feu futur, les émissions moyennes de GES ont été estimées à 842 Mg ha^{-1} CO_2-eq avec un écart-type de 466 Mg ha^{-1} $CO_{2\text{-éq}}$. En outre, nous avons déterminé les principaux paramètres contribuant à l'incertitude de cette estimation. Dans les approches rétrospectives, la zone endommagée par le feu et la densité apparente du sol ont été les deux principales sources d'incertitude, contribuant respectivement à environ 54 % et 39 %. Dans les approches prospectives, la profondeur brûlée était la principale source d'incertitude avec 94,2%. La contribution des facteurs d'émission à ces incertitudes pour les quatre gaz analysés ici était négligeable. Nos résultats montrent donc l'importance de se concentrer sur la profondeur brûlée, la zone endommagée par le feu et la densité apparente do sol pour diminuer l'incertitude dans l'estimation des émissions de GES provenant de la combustion de tourbe dans les feux de forêt.

Chapitre 2. Évaluations générales

Ce chapitre fournit les informations de base et les paramètres utilisés tout au long de cette thèse pour développer les différents scénarios de valorisation de la biomasse sur les tourbières. Plus spécifiquement, la première partie du chapitre présente la zone d'étude, Ogan Komering Ilir (OKI), et le contexte dans lequel les évaluations ont été réalisées. La partie II fournit une estimation des émissions de GES résultant de la combustion de la tourbe liée à l'activité des incendies pour l'ensemble de la zone d'étude. Cette estimation était une condition préalable pour le Chapitre 3 dans lequel il est question d'un scénario "Business as usual" dans la comparaison avec d'autres scénarios de valorisation de la biomasse. Enfin, dans la partie III, une évaluation de la distance liée au transport de la biomasse a été réalisée, en supposant différents emplacements d'usines. Cette évaluation a également été utilisée pour évaluer l'impact du transport de la biomasse en termes d'émissions de GES dans le chapitre 3 et le coût du transport de la biomasse vers les usines dans le chapitre 4.

PARTIE I. ZONE D'ÉTUDE

Notre zone d'étude est Ogan Komering Ilir (OKI), une régence de la province de Sumatra Selatan, située dans la partie sud de l'île de Sumatra. Nous nous sommes concentrés sur les trois principales utilisations des sols tourbeux dans le district d'OKI, qui sont également considérés pour leur potentiel de biomasse à valoriser : (i) les tourbières dégradées, (ii) les plantations de palmiers à huile et (iii) les plantations de bois à pâte. Les plantations de bois à pâte couvrent la majeure partie de la zone de plantation. La valorisation potentielle de la biomasse prise en compte est constituée de buissons et d'herbe pour les tourbières dégradées, de résidus de tronc, de frondes, de grappes de fruits vides, de fibres et de coquilles pour les plantations de palmiers à huile et de résidus d'exploitation de tronc et de branches de plus de 8 cm de diamètre pour les plantations de bois à pâte.

PARTIE II. ÉMISSIONS DE GAZ À EFFET DE SERRE PROVENANT DE LA COMBUSTION DE LA TOURBE DANS LE SOL D'OKI

1. Introduction

OKI est l'une des zones touchées par les incendies dans la province de Sumatra Selatan (Laithier, 2016). Certains d'entre eux se produisent dans des tourbières dégradées, où le feu est utilisé pour le défrichement, la chasse et la collecte de produits forestiers non ligneux ou est causé par accident, sans surveillance ni contrôle, ce qui entraîne l'extension du feu (Sinclair et al., 2020). Le feu peut également se produire dans les plantations, où le brûlage est utilisé comme traitement de préparation du site.

Dans cette partie, nous avons estimé les émissions de GES provenant de la combustion des sols tourbeux pour les trois types d'utilisation des sols susmentionnés dans la zone d'OKI. Afin d'obtenir une estimation au niveau régional des émissions de GES dues à la combustion des sols tourbeux, nous avons effectué une analyse de l'occurrence des incendies dans la zone d'OKI pour la période 2002-2018. Cette estimation est l'une des sources d'émission utilisées dans le Chapitre 3 pour définir le scénario "business as usual". Le scénario "business as usual" est la base de référence pour mesurer l'impact de la mise en œuvre des scénarios alternatifs proposés pour la gestion des tourbières (IPCC, 2018).

2. Matériel et méthodes

2.1. Occurrence des incendies

L'évaluation de l'occurrence des incendies a été réalisée à l'aide de géo-données vectorielles de 1) la division administrative de Sumatra Selatan, 2) l'utilisation des terres dans l'OKI, 3) les points chauds des incendies et 4) une taille de grille de 889 m x 891 m par pixel (79,21 ha pixel-1), ce qui correspond approximativement à une grille de 30". La période 2002-2018 a été choisie comme période de référence (IPCC, 2018) en fonction de la disponibilité des données sur les points chauds des incendies. Les points chauds des incendies ont été détectés par Terra and Aqua de la NASA, et les données ont été recueillies de juin 2002 à décembre 2018.

Afin d'estimer la fréquence des incendies en fonction de l'utilisation des terres, la grille de 30" a été superposée à la couche d'utilisation des terres et l'activité des incendies a été évaluée dans chaque pixel de la grille. Le nombre moyen d'incendies a été calculé comme étant le nombre d'années avec au moins un point chaud sur la période 2002-2018.

3. Résultats et discussion

Les résultats ont montré que les 70%, 45% et 76% des pixels des tourbières dégradées, des palmiers à huile et des plantations de bois à pâte respectivement, ont été touchés par des incendies au cours de la période 2002-2018. L'émission totale de GES provenant de la combustion des sols tourbeux a été estimée pour cette période à 76x106 Mg $CO_{2\text{-éq}}$ pour les tourbières dégradées, 36x106 Mg $CO_{2\text{-éq}}$ pour la plantation de palmiers à huile et 321x106 Mg $CO_{2\text{-éq}}$ pour la plantation de bois à pâte. Des facteurs de correction ont été appliqués à la profondeur du brûlage en fonction du fait que le feu s'est produit dans une tourbière dégradée, sur la base d'un modèle de Konecny et al. (2016). Après application de ces facteurs de correction, nous avons obtenu 37x106 Mg $CO_{2\text{-}}$

$_{éq}$. Cette dernière valeur est utilisée tout au long de la thèse à la place de 76x106 Mg $CO_{2\text{-éq}}$. Les facteurs de correction ne sont pas appliqués aux plantations de palmiers à huile et de bois à pâte car on ne sait pas si le modèle obtenu par Konecny et al. peut être reproduit pour des types d'utilisation des terres autres que les tourbières dégradées. Cependant, cela peut signifier une surestimation des émissions de GES estimées ici.

4. Conclusions

Nous avons constaté que les plantations de bois à pâte étaient celles qui contribuaient le plus en OKI pour trois raisons principales : la grande surface des plantations dans la zone étudiée, le pourcentage le plus élevé de pixels ayant subi un incendie et la plus grande zone brûlée affectée par un pixel parmi les trois utilisations des terres.

Les estimations sont soumises à une importante source d'incertitude. La surface brûlée par pixel n'est pas effectuée dans cette étude, et elle est basée sur une autre étude développée dans un contexte similaire au nôtre. Il est recommandé d'effectuer une évaluation de la surface brûlée en OKI afin d'affiner l'estimation des émissions de GES pour la zone étudiée.

PARTIE III. LE TRANSPORT DE LA BIOMASSE VERS LES USINES

1. Introduction

Dans le district d'OKI, les routes et les voies navigables sont utilisées pour le transport de marchandises, le choix de l'itinéraire préféré dépendant des conditions météorologiques (Samuel, 2015). Dans certains cas, le fret doit être déplacé d'un transport à l'autre sur le même trajet en raison du mauvais état des routes. Pendant la saison sèche, le niveau des voies navigables baisse, ce qui rend impossible l'utilisation de bateaux de fret mais permet le transport par la route. Au contraire, la saison des pluies favorise le transport sur les voies navigables et l'empêche sur les routes.

Dans cette partie, une évaluation des distances a été réalisée afin d'obtenir les distances minimales, maximales et moyennes pour le transport de la biomasse en OKI. En outre, nous avons défini cinq sites d'usine qui pourraient accueillir la biomasse collectée dans les trois utilisations des terres selon des scénarios alternatifs. L'objectif était d'estimer l'influence de la distance du transport de la biomasse sur les émissions totales de GES au Chapitre 3 et l'influence de la distance sur les coûts de transport au Chapitre 4.

2. Méthodes

L'évaluation de la distance du transport de la biomasse a été réalisée à OKI et à Palembang. Nous avons défini cinq sites d'usines potentiels où nous avons considéré qu'une usine de valorisation de la biomasse pouvait être installée, comme suit : APP, Palembang, Secukai et Pedemaran, Sungai Lumpur.

Pour évaluer la distance de transport de la biomasse, nous avons obtenu des géo-données des routes et des voies navigables à partir d'études récentes dans la même région (Laithier, 2016 ; Samuel, 2015). Pour estimer la distance par pixel attribuée aux cartes matricielles, des valeurs du coût de friction de l'étude de Desprès (2015) ont été attribuées à chaque pixel. Le coût de frottement est un coefficient en kilomètres pour calculer la distance réelle en fonction de l'état des voies. Dans le cas présent, un coût de friction de 0,07 km par pixel pour les voies navigables et les routes a été attribué et 0,14 km par pixel pour les routes. Le coût de frottement en tout-terrain est plus du double du pixel en raison de la tortuosité du chemin (Desprès, 2015). La distance entre un point quelconque et la route et la voie d'eau a été calculée ensemble en raison du fait que, dans certains cas, les conditions météorologiques ou le chemin vers la destination finale nécessitent l'utilisation des deux types de routes. Enfin, la distance de tout point hors route et des routes et voies navigables à chaque usine a été calculée. Les principaux outils utilisés ont été r.mapcalc, r.patch et r.cost du logiciel SIG GRASS.

3. Résultats et discussion

Nous avons obtenu que les voies navigables donnent un accès plus large à la zone d'étude. La distance moyenne de n'importe quel point aux voies navigables les plus proches était de 49 km (min=0, max=233) tandis que la distance moyenne à la route la plus proche était de 122 km (min=0, max=347). La distance moyenne à la route ou à la voie d'eau la plus proche dans la zone d'étude était de 23 km (min= 0, max= 133).

La distance moyenne entre les cinq sites d'usines et tout point de sortie de route était similaire. Nous avons noté que Palembang, Pedemaran et Secukai ont accès aux deux types de voies, ce qui permet une meilleure accessibilité du transport de la biomasse tout au long de l'année. Les sites d'APP et de Sungai Lumpur étaient limités aux voies navigables, ce qui est important à prendre en compte pour les aspects logistiques. La distance pour accéder à une route depuis les usines est d'environ 0 à 9 km.

4. Conclusion

L'évaluation de la distance a permis d'identifier les points les plus proches et les plus éloignés des routes, des voies navigables et des emplacements d'usines. Les voies navigables donnent un accès plus large à la zone d'étude. Cependant, les voies navigables et les routes qui s'y trouvent sont longues et ne sont pas disponibles toute l'année. Pour cette raison, la distance des cinq sites d'usines a été obtenue en considérant les deux types de routes ensemble. Cela peut ajouter un coût supplémentaire dû au changement de la biomasse d'un transport à l'autre, qui est examiné au chapitre 4. Toutefois, l'étude a été réalisée en tenant compte du contexte réel de la zone d'étude.

Chapitre 3. Émissions de gaz à effet de serre sur le cycle de vie de la valorisation de la biomasse en OKI

1. Introduction

Cette préparation des terres à l'aide de feux augmente le risque d'expansion du feu vers les terres environnantes et contribue de manière significative au changement climatique en raison de la perte de carbone (Farmer et al., 2011). Alors que la biomasse sur la tourbière brûle, une partie des sols tourbeux est également brûlée, ce qui augmente les émissions de GES dues aux incendies. Dans ce chapitre, plusieurs scénarios d'atténuation sont analysés afin de comparer avec les scénarios de ”business as usual”, leur contribution globale au changement climatique en termes de $CO_{2\text{-éq}}$. La comparaison des scénarios d'atténuation avec le scenario ”business as usual” a permis de savoir s'il existe une additionnalité pour la mise en œuvre de scénarios d'atténuation en OKI comme alternative à la gestion actuelle des terres. Dans ce contexte, l'additionnalité est l'émission de GES qu'il est possible d'éviter par la mise en œuvre de scénarios d'atténuation (IPCC, 2018).

2. Méthodologie

Trois types de biomasse correspondant aux trois utilisations des terres analysées dans cette étude ont été pris en compte pour la production de bioéthanol, la production combinée de chaleur et d'électricité et la fabrication de panneaux. Les cinq scénarios évalués sont les suivants : 1) ”Business as usual” avec occurrence des d'incendies, 2) ”Business as usual” sans incendies, 3) Valorisation prospective de la biomasse en conditions drainées, 4) Valorisation prospective de la biomasse en conditions non drainées et 5) Restauration des tourbières. Les trois types de scénarios de valorisation de la biomasse analysés sont la production de bioéthanol, la production combinée de chaleur et d'électricité et la fabrication de panneaux. L'impact de chaque scénario pour les trois utilisations des terres analysées dans cette étude a été estimé à l'aide d'un outil d'évaluation du cycle de vie. L'unité fonctionnelle de cette ACV est la gestion des tourbières. L'unité fonctionnelle sélectionnée est donc 1 ha de tourbière gérée pendant 1 an (1 ha an). Selon la portée de l'étude, parmi les différents critères considérés dans l'ACV, le critère choisi est celui du "changement climatique".

Les postes d'émission évaluées pour chaque scénario sont les suivantes : Les flux de gaz à effet de serre provenant des sols organiques, la séquestration du C dans la biomasse et les résidus en surface, la combustion de la tourbe dans les sols à la suite d'incendies, les processus de valorisation de la biomasse et la substitution à partir de la valorisation de la biomasse. Ensuite, un bilan des émissions de GES a été réalisé afin d'estimer l'additionnalité pour la mise en œuvre de scénarios d'atténuation en tant que gestion alternative des terres.

3. Résultats et discussion

Les émissions de GES évaluées pour le scénario BAU avec occurrence d'incendies dans les tourbières dégradées, les plantations de palmiers à huile et les plantations de bois à pâte étaient respectivement de 70,60±30, 139,40±31 et 159±27 Mg $CO_{2\text{-éq}}$ ha^{-1} an^{-1}. Les émissions de GES évaluées pour le BAU sans incendie étaient respectivement de 18,45±12, 85,08±21 et 108,3±15 Mg $CO_{2\text{-éq}}$ ha^{-1} an^{-1} pour les tourbières dégradées, les plantations de palmiers à huile et les plantations de bois à pâte. En ce qui concerne le scénario de restauration, les émissions de GES estimées étaient les mêmes pour les trois utilisations des terres, soit - 0,90 Mg $CO_{2\text{-éq}}$ ha^{-1} an^{-1}.

Concernant les scénarios de valorisation de la biomasse par l'unité fonctionnelle de 1 ha, pour les tourbières dégradées, la valorisation de la biomasse pourrait permettre d'éviter environ 74% des émissions de GES en conditions drainées et 99% en conditions non drainées par rapport au scénario "business as usual" avec occurrence d'incendie. Pour la plantation de palmiers à huile, la valorisation de la biomasse pourrait permettre d'éviter environ 60% des émissions de GES en conditions drainées par rapport au scénario "business as usual" avec occurrence d'un incendie. Dans les plantations de bois à pâte, la valorisation de la biomasse pourrait permettre d'éviter environ 40% des émissions de GES en conditions drainées par rapport au scénario BAU avec occurrence d'un incendie.

Les scénarios en conditions non drainées réduisent considérablement les émissions de GES par rapport au "business as usual", car ils réduisent les gaz de flux provenant de l'oxydation de la tourbe et permettent la séquestration du carbone dans le sol tourbeux. Cependant, les scénarios en conditions non drainées sont envisagés uniquement pour les tourbières dégradées, car les conditions de saturation d’eau ne sont pas adéquates pour les cultures de palmiers à huile et de bois à pâte. Les scénarios de valorisation de la biomasse dans des conditions non drainées sont un exemple de systèmes de paludiculture, où les plantations pourraient être gérées dans des conditions de saturation d’eau.

Au niveau régional d'OKI, l'impact de la valorisation de la biomasse en conditions drainées pourrait réduire les émissions de GES de 10% dans les tourbières dégradées, de 2% dans les plantations de palmiers à huile et de 4% dans les plantations de bois à pâte. Les différences entre les trois utilisations des terres peuvent s'expliquer par le niveau de drainage, qui est le plus bas pour les tourbières dégradées parmi les trois utilisations des terres, suivi par les plantations de palmiers à huile et de bois à pâte.

4. Conclusion

Les résultats ont montré que les principales sources d'émission pour tous les scénarios étaient les "flux de gaz à effet de serre provenant des sols organiques" et la "combustion de tourbe". Cela signifie que l'effet de la gestion des terres (drainage/feu) est plus important que le type de valorisation de la biomasse analysé dans cette étude. Passer des pratiques actuelles de nettoyage des terres par le feu à la valorisation de la biomasse pourrait permettre d'éviter entre 2 et 10 % des émissions de GES.

Les scénarios en conditions non drainées réduisent considérablement les émissions de GES par rapport au "business as usual", car ils réduisent les gaz de flux provenant de l'oxydation de la tourbe et permettent la séquestration du carbone dans le sol tourbeux. Cependant, les scénarios en conditions non drainées sont envisagés uniquement pour les tourbières dégradées, car les conditions de saturation d’eau ne sont pas adéquates pour les cultures de palmiers à huile et de bois à pâte.

La valorisation de la biomasse peut être une option pour diminuer la brume des incendies qui ont un impact sur le changement climatique mais qui causent également d'autres types de problèmes tels que les problèmes de santé causés par les matières fines particulières (PM2.5) ou les pertes économiques associées à la brume pour la gestion des terres avec les incendies.

Chapitre 4. - Évaluation socio-économique des scénarios d'atténuation des émissions en OKI

1. Introduction

Les résultats obtenus au chapitre 3 suggèrent un concept permettant de mettre en œuvre différents scénarios de gestion des terres au lieu de brûler la biomasse sur les tourbières, afin d'atténuer les émissions de GES. Les aspects socio-économiques et politiques sont essentiels pour développer ces scénarios. Nous avons analysé les coûts d'approvisionnement en biomasse pour différents scénarios de gestion des terres évalués au Chapitre 3. Nous avons tenu compte en particulier des limitations nécessaires pour assurer la formation de tourbe. L'objectif de ce chapitre est de tracer les limites de ce qui est faisable et de ce qui ne l'est pas, et où. Les critères de mise en œuvre des scénarios de gestion des terres sont évalués sur la base de l'intensité des incendies, de l'accessibilité de la biomasse pour les industries potentielles et du coût.

2. Méthodes

Tous les calculs de coûts sont basés sur les calculs de distance du SIG déjà présentés en détail au chapitre 2. L'algorithme de ces calculs de distance mesure la plus courte distance hors route de tout pixel par rapport à la route la plus proche ou aux voies navigables les plus proches. Il mesure ensuite la distance entre la route ou la voie navigable et l'emplacement potentiel de l'usine. Afin de simplifier l'analyse et les comparaisons des scénarios, les pixels de la carte sont découpés en zones successives tous les 100 km, à partir de chaque emplacement potentiel d'usine.

Les facteurs de coût pris en compte pour la mise en œuvre des scénarios de gestion des terres à des fins d'atténuation sont le coût de transport de la valorisation de la biomasse, le coût de la biomasse et le coût de la restauration des tourbières. Les facteurs techniques évalués sont la biomasse disponible et la fréquence des incendies dans chaque zone successive de 100 km.

Nous avons évalué la mise en œuvre des scénarios d'atténuation obtenus dans le Chapitre 3 en utilisant trois critères différents :

1) Le premier critère est l'occurrence des 'incendies, basé sur l'idée que les scénarios d'atténuation de la gestion des terres doivent agir en priorité sur les zones où les occurrences d'incendie sont les plus importantes.

2) Le deuxième critère est l'économie industrielle froide/neutre, basée sur l'idée que les meilleurs scénarios d'atténuation devraient être appliqués là où le plus de biomasse pourrait être valorisée au coût moyen le plus bas possible. Cela garantirait des effets d'atténuation maximaux, plus de marges pour rémunérer les acteurs locaux de la collecte et du transport de la biomasse, et plus de marges pour assurer la durabilité à long terme.

3) Le troisième critère est un principe de parcimonie, reconnaissant que toute la biomasse ne peut pas être évaluée à un coût qui garantirait l'équité pour les populations locales. C'est là que la socio-économie entre en jeu : il existe déjà un marché pour la biomasse en Indonésie, et en première analyse, on peut considérer le prix observé comme un équilibre négocié.

Pour chaque critère, nous avons évalué l'émission de GES qui peut être réduite au niveau régional en OKI sur la base du coût et des facteurs techniques mentionnés ci-dessus.

3. Résultats et discussion

3.1. Premier critère : où les incendies se produisent-ils le plus fréquemment ?

Nous avons évalué l'occurrence des incendies dans les zones successives de 100 km des cinq sites d'usines potentiels. Nous n'avons pas trouvé de différence significative selon les trois principales utilisations du sol, ou selon les zones de distance en raison de la grande variance. Pour cette raison, nous n'avons pas utilisé ce critère pour évaluer la mise en œuvre des scénarios d'atténuation.

3.2. Deuxième critère : quelle est la disponibilité de la biomasse et son coût ?

Premièrement, nous examinons la biomasse disponible dans chaque 100 km de chaque site industriel potentiel pour savoir si la zone est homogène dans chacun d'eux ou non. Nous avons trouvé une hétérogénéité dans chaque zone en termes de biomasse disponible. Les zones avec le plus de biomasse disponible potentielle obtenue étaient les premiers 200 km de Pedemaran pour les tourbières dégradées, les premiers 200 km de Secukai pour le palmier à huile et les premiers 200 km de Sungai Lumpur pour la plantation de bois à pâte. Ces zones représentent environ 80 à 97 % de chaque utilisation des terres, n'excluant que les zones les plus éloignées, ce qui peut augmenter le coût du transport pour une petite zone.

En ce qui concerne les émissions de GES évitées grâce à la valorisation de la biomasse dans ces zones, nous avons obtenu que la mise en œuvre de scénarios de valorisation de la biomasse en conditions drainées dans des tourbières dégradées a permis de réduire d'environ 8 % les émissions de GES par rapport au "business as usual" total des tourbières dégradées en OKI. En conditions non drainées, la réduction est d'environ 100% et permet même la séquestration du carbone. Dans les plantations de palmiers à huile, les scénarios de valorisation de la biomasse pourraient réduire d'environ 3 % les émissions de GES par rapport au "business as usual" total des plantations de palmiers à huile en OKI. Enfin, la valorisation de la biomasse dans les plantations de bois à pâte pourrait réduire d'environ 4 % les émissions de GES par rapport au "business as usual" de cette utilisation des terres. Au total, les émissions de GES réduites par la mise en œuvre des scénarios de valorisation de la biomasse dans les zones sélectionnées des trois utilisations des terres pourraient être réduites de 4 % par rapport au "business as usual" total de l'OKI.

Dans un rayon de 200 km des sites potentiels d'usines mentionnés ci-dessus, le coût de la réduction d'une tonne d'émissions de GES dans une tourbière dégradée est de 23 dollars, 16 dollars dans une plantation de palmiers à huile et 10 dollars dans une plantation de bois à pâte.

3.3. Troisième critère : où la biomasse peut-elle faire une différence pour les populations locales ?

Dans le dernier paragraphe, nous avons évalué les zones les plus propices à la valorisation de la biomasse pour l'industrie, en ce qui concerne la biomasse disponible et le coût dans un rapport de 200 km des sites d'usines. Ici, nous avons évalué les zones les plus appropriées pour la population locale pour vendre la biomasse à l'industrie.

La rémunération acceptable versée à la population locale pour une tonne se situe entre 8,8 et 9,5 dollars US. Il s'agit de la rémunération acceptée pour la population locale et pour l'industrie sur la base de l'hypothèse définie dans la section 2.1. Pour garantir ce prix, nous avons calculé les zones limites où il est possible de le conserver.

Selon la Fig. 1, les zones blanches correspondent aux zones où le marché de la biomasse fonctionne pour les deux parties, la population locale et l'industrie. Cela signifie que dans ces zones, nous pouvons obtenir une réduction des émissions de GES pour la valorisation de la biomasse au lieu de la brûler, juste pour dynamiser ce marché. Les zones en rouge correspondent aux zones où le coût de la biomasse est supérieur à la marge que l'industrie est prête à payer, par conséquent, le local ne fera pas de profit. Dans ces zones, des alternatives autres que la valorisation de la biomasse devraient être envisagées pour réduire les émissions de GES.

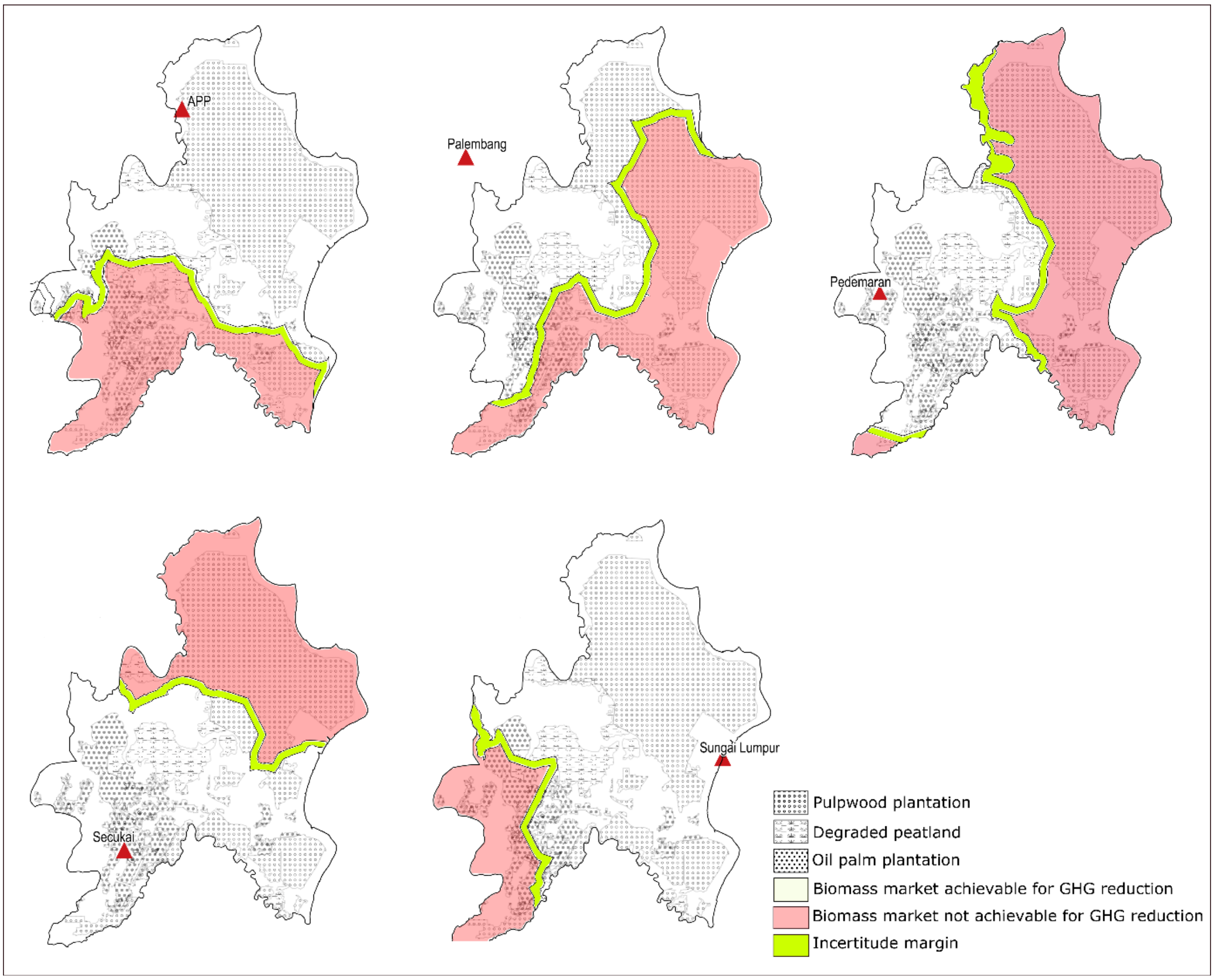

Figure 1. Classification des zones selon le coût pratique de la biomasse pour la population locale basée sur le troisième critère.

Nous avons calculé la quantité de biomasse contenue dans les zones où le marché de la biomasse est réalisable et les émissions de GES qu'il est possible d'éviter pour mettre en œuvre des scénarios de valorisation de la biomasse. Nous avons obtenu que la valorisation de la biomasse de ces zones pourrait permettre d'éviter environ 4 à 6 % des émissions de GES par rapport au "business as usual" en OKI. Le reste de la biomasse contenue dans les zones rouges ne peut pas être valorisé par l'industrie.

Parmi les cinq sites d'usines potentiels, Sungai Lumpur couvre presque la totalité des trois utilisations des terres où le marché de la biomasse est réalisable. Cela indique que cet emplacement peut être un lieu intéressant pour l'installation d'une usine. De plus, ce site a un accès à l'océan, ce qui est considéré pour l'exportation des produits finis vers les pays voisins.

Pour la biomasse contenue dans les zones où le marché de la biomasse n'est pas réalisable, nous avons évalué des options alternatives. Pour les tourbières dégradées, nous avons évalué la mise en place d'un scénario de restauration. Pour les plantations de palmiers à huile et de bois à pâte, nous avons évalué le paiement incitatif pour ne pas utiliser le feu. Le coût de la mise en œuvre de ces scénarios doit être financé par le gouvernement ou toute autre organisation intéressée par la réduction de l'impact des tourbières sur le changement climatique.

La mise en œuvre du scénario de restauration dans les tourbières dégradées permet de réduire de 100% les émissions de GES par rapport au "business as usual" des tourbières dégradées et permet la séquestration du carbone. Le coût de la réduction d'une tonne d'émissions de GES est d'environ 100 dollars US pour la première année. En ce qui concerne le paiement incitatif pour la non-utilisation du feu pour la préparation des terres envisagé pour les zones rouges des plantations de palmiers à huile et de bois à pâte, la réduction des émissions de GES est d'environ 2% par rapport au "business as usual" de cette utilisation des terres. Le coût pour le gouvernement de la réduction d'une tonne d'émissions de GES est de 4 dollars US.

5. Conclusion

En utilisant différents outils et critères comme le SIG, les scénarios d'atténuation et les aspects socio-économiques, nous avons identifié les domaines dans lesquels l'impact des incendies peut être réduit en stimulant un marché de la biomasse. Nous avons affiné les domaines où le marché de la biomasse peut être développé en obtenant un avantage pour le gouvernement, pour la population locale, pour les industries potentielles et pour l'environnement.

Parmi les cinq sites d'usines potentiels, nous avons déterminé que l'APP et Sungai Lumpur sont de bonnes options pour envisager l'installation d'une usine de valorisation de la biomasse. Les deux sites couvrent environ 80 % de chacune des trois utilisations des sols évalués.

Les scénarios de gestion des terres évalués ici, peuvent fournir un nouveau revenu à la population locale en tirant profit des résidus de biomasse qui sont actuellement brûlés sur les tourbières. En même temps, il s'agit d'une alternative pour réduire les émissions de GES des incendies. Les scénarios d'atténuation présentés ici sont une option pour encourager la population locale à ne pas utiliser le feu pour le défrichement des terres et cela ne devrait pas devenir un obstacle à la croissance économique.

Título: Evaluación de diferentes escenarios de gestión de turberas para reducir las emisiones de GEI de los incendios. Un estudio de caso en las turberas tropicales de Ogan Komering Ilir, Indonesia.

Palabras clave: Bioenergía, turberas, biomasa, cambio climático, bruma de incendios

Resumen:

Las turberas tropicales desempeñan un papel importante como reservas de carbono, almacenando aproximadamente 350 000 TgC. En las últimas décadas, los cambios en el uso de la tierra y en las prácticas de gestión de las plantaciones forestales y agrícolas, como el uso de fuego y el drenaje, han causado una importante cantidad de pérdida de carbono. En Indonesia, estos incendios afectan tanto a la economía como a la salud pública de toda la región. En esta tesis, analizamos diferentes escenarios de mitigación para reducir los incendios en turberas, por medio de la conversión de la biomasa superficial en bioenergía u otros bio-productos.

En primer lugar, estimamos un escenario como base "business as usual" (BAU) evaluando las fuentes de emisión de la actual gestión de la tierra. Luego investigamos los posibles escenarios de mitigación, incluyendo la valorización de la biomasa y la restauración de las turberas como alternativas de gestión de la tierra. Por último, evaluamos el impacto en términos de cambio climático y criterios socioeconómicos para la implementación de estos escenarios de mitigación. Este estudio se llevó a cabo mediante un estudio de caso en el distrito de Ogan Komering Ilir (OKI), Indonesia.

El análisis de las emisiones de gases de efecto invernadero (GEI) en el escenario BAU muestra que las zonas afectadas por el fuego emiten 70,60±30, 139,40±31 y 159±27 Mg de CO_2-eq ha^{-1} año^{-1} para las turberas degradadas, la plantación de palma aceitera y la plantación de madera para pulpa, respectivamente. Las zonas no afectadas por los incendios liberan 18,45±12, 85,08±21 y 108,3±15 Mg CO_2-eq ha^{-1} año^{-1}, respectivamente. Para el escenario de restauración, GEI son similares para los tres usos de la tierra, de -0,9 Mg CO_2-eq ha^{-1} año^{-1}.

Seguidamente, evaluamos la viabilidad de los escenarios de valorización de la biomasa para su implementación en OKI en base a criterios socioeconómicos. En las áreas donde la creación de dicho mercado de biomasa es factible, predijimos una reducción de entre el 4 % y 6 % de las emisiones de GEI en comparación con BAU. Impulsar el mercado de la biomasa en estas áreas permite reducir la ocurrencia de incendios sin inversión gubernamental. Por el contrario, la industria no será capaz de valorizar la biomasa donde no se puede lograr un mercado de biomasa económicamente viable. Para estas áreas, sugerimos más bien centrar los esfuerzos en el pago de incentivos o en estrategias de restauración de turberas.

Concluimos presentando la valorización de la biomasa como una alternativa prometedora a las prácticas actuales, que podría reducir el impacto negativo de los incendios y generar al mismo tiempo nuevos ingresos para la población.

Title: Evaluation of different peatland management scenarios to reduce GHG emissions from fires. A case study in tropical peatlands in Ogan Komering Ilir, Indonesia.

Keywords: Bioenergy, peatland, biomass, climate change, haze.

Abstract:

Tropical peatlands play an important role as carbon pools, storing approximately 350,000 TgC. Over the last decades, changes in land use and land management practices for forestry and agricultural plantations, such as the use of fires and drainage, have led to a significant amount of carbon loss. In Indonesia, these fires affect both the economy and the public health of the entire region. In this thesis, we considered different mitigation scenarios to reduce peatland fires, such as converting aboveground biomass into bioenergy or other bio-products.

First, we estimated a business as usual (BAU) scenario by evaluating sources of emission of the current land management. We then investigated potential mitigation scenarios, including biomass valorization and peatland restoration, as alternative land management options. Finally, we evaluated the impact in terms of climate change and socio-economic criteria of the implementation of these mitigation scenarios. This study was based on a case study in the Ogan Komering Ilir (OKI) district of Indonesia.

The analysis of GHG emissions in the BAU scenario shows that areas affected by fire release 70.60±30, 139.40±31 and 159±27 Mg CO_2-eq ha^{-1} yr^{-1} for degraded peatland, oil palm plantations and pulpwood plantations, respectively. Areas not affected by fires release 18.45±12, 85.08±21 and 108.3±15 Mg CO_2-eq ha^{-1} yr^{-1}, respectively. For the restoration scenario, we found similar GHG emissions of -0.9 Mg CO_2-eq ha^{-1} yr^{-1} for the three land uses.

Following this assessment, we evaluated the feasibility of the biomass valorization scenarios in OKI based on socio-economic criteria. In the areas where creating such a biomass market is feasible, we predicted a reduction of between 4 % and 6 % of GHG emissions compared with BAU. Boosting the biomass market in these areas could make it possible to reduce fire occurrences without government investment. On the contrary, industry will not be able to valorize the biomass in the case where no economically viable biomass market is feasible. For these areas, we instead suggest focusing efforts on incentive payments or peatland restoration strategies.

We concluded by presenting biomass valorization as a promising alternative to current practices, potentially reducing the negative impact of fires while generating a new income for the population.

Titre: Évaluation de différents scénarios de gestion des tourbières pour réduire les émissions de GES dues aux incendies. Une étude de cas dans les tourbières tropicales d'Ogan Komering Ilir, en Indonésie

Mots clés : Bioénergie, tourbières, biomasse, changement climatique, haze.

Résumé:

Les tourbières tropicales jouent un rôle important en tant que réservoirs de carbone, en stockant environ 350 000 TgC. Au cours des dernières décennies, les changements dans l'utilisation des terres et les pratiques de gestion des plantations forestières et agricoles, tels que le recours aux incendies et au drainage, ont entraîné une perte importante de carbone. En Indonésie, ces incendies affectent à la fois l'économie et la santé publique de toute la région. Dans cette thèse, nous avons envisagé différents scénarios d'atténuation pour réduire les incendies de tourbières, comme la conversion de la biomasse aérienne en bioénergie ou en d'autres bioproduits.

Tout d'abord, nous avons estimé un scénario de maintien du statu quo (BAU) en évaluant les postes d'émission de la gestion actuelle des terres. Nous avons ensuite étudié des scénarios d'atténuation potentiels, notamment la valorisation de la biomasse et la restauration des tourbières comme autres modes de gestion des terres. Enfin, nous avons évalué l'impact en termes de changement climatique et de critères socio-économiques de la mise en œuvre de ces scénarios d'atténuation. Nous avons réalisé cette étude à travers une étude de cas dans le district d'Ogan Komering Ilir (OKI), Indonésie.

L'analyse des émissions de GES dans le scénario BAU montre que les zones touchées par les incendies rejettent respectivement 70,60±30, 139,40±31 et 159±27 Mg CO_2-eq ha^{-1} an^{-1} pour les tourbières dégradées, les plantations de palmiers à huile et les plantations de bois à pâte. Les zones non touchées par les incendies rejettent respectivement 18,45±12, 85,08±21 et 108,3±15 Mg CO_2-eq ha^{-1} an^{-1}. Pour le scénario de restauration, nous avons trouvé des émissions de GES similaires pour les trois utilisations des terres, de -0,9 Mg CO_2-eq ha^{-1} an^{-1}.

Suite à cette évaluation, nous avons évalué la faisabilité des scénarios de valorisation de la biomasse dans l'OKI sur la base de critères socio-économiques. Dans les zones où la création d'un tel marché de la biomasse est réalisable, nous avons prévu une réduction de 4 à 6 % des émissions de GES par rapport à l'OKI. La relance du marché de la biomasse dans ces zones pourrait permettre de réduire les occurrences d'incendie sans investissement gouvernemental. Au contraire, l'industrie ne sera pas en mesure de valoriser la biomasse là où aucun marché de la biomasse économiquement viable ne peut être réalisé. Pour ces zones, nous suggérons plutôt de concentrer les efforts sur les paiements incitatifs ou les stratégies de restauration des tourbières.

Nous avons conclu en présentant la valorisation de la biomasse comme une alternative prometteuse aux pratiques actuelles, susceptible de réduire l'impact négatif des incendies tout en générant un nouveau revenu pour la population.