Improving environmental sustainability of palm oil production in Thailand

Kanokwan Saswattecha

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Improving environmental sustainability of palm oil production in Thailand

Kanokwan Saswattecha

Thesis

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Disclaimer: Chapters 2-6 have been published as peer reviewed scientific articles. The text, figures and tables of the published and submitted articles have been adjusted to the PhD thesis format. Editorial changes were made for reasons of uniformity of presentation in this thesis. References should be made to the original articles.

Chapter 1

Introduction

1. INTRODUCTION

1.1. Background

Palm oil industry in Thailand

Palm oil is essential for food, pharmaceutical, and fuel industries (Sarmidi et al., 2009). Global demand for palm oil has increased significantly; from 32 million tons in 2005, to 54 million tons in 2013. Thailand is currently ranked as the third largest palm oil producing country in the world (FAOSTAT, 2016a). Today, more than 100 palm oil mills are registered (DIT, 2016) and the area of oil palm plantations doubled in 2015 compared to 2005 (OAE, 2016a). As a result, palm oil production in the country has almost tripled in the years since 2005 (FAOSTAT, 2016b). This rapid increase in production over the past decade is driven by The Royal Thai Government policy to promote the production and consumption of biodiesel (Daniel and Gheewala, 2010; Kumar et al., 2013).

In recent years, the use of B7 (a mixture of diesel with 7% biodiesel) was mandated in Thailand which enforced biodiesel production and consumption (DEDE, 2012a; Preechajarn and Prasertsri, 2012). To meet this goal, the Ministry of Agriculture and Cooperatives developed and launched a strategic plan and roadmap for the palm oil industry, for the period 2012-2026. These plans have set targets to increase palm oil production (1) by expanding the oil palm area from 0.7 to 1.2 million ha; (2) by increasing the yield of fresh fruit bunches (FFB) from 19 to 22 ton/ha/year, and (3) by increasing the oil extraction rate to 20% (OAE, 2016a, 2014). However, these targets are difficult to achieve.

Small-scale oil palm plantations belonging to smallholder farmers are prevalent in Thailand, accounting for over 70% of oil palm area in (Dallinger, 2011; Termmahawong, 2014). Smallholder farmers usually do not have the necessary vehicles (specifically trucks) to carry and deliver their FFB to mills. As a result, it is common in Thailand for FFB harvesting, collecting and delivery services to be carried out by middlemen.

Smallholder farmers typically have limited knowledge on best management practices, lack access to good quality seedlings and have insufficient credits to supply the right amount of fertilisers (Dallinger, 2011; Dallinger et al., 2013; Termmahawong, 2014). These limitations result in relatively low FFB quality and yields in Thailand.

Most palm oil mills are located in southern Thailand. These mills are mostly stand-alone businesses, without their own plantations. Their FFB supply typically relies heavily on the smallholder farms mentioned above. If there are too many mills in the same area, this leads to increased competition to obtain FFB from smallholder farmers. Mills are often operating below their full capacity due to insufficient FFB supply. To maintain minimum operations, mills have limited (if any) opportunities to reject poor quality FFB (i.e. unripe fruits) from either middlemen or farmers. Using poor quality FFB can lower the oil extraction rate and increase waste generation in mills (Dallinger, 2011; Dallinger et al., 2013; Termmahawong, 2014). Additional contributing factors to low extraction include inefficient oil recovery from the palm oil waste stream.

The quality of FFB is generally poor in Thailand because of inappropriate pricing of FFB and poor management of middlemen. The FFB price is determined by the weight of fruit bunches. In the case of loose fruits, a higher price is given, which is also determined by weight (Termmahawong, 2014). Thus quality plays no role in pricing methods. This motivates smallholders and middlemen to harvest bunches without consideration of fruit ripeness. Middlemen sometimes attempt to increase the weight of FFBs by mixing sand and to generate more loosen fruits by spraying water.

These limitations of smallholder farmers and the problems associated with the use of poor quality FFB (i.e. poor quality seedlings, harvesting unripe fruits and poor management of middlemen) have been encountered for many decades, yet they remain unsolved. It is very challenging for all relevant stakeholders (i.e. policy makers, farmers and millers) to overcome these problems.

Environmental impacts of palm oil industry

Many studies show that there are a range of environmental problems associated with oil palm expansion. Land use change, caused by expansion, can take place in either natural or other arable areas. This change in land use may result in greenhouse gas (GHG) emissions or changing carbon storage, depending on the type of land use which was in place prior to its conversion to oil palm plantations. If forests or peatlands are cleared for planting oil palm, stored carbon will be released into the atmosphere. This holds especially for peatland clearance. Cultivating oil palm on peatlands will induce ongoing GHG emissions because of drainage and peat oxidation (Achten and Verchot V., 2011; Croezen et al., 2010; Ernst & Young, 2011; F. Danielsen et al., 2008; Gnanavelrajah et al., 2008; Kim and Dale, 2011; Lapola et al., 2010; Marshall et al., 2011; Mathews and Tan, 2009; Sanchez et al., 2012; Silalertruksa and Gheewala, 2012). Even though several studies indicate that land use change is a potential source of GHG emissions, changing cropland or degraded land may lead to sequestration and storing carbon dioxide from the atmosphere (Silalertruksa et al., 2012b).

A rapid increase of palm oil production may induce deforestation due to a lack of additional arable land to cultivate the oil palm. Besides the crucial issue of GHG emissions; habitat loss and biodiversity destruction are also considered serious effects of biodiesel production (Baan et al., 2012; Canals et al., 2006; F. Danielsen et al., 2008; Geyer et al., 2010; Lindeijer, 2000; Michelsen, 2008; Schmidt, 2008; Wilcove and Koh, 2010; Yaap et al., 2010). A large reduction of bird species was reported due to the loss of their habitats, which resulted from the conversion of forests to oil palm and rubber plantations, accounting for at least 60% decrease in species richness (Aratrakorn et al., 2006). However, the knowledge of biodiversity decline caused by oil palm expansion in Thailand, such as replacing rubber plantations with oil palm plantations, is still limited. Thus, both habitat loss and biodiversity decline are considered in this research, in order to gain insight into the relation between oil palm expansion and biodiversity loss.

Replacement of natural forest by oil palms can increase flood risk since the buffering capacity of plantations is generally smaller than that of natural forest. The use of heavy machinery during planting or harvesting can lead to soil compaction which also increases flood risk (Kobiyama, 2011; Nikolova et al., 2007). An increase in surface runoff that is loaded with eroded soil particles, nutrients and pesticides can deteriorate water quality and affect aquatic species, potentially leading to biodiversity loss (Comte et al., 2012; Kumar et al., 2013). Also in Thailand, Babel (2011) reported that the expansion of oil palm into forests increases nutrient loading and soil erosion to the surface water.

The conversion of rubber plantations, rice fields and orchard plantations to oil palm are the main expansion trends in Thailand (Thongrak and Kiatpathomchai, 2011). The loss of these croplands can lead to the use of natural ecosystems or cropland elsewhere. In a worst case scenario, natural forests are cleared. This deforestation can be considered as an indirect land use effect of oil palm production. Considering both direct and indirect effects, it is clear that the oil palm expansion in the past decades has threatened the valuable ecosystem functions and services provided by natural forests.

There are several sources of GHGs along the production chain. As indicated above, there may be GHG emissions from land use change caused by oil palm expansion. Additionally, nitrous oxide (N_2O) is released when using fertilisers in oil palm plantations. Mills are also GHG sources, specifically of methane, which is released when treating palm oil mill effluent without a biogas capture system (Kaewmai et al., 2012; Silalertruksa and Gheewala, 2013), and also because of the open dumping empty fruit bunches (Bessou et al., 2014).

Moreover, the excessive use of fertilisers to maximise oil palm yields in plantations may also cause eutrophication. This is because part of the applied fertilisers is lost through leaching and runoff, thereby increasing nitrogen and phosphorus concentration in surface waters (Achten et al., 2010; Bijay et al., 1995; Comte et al., 2012; Dumelin, 2009; Tung et al., 2009). This especially holds for immature oil palm plantations, as the roots of young palm trees are not yet developed enough to allow the uptake of nutrients (Goh et al., 2003; Ng et al., 2003). The eutrophication potential of biodiesel produced from palm oil is found to be higher than that for conventional diesel (Achten et al., 2010; Dumelin, 2009). Also, the use of pesticides (i.e. furadan) and herbicides (i.e. paraquat and glyphosate) in the plantations has been reported (Pleanjai et al., 2009) which may result in a toxicity risk for farm workers.

Fuel combustion in agricultural machines during land preparation and palm oil processing typically generates several air pollutants; namely particulate matter (PM), sulphur dioxide (SO2), nitrogen oxides (NOx), volatile organic compounds (VOCs) and carbon monoxide (CO). These pollutants are acidifying compounds, precursors of smog formation as well as being toxic to human health (Achten et al., 2010; Dumelin, 2009). Thus, increasing palm oil production will eventually result in the increase of environmental problems.

Options to reduce environmental impacts

The Roundtable on Sustainable Palm Oil (RSPO) is an international sustainability standard recently introduced and implemented in the Thai palm oil industry. Only a few groups of Thai smallholder farmers and palm oil mills are currently certified by RSPO (RSPO, 2015, 2012). In RSPO requirements, there are criteria concerning best management practices in oil palm plantations and palm oil mills which are principally designed to increase yields and lower emissions (RSPO, 2013a). Encouraging palm oil producers (both farmers and millers) to change current practices and transition towards best management practices is therefore vitally important in order to overcome the afore mentioned challenges.

Moreover, several options with the aim of reducing environmental impacts have been introduced to the palm oil industry. For instance, at the oil palm plantations, a more efficient use of fertilisers can reduce inputs, as well as avoiding nitrous emissions and nitrate and phosphorus leaching to the surface waters (Bah et al., 2014). Managing cover crops in the plantations instead of using herbicides can reduce herbicide residues leaching into the soil and surface water bodies (Samedani et al., 2014). Harvesting ripe fruits is highly recommended as it can increase yields and ensures high oil content in the palm fruits (AgriSource, 2005). At the palm oil mills, applying a biogas capture system to mill effluent (Kaewmai et al., 2013a), converting empty fruit bunches to compost (Schuchardt et al., 2008; Singh et al., 2010; Stichnothe and Schuchardt, n.d.) or pellets (Chavalparit et al., 2006; Chiew and Shimada, 2013) and producing electricity from empty fruit bunch combustion (ABO, 2010; Chiew and Shimada, 2013; Patthanaissaranukool et al., 2013) are suggested in order to avoid (or minimise) methane emissions. However, there may be unintended side-effects of these options, specifically on emissions associated with other environmental problems. Also, the cost-effectiveness of these options are not extensively analysed. This thesis therefore analyses both primary and side-effects of the mitigation options, as well as its cost-effectiveness.

Knowledge gaps

From the above, it is clear that oil palm plantations have rapidly expanded and product demand has greatly increased in the past decade. Inevitably, their associated environmental impacts have been on the rise as well. Thus, it is controversial whether palm oil in Thailand is produced sustainably. Even though many studies suggest several options to reduce environmental impacts, the consideration of the side-effects and the cost-effectiveness of these options is missing in Thailand.

There is a need for an integrated assessment of the overall environmental impacts of the palm oil industry; including landscape (i.e. oil palm expansion effects on ecosystem services supply) and sectoral analyses (i.e. emissions and environmental impacts of palm oil production). In addition, improved understanding of the cost-effectiveness of mitigation options and analyses of alternative scenarios, and their environmental consequences, in the Thai palm oil industry can provide relevant information to decision makers. This can contribute to enhancing the environmental sustainability of the national palm oil industry.

1.2. Overall objective and research questions

The overall objective of this thesis is to analyse the environmental impacts of the palm oil industry in Thailand in the past and future, and to examine options to enhance the environmental performance of the sector. To achieve this objective four research questions (RQs) are formulated:

Research question 1: What are the effects of past oil palm expansion through land use change on ecosystem services?

Research question 2: What are the environmental impacts associated with past palm oil production in Thailand?

Research question 3: What are the available options to reduce environmental impacts of palm oil production in Thailand and its cost-effectiveness?

Research question 4: What are the possible future scenarios for the palm oil industry in Thailand, and what are the associated environmental impacts?

1.3. Scope of the thesis and analytical approaches and tools

This thesis focuses on the environmental impacts of land conversion, palm oil plantations and palm oil mills in the past and future. Six tools are applied in the landscape and sectoral approaches to analyse the environmental impacts (Table 1.1). In Thailand, several existing studies assess the environmental impacts of the palm oil industry by using either the landscape or sectoral approach alone. For instance, Kaewmai et al. (2012) assess greenhouse gas emissions and Patthanaissaranukool et al. (2013) assess carbon emissions of oil palm plantations and palm oil mills based on the sectoral approach alone. Studies using an integrated assessment between the landscape and sectoral approaches are limited. Therefore, this thesis quantifies the environmental impacts of the palm oil industry using such an integrated assessment. This thesis would be able to provide the comprehensive information necessary to answer the overall objective and research questions. In the following paragraphs, the analytical approaches used in this thesis are described in more detail.

To answer research question 1, a model is developed based on the landscape approach. A combination of spatial modelling and ecosystem services indicators is used to answer the direct and indirect land use change caused by the expansion of oil palm area. Next, the land use change effects on three selected ecosystem services are quantified; which are carbon storage, biodiversity conservation and crop provisioning service.

To answer research questions 2 and 3, a model is developed based on the sectoral approach. The environmental performance indicators and a partial life cycle assessment are used in combination to define the system, and to quantify potential environmental impacts of the oil palm plantations and palm oil mills in research question 2. Six environmental impacts are selected and analysed; namely, global warming, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater ecotoxicity. In research question 3, a cost-effectiveness analysis is used to better understand the effects of mitigation options and their cost-effectiveness. The sectoral model that was previously developed is expanded to analyse the reduction potentials of these mitigation options and their associated costs. Also, the side-effects of these options while applying are included in the model.

In research question 4, the landscape and sectoral approaches are integrated through a scenario analysis. A set of future scenarios are developed to reflect different environmental management plans of the palm oil industry in Thailand for the next several decades. Next, their consequences on the environment are analysed to better understand the implications of these scenarios.

The Tapi river basin is selected as a case study for RQs 1 and 2 to demonstrate the application of landscape and sectoral models. For RQs 3 and 4, our analyses are upscaled to consider Thailand as a whole.

Table 1.1 Overview of scope of work and analytical tools applied to address the four research questions

Research questions	**Scope of the thesis**		**Analytical tools**					
			Landscape approach		Sectoral approach			
	Focus of the analysis	**Study area**	Spatial modelling	Ecosystem services indicators	Environmental performance indicators	Partial life cycle assessment	Cost-effectiveness analysis	Scenario analysis
1	Environmental impacts of land conversion in the past	Tapi river basin	■	■				
2	Environmental impacts of oil palm plantations and palm oil mills in the past	Tapi river basin			■	■		
3	Environmental impacts of oil palm plantations and palm oil mills in the past	Thailand			■	■	■	
4	Environmental impacts of land conversion, oil palm plantations and palm oil mills in the future	Thailand		■	■	■	■	■

1.4. Structure of the thesis

This thesis consists of seven chapters, including this introduction (Chapter 1). Chapters 2, 3, 4, 5 and 6 address RQs 1, 2, 3 and 4, respectively. Figure 1.2 shows an overview structure of the thesis and the linkages between RQs. In the following paragraphs, a brief summary of each chapter is provided.

Chapter 2 models the land use change caused by oil palm expansion and its effects on ecosystem services to answer RQ 1. Direct land use change and indirect land use change are analysed in this chapter. Next, its effects on selected ecosystem services are quantified to better understand the extent to which oil palm expansion causes the deterioration of ecosystem services.

Chapter 3 presents the environmental impacts of palm oil production in Thailand, and addresses RQ2. Key sources of emissions and environmental impacts are highlighted. Recently, a concern on sustainability in palm oil production has been raised and is still under debate. The Roundtable on Sustainable Palm Oil (RSPO), a recognised standard of international sustainability for palm oil production, has recently been introduced in Thailand to ensure that Thai palm oil can be produced in a sustainable manner. The palm oil producers are therefore classified into three categories, reflecting different RSPO regimes. This is to better understand if RSPO would improve the environmental performance of Thai palm oil production and eventually improve environmental conditions.

Chapter 4 is a variation of Chapter 3. This chapter focuses only on non-CO_2 greenhouse gas emissions of palm oil production in Thailand. Therefore, only CH_4 and N_2O emissions from the oil palm plantations and the palm oil mills are included in this chapter. In addition to RQ 2, this chapter also addresses RQ 3. Available options to reduce non-CO_2 greenhouse gas emissions are studied and discussed in this chapter.

Chapter 5 is connected to Chapters 3 and 4. This chapter analyses the options available for reducing environmental impacts of the oil palm plantations and the palm oil mills, and to answer RQ 3. These options are identified according to the key sources of emissions and environmental impacts. Consequences on reduction potentials and associated costs are analysed to better understand which options are the most physically-effective and which are most economically-effective in reducing environmental impacts.

Chapter 6 shows the integrated environmental assessment. The sectoral model, developed in Chapter 3 and 5, and the landscape model, developed in Chapter 2, are integrated through the scenario analysis. Possible future scenarios of the Thai palm oil industry in 2050 are developed and analysed to address RQ 4. Here, the most effective scenario for improving environmental sustainability of the palm oil industry in Thailand can be answered. The answers from RQ 4 could be useful for the policy makers to develop future policies and plans that can improve sustainability of Thai palm oil production. As a result, key messages on possible pathways to improve environmental sustainability of the industry on a national level are answered in this chapter.

Finally, Chapter 7 provides the main conclusion and a general discussion of this thesis. The answers to the RQs, a final synthesis of the main research findings and further recommendations for researchers and palm oil sector are presented.

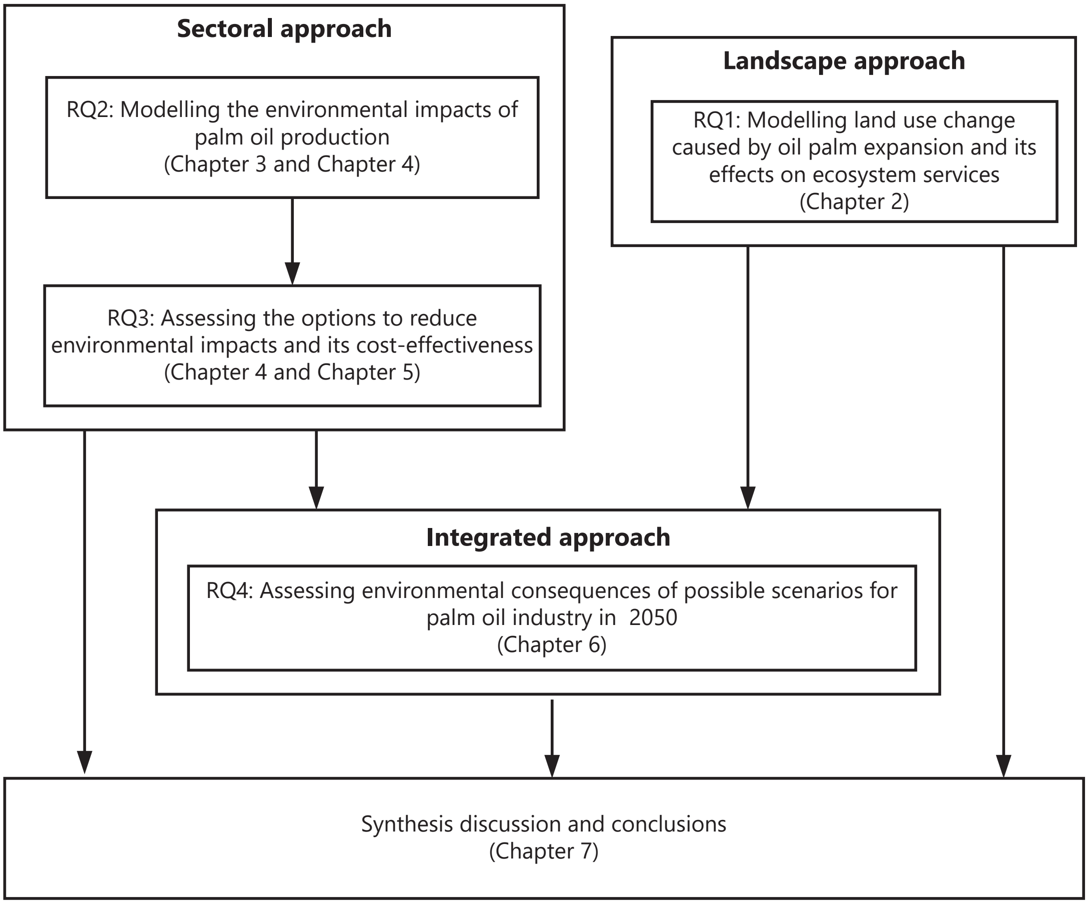

Figure 1.2 Structure of the thesis and the linkages between research questions

Chapter 2

Effects of oil palm expansion through direct and indirect land use change in Tapi river basin, Thailand

2. EFFECTS OF OIL PALM EXPANSION THROUGH DIRECT AND INDIRECT LAND USE CHANGE IN TAPI RIVER BASIN, THAILAND

Abstract

The Thai government has ambitious plan to further promote the use of biodiesel. However, there has been insufficient consideration on the environmental effects of oil palm expansion in Thailand. This paper focusses on the effects of oil palm expansion on land use. We analysed the direct and indirect land use change caused by the oil palm expansion and its effects on ecosystem services supply.

Our analysis shows that between 2000 and 2009 direct-land-use-change (dLUC) related to oil palm expansion was more prevalent than indirect-land-use-change (iLUC). dLUC involved new oil palm plantations replacing cropland rather than natural ecosystems. Rubber was most frequently replaced by oil palm but there was also conversion of natural ecosystems. Later, between 2009 and 2012, iLUC strongly increased. Forests were cleared for rubber production as an indirect effect of oil palm expansion.

We also quantified the effects of land use change on selected ecosystem services. Oil palm expansion led to increased production of fresh-fruit-bunches, however, it reduced other crop production such as latex, rice and fruits. Biodiversity conservation was also negatively affected. Carbon storage was positively affected by conversion of unused land, rice, and orchard area by oil palm, but negatively affected by the conversion of forests.

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2.1. Introduction

Biofuels are increasingly considered as an alternative to fossil fuels, in spite of associated environmental and social impacts (Kumar et al., 2013; Naylor et al., 2007; Silalertruksa et al., 2012b; Wattana, 2014). The Royal Government of Thailand initiated a campaign in 2005 to promote biodiesel production and consumption (DEDE, 2012a, 2008; Kumar et al., 2013; Preechajarn, 2010; Preechajarn and Prasertsri, 2012). To meet the policy target, large amounts of palm oil, which is used as main feedstock for biodiesel production, are required. As a result, palm oil production and cultivation have doubled between 2005 and 2012 (FAOSTAT, 2013; OAE, 2013). This rapid increase in oil palm area is likely to continue in the coming years.

A range of environmental effects is associated with oil palm expansion. Several studies show that greenhouse gas (GHG) emissions may increase when forests or peatland are cleared for oil palm (Achten and Verchot V., 2011; Croezen et al., 2010; Ernst & Young, 2011; F. Danielsen et al., 2008; Gnanavelrajah et al., 2008; Kim and Dale, 2011; Lapola et al., 2010; Marshall et al., 2011; Mathews and Tan, 2009; Sanchez et al., 2012; Silalertruksa and Gheewala, 2012). Conversion of forests to oil palm plantations dose not only release GHG emissions, but also leads to biodiversity loss (Baan et al., 2012; Canals et al., 2006; F. Danielsen et al., 2008; Geyer et al., 2010; Lindeijer, 2000; Michelsen, 2008; Schmidt, 2008; Wilcove and Koh, 2010; Yaap et al., 2010). For instance, at least 60% of the bird species richness disappeared due to loss of their habitats by oil palm and rubber plantations in southern Thailand in 2004 (Aratrakorn et al., 2006). In addition, conversion of natural forests to oil palm plantations can affect the water flow regulation service provided by natural forests (Kumar et al., 2013) and increase flood risks (Kobiyama, 2011; Nikolova et al., 2007).

Hence, land use change caused by oil palm expansion threatens ecosystem functions and services provided by natural forests in Thailand. This land use change might have caused deforestation directly and indirectly (Creutzig et al., 2015; Finkbeiner, 2014; Kim and Dale, 2011; Marshall et al., 2011; O'Hare et al., 2011; Wicke et al., 2012). To what extent, however, is not clear. More information on the associated land use change and its effects on ecosystem services in Thailand is therefore needed. Such a quantitative analysis is important for a better understanding of the environmental problems and to design problem-oriented solutions for policy makers. The objectives of this study, therefore, are to analyse direct and indirect land use change caused by oil palm expansion and to analyse its effects on selected ecosystem services. Our result could therefore provide a better understanding of land use change and associated effects on a few selected ecosystem services and support the policy makers to design the right policy that minimize environmental impacts of oil palm expansion in Thailand.

2.2. Method

2.2.1. Study area

The Tapi river basin, a major basin in the southern part of Thailand, was selected as a case study to analyse the effects of oil palm expansion on selected ecosystem services. This river basin covers a total area of 13,450 km^2, and spans three provinces; Surat-thani (69% of the basin), Nakhon-si-thammarat (17% of the basin), and Krabi (13% of the basin) (Figure 2.1) (Haii, 2012). We selected this area because Surat-thani and Krabi are the first and second largest oil palm producing provinces in Thailand, respectively. Note that this basin includes areas where the oil palm expansion has been ongoing for several decades (Krabi and Surat-thani) and areas where the expansion is more recent (Nakhon-si-thammarat).

Figure 2.1 Location of the Tapi River Basin in Thailand.

2.2.2. Land use categories

The effects of land use change on ecosystem services depend on the type of land use that is replaced. For instance, Thongrak & Kiatpathomchai (2011) indicated that in Thailand oil palm is mainly replacing rubber plantations, rice fields, abandoned rice fields and orchard plantations. However, local media (Anonymous, 2010) reported the clearing of peatland for oil palm in the Tapi river basin. Siangjaeo et al. (2011) revealed that land conversion of unused land to oil palm plantations positively affects the carbon storage.

In our analysis, we derived land use datasets of the Tapi river basin from the Land Development Department (LDD), Ministry of Agriculture and Cooperatives. The LDD land use data are digital with scale of 1:50,000 for the year 2000 and of 1:25,000 for the years 2009 and 2012, and with polygons representing 191 different land use categories. We aggregated and reclassified land use categories from 191 to 12 categories for the purpose of our research. For example, natural evergreen forest, disturbed evergreen forest and forest plantation are aggregated together and reclassified to forest category. Next, the reclassified land use maps were converted to raster format (cell size 30x30). We followed the definition of land use and land use categories from LDD (LDD, 1999).

The aggregated 12 land use categories include (1) forests (consisting of natural evergreen forest, disturbed evergreen forest and forest plantation). Note that more than 98% of total forest area in the Tapi river basin is the natural evergreen forest, (2) wetlands and peatland, (3) mangrove, (4) oil palm plantation, (5) rubber plantation, (6) orchard plantation, (7) rice field, (8) abandoned rice field, (9) unused land (consisting of grass & scrub land and marsh & swamps), (10) other agriculture (consisting of field crops, other perennials, horticultures, pasture land and farm houses, aqua-cultural land, and mine pits), (11) water (compositing of natural water bodies and built-up reservoir) and (12) built-up area (compositing of commercial area, villages, transportation utilities and industrial area).

2.2.3. Modelling land use change

We analysed both direct and indirect land use change effects. Direct land use change (dLUC) refers to the direct conversion of land to oil palm plantations (Elizabeth Marshall 2011). However, when cropland is replaced by oil palm, there may be an indirect effect on land use elsewhere when there is still a demand for these crops. In such cases cropland or natural ecosystems elsewhere may be converted to substitute the cropland that were replaced by oil palm (Creutzig et al., 2015; Finkbeiner, 2014; Kim and Dale, 2011; Wicke et al., 2012). In some cases , also natural ecosystems, such as forests and peatland, might be changed to cropland that are replaced by oil palm. This refers to indirect land use change (iLUC) in this study. We acknowledged the difficulties in singling of the different causes of land use change including indirect land use (Croezen et al., 2010; Dendoncker et al., 2008; O'Hare et al., 2011; Ray et al., 2012; Verstegen et al., 2015). Therefore, we followed a two-pronged approach where we analyse both land use change patters based on maps and farmer interviews for their motivation to engage in land use change, as elaborate below.

(a) *Direct land use change (dLUC) -* We analysed dLUC between 2000 and 2009 and between 2009 and 2012, based on the land use datasets. Conditional analysis in ArcGIS 10.0 was used to identify different types of land use that are converted to oil palm cultivation in the study area. This land use change (in hectares (ha)) is considered as “gross change”. Land use change is, however, dynamic. While in some places certain land use types are converted to oil palm production, in other places oil palm plantations may be converted to other land use types. For instance, suppose that the maps indicate that 90,000 ha of rubber were converted to oil palm production (gross change) and that meanwhile 20,000 ha of oil palm were converted to rubber production. To calculate “net change”, we subtracted this 20,000 from the gross change. We thus considered only the positive net change as dLUC effect of oil palm expansion.

(b) *Indirect land use change (iLUC)* –We identified the iLUC effects in the Tapi river basin using the same procedure as for the dLUC analysis. We thus identified land conversions and calculated the net and gross area changes for some other crops (i.e. rubber, orchards and rice). We only considered the positive net change as iLUC effect of oil palm expansion. Note that we ignored iLUC effects outside the Tapi river basin.

(c) *Interview farmers* –Drivers of land use change are complex, in particular indirect land use change. As a supplement to our spatial analysis, we therefore interviewed farmers in order to better understand their decisions and motivations towards LUC in the Tapi river basin.

We categorized farmers into three groups; 1) farmers who recently started oil palm cultivation, 2) farmers who recently started rubber cultivation, and 3) farmers who recently started both rubber and oil palm cultivation, and switched in some plots from rubber to oil palm. Farmer characteristics are presented in Table 2.1. The Tham-Phannara and Thungyai districts in Nakhon-si-thammarat were selected as sampling sites because our LUC analysis identified these districts as hotspots of deforestation associated with dLUC and iLUC. In total, 37 randomly selected farmers were interviewed. Note that the two most important oil palm producing provinces in the Tapi river basin are Suratthani and Krabi. However, oil palm has been cultivated in these provinces at large scale for several decades. Therefore, we considered Nakhon-si-thammarat province is more relevance for analysing the effects of LUC with farmer interviews. We, however, used farmer interviews from Prasaeng and Bannaderm districts, Suratthani province (conducted in June 2012) from Nualnoom (2014) to compare our results.

Table 2.1 Overview of interviews with farmers in the Tham-Phannara and Thungyai districts in Nakhon-si-thammarat (Tapi river basin).

Group	Characteristics	Objectives	Sample (Number of persons)
1	Farmers who recently started oil palm cultivation	To better understand the reasons for direct land use change	14
2	Farmers who recently started rubber cultivation	To better understand the reasons for indirect land use change	13
3	Farmers who recently started both oil palm and rubber cultivation, and switched in some plots from rubber to oil palm	• To better understand the reasons for both direct and indirect land use change • To better understand the motivation of farmers to grow rubber or oil palm	10

2.2.4. Modelling ecosystem services

In accordance with the ecosystem services (ESS) typology presented in The Economics of Ecosystems and Biodiversity study (Mace et al., 2012; TEEB, 2010), we selected (1) food (i.e. rice and fruits) and non-food (i.e. Fresh-Fruit-Bunch (FFB) and latex), (2) carbon storage and (3) biodiversity conservation to represent the provisioning, regulating and habitat services categories, respectively. The analytical approaches, indicators, input dataset, and data sources for modelling and quantifying changes in selected ESS are summarized in Table 2.2.

These ecosystem services were selected because they have been mentioned by local sources (websites and farmers) and/or in scientific literature and reports. For instance, Siangjaeo et al. (2011) and Silalertruksa & Gheewala (2012) reported that stored carbon is released to the atmosphere when forests or peatland are cleared for oil palm. Losses of natural forests and peatland that are important habitats for living species, can eventually cause negative impacts on biodiversity (Aratrakorn et al., 2006; F. Danielsen et al., 2008; Geyer et al., 2010; Johnson and Zuleta, 2013; Koh and Wilcove, 2008; Mastrangelo and Gavin, 2012). Moreover, they could potentially affect water flow regulation provided by natural forests (Kobiyama, 2011; Kumar et al., 2013; Nikolova et al., 2007). Note that the water flow regulation service is not a main focus in this study. However, we discussed the implication of land use change on hydrology services in the discussion section (see section 4.1).

Information on the selected services are crucial for policy makers, and for land use and development planning in order to minimise negative impacts on the environment and society (Inge et al., 2013; Kang et al., 2013; Klug, 2012; Maler et al., 2008).

Food and non-food production

We used the production change (in ton), as indicator for modelling food and non-food provisioning services (Table 2.2). The growing period; the period between crop establishment and maturity, varies among crops. For instance, the growing period for oil palm is typically 3 years and that for rubber is 7 years (OAE, 2011a). Therefore, for the period between 2000 and 2009 (9 years of change), all crops (i.e. FFB for oil palm, latex for rubber, rice for rice fields and fruits for orchards) that were new in 2000 were taken into account in our analysis. This is because by the year 2009, they had reached maturity. For the period between 2009 and 2012 (4 years of change), orchard and rubber plantations that were established in 2009 were excluded from our analysis because by the year 2012, they had not reached maturity. In the latter case, only oil palm and rice were, therefore, considered.

Biodiversity conservation

Accounting for aspects of biodiversity is complex and as such experimentation of biodiversity accounting in Thailand is scarce. UNEP-WCMC (2015) indicates that information on ecosystem diversity from a spatial analysis can inform the Biodiversity Account. We therefore assessed the biodiversity conservation service based on habitats loss. In our assessment, only the declination of natural ecosystems from the land use analysis were taken into account in the model because of their role as important habitats for living species.

Carbon storage

Carbon stock change is used as an indicator for modelling carbon storage service. Our analytical approach is based on the stock difference method from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Volume 4 on Agriculture, Forestry and Other Land Use (IPCC, 2006a). The IPCC Guidelines, however, do not provide default values of carbon stock pools (i.e. above- and below-ground biomass, dead organic matter and soil organic carbon) for all the land use types defined in this study. Meanwhile, many local studies on carbon stock pools for specific types of land use are available for Thailand. We, therefore, assessed the carbon stock of different land use units based on information from these local and national studies (see Appendix, Table A1) and we applied a lookup table approach to analyse total carbon stocks per land use type (Remme et al., 2014; Sumarga and Hein, 2014).

Table 2.2 Indicators, approaches and input data used to quantify changes in selected ecosystem services.

Ecosystem services	Indicator	Approach	Data	Source of data
(1) Food and non-food production - Rice production - Fruits production - FFB production - Latex production	Production change (ton)	Production change = P x A where; P = Annual crop productivity, in ton/ha/year, A = Area of land use change in the basin, in ha	- Annual crop productivity in the basin in 2000,2009 and 2012 - Area of land use change in the basin due to oil palm expansion (dLUC and iLUC), in ha	- OAE (2013, 2009) - Results from dLUC and iLUC analysis (this study)
(2) Biodiversity conservation	Habitat loss (ha)	Habitat loss = A_{eco} where; A_{eco} = Area of natural ecosystem loss in the basin, in ha	- Loss of natural ecosystems, in ha, caused by oil palm expansion (both dLUC and iLUC)	- Results from dLUC and iLUC analysis (this study)
(3) Carbon storage	Carbon stock change (ton C)	Carbon stock change = $(C_{biomass} + C_{dom} + C_{soil})$ x A where; $C_{biomass}$ = Carbon stock in above-ground and below-ground biomass, in ton C/ha C_{dom} = Carbon stock in dead organic matter (i.e. dead wood debris and litter), in ton C/ha C_{soil} = Carbon stock in mineral soil, in ton C/ha A = Area of land use change in the basin, in ha	- Carbon stock pools ($C_{biobass}$, C_{dom} and C_{soil}) for specific land use - Area of land use change in the basin due to oil palm expansion (dLUC and iLUC), in ha	Literature (Bunyavejchewin and Nuyim, 1996; Chiarawipa et al., 2012; IPCC, 2006a; Khalid et al., 1999a, 1999b; Kridiborworn, 2010; Pibumrung, 2007; Siangjaeo et al., 2011; Sriladda and Puangjit, 2007; Verwer and Meer, 2010; Wanthongchai et al., 2013)

2.3. Results

2.3.1. Land use

In the year 2000, rubber plantations covered 48% of the Tapi river basin (Figure 2.2). Forest areas covered 29%, and oil palm plantations covered only 7% of the basin. Other natural land (i.e. mangrove forests and peatland) was rare and covered less than 0.3% of the basin. The area under oil palm plantations doubled between 2000 and 2009, with an average annual expansion rate of 12% (Figure 2.2). The increase in oil palm areas is a result of policies promoting the use of biodiesel at national level and enhancing oil palm development at provincial level (see our discussion in section 4.2). On the other hand, the total area of rubber plantations, rice and abandoned rice fields decreased considerably since 2000. The total area used for rubber cultivation, however, moderately changed . By the year 2009, 41% of the basin was still used for rubber cultivation. The areas of natural forests and mangroves increased by 2% and 91%, respectively, between 2000 and 2009, albeit from very small initial areas. This increase may be related to enhanced mapping methods in 2009 compared to 2000. Note that the Cabinet of the Thailand government's resolution regarding recalling of natural conservation areas on July 30th, 1998, which remained effective until 2012 (Srisaowalak, 2010), which promoted the protection of these natural ecosystems.

Between 2009 and 2012 oil palm still expanded at the expense of rice, abandoned rice, orchards and unused land. We calculated an average annual expansion rate for oil palm at 2% for the period 2009-2012. This expansion rate was lower than that for the period 2000-2009.

2.3.2. Direct land use change

We analysed direct land use change (dLUC) caused by oil palm expansion in the Tapi river basin during the study periods (2000-2009 and 2009-2012; see Table 2.3). Palm oil was expanded at the expense of several different land use types (Figure 2.3). Moreover, the losses of rubber, orchards and rice fields caused indirect land use change (iLUC) effects (see section 3.3).

Approximately one-third of the oil palm area in 2009 were existing plantations that were planted before the year 2000 (Figure 2.3). Two-thirds were more recent plantations. A significant number of rubber plantations were replaced by oil palm plantations. This accounts for 68% of the new oil palm area in 2009 (net change). About 12% of the oil palm was planted on unused land. Forest conversion was relatively low (4% of oil palm plantations). However, expressed as the percentage of forest loss, this type of conversion was much more substantial.

Also, in the second period (2009-2012), new oil palm was mostly established on cropland rather than on natural land. In the year 2012, almost the whole oil palm area (96%) consisted of plantations that already existed before 2009. The small area of new oil palm plantations replaced rubber (28% of the new oil palm area in 2012), unused land (17%) and orchards (17%) (net changes). Forest conversion involving dLUC to oil palm was again relatively low at 3.5% of the new oil palm area in 2012. When expressed as the percentage of forest loss, its magnitude was much higher than number is found.

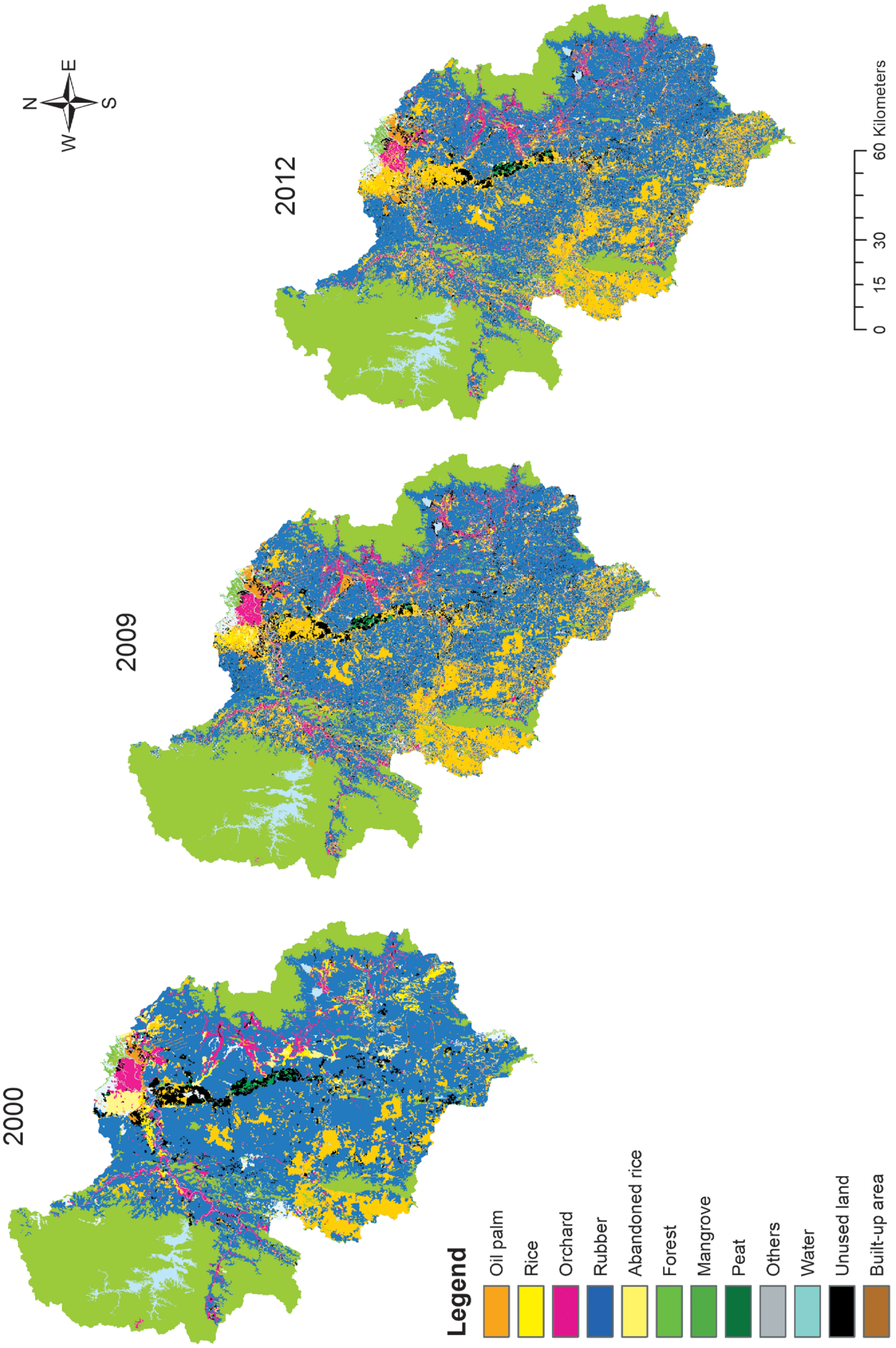

Figure 2.2 Land use maps in 2000, 2009 and 2012 (modified from original land use maps by LDD).

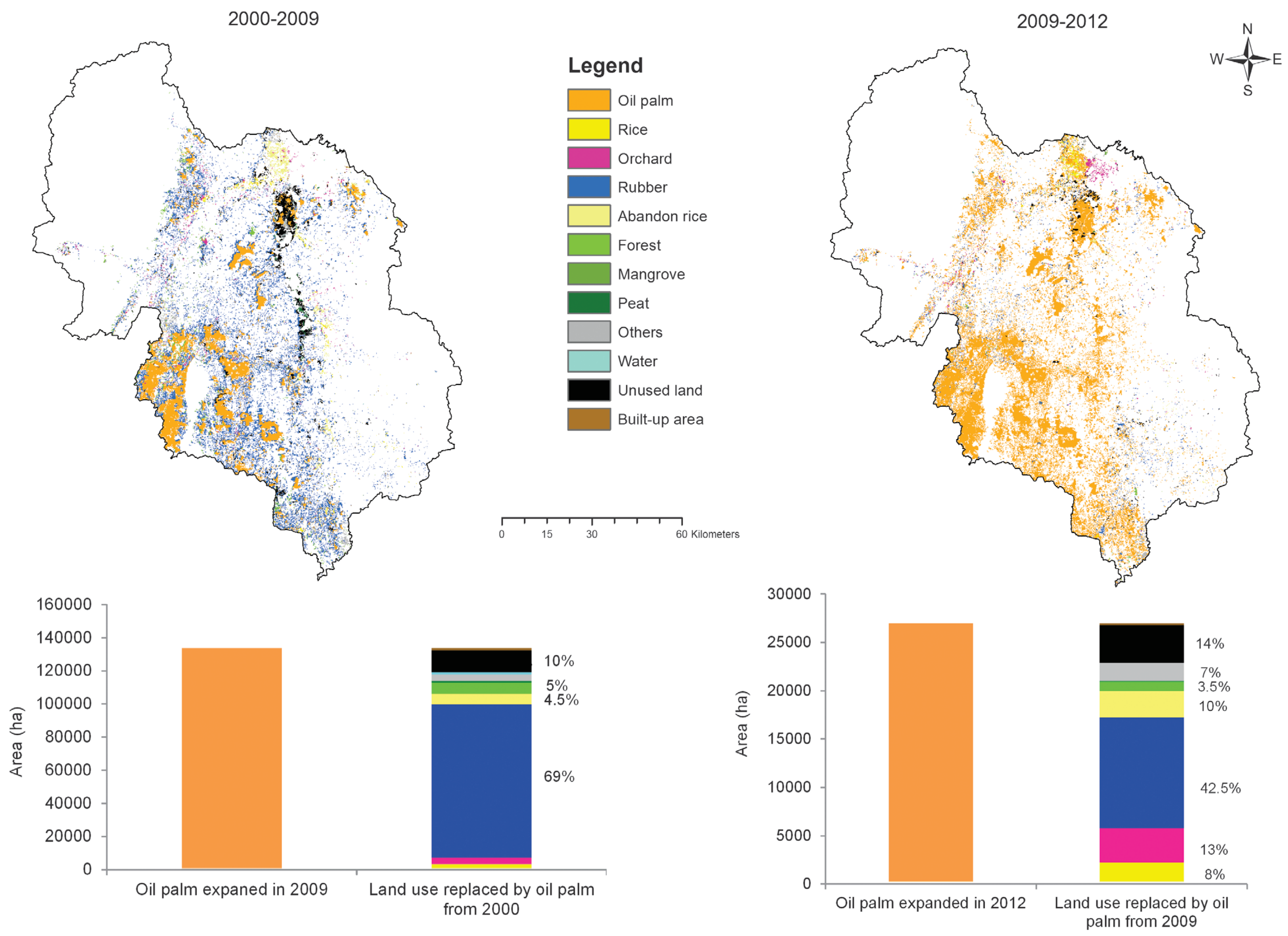

Figure 2.3 Area of land converted to oil palm plantations (gross change, by land use type) in the periods 2000-2009, and 2009-2012.

Table 2.3 Gross and net direct land use change (dLUC) caused by oil palm expansion in the periods 2000-2009, and 2009-2012 in the Tapi River Basin.

Land use type	Planted area 2000, in ha (% of the basin)	2000-2009		Planted area 2009, in ha (% of the basin)	2009-2012		Planted area 2012, in ha (% of the basin)
		Converted to palm oil (gross[1]), in ha	Converted to palm oil (net[2]), in ha		Converted to palm oil (gross[1]), in ha	Converted to palm oil (net[2]), in ha	
Cropland							
- oil palm	97,950 (7%)	-	-	200,191 (15%)	-	-	220,115 (16%)
- rubber	644,514 (48%)	92,668	69,355	554,544 (41%)	11,470	5,542	575,418 (43%)
- rice	26,363 (2%)	3,237	3,186	8,750 (0.65%)	2,232	2,131	2,911 (0.22%)
- orchards	50,249 (4%)	4,054	3,111	49,484 (4%)	3,541	3,433	41,879 (3%)
- abandoned rice	22,844 (2%)	6,067	5,980	9,253 (0.69%)	2,719	2,675	3,902 (0.29%)
Sub-total		106,027	81,632		19,961	13,781	
Natural and unused land							
- forest	393,735 (29%)	6,972	3,952	403,179 (30%)	932	932	393,003 (29%)
- mangrove	1,728 (0.13%)	8	8	3,301 (0.25%)	88	87	3,217 (0.24%)
- Wetlands and peat land	3,673 (0.27%)	863	844	2,184 (0.16%)	50	49	2,068 (0.15%)
- unused land	37,429 (3%)	13,167	11,777	34,497 (3%)	3,896	3,419	26,881 (2%)
Sub-total		21,009	16,581		4,966	4,487	
Other							
- Water	28,587 (2%)	1.272	828	30,872 (2%)	19	2	31,004 (2%)
- Built-up area	16,900 (1.3%)	1,503	-227	35,159 (3%)	199	-1	33,810 (2%)
- Other agriculture land	21,274 (2%)	3,958	3,427	13,652 (1%)	1,847	1,722	11,220 (0.83%)
Sub-total		6,733	4,255		2,066	1,724	
TOTAL		133,769	102,468		26,993	19,993	

[1] ***gross*** *= area converted to oil palm. The gross values are taken from the spatial analysis by ArcGIS 10.0.*

[2] ***net*** *= area converted to oil palm (**gross**) minus the area of oil palm converted to other types of land use. Positive values of this net change are considered the direct land use change (dLUC). A negative net change indicates that the area of oil palm replaced by other land use types exceeds the area converted to oil palm.*

2.3.3. Indirect land use change

We analysed the iLUC effects of oil palm expansion into rubber, rice and orchard areas (Table 2.4 and Figure A1 in the Appendix A). We observed that the iLUC effects as a result of rice and orchard conversions were insignificant; there is not much land conversion to rice and orchards elsewhere in the basin (Table A2 and Figure A1, in the Appendix A). For rubber, this is different. Palm was replacing rubber in large areas in the basin. As a result, rubber was planted elsewhere in the basin by replacing other land use types. We, therefore, focused on the iLUC effects of oil palm expansion into rubber areas.

In the first study period (2000-2009), new rubber mainly replaced forests (natural ecosystems), accounting for 23% of new rubber area in 2009 (gross change), followed by oil palm (21%), orchards (15%) and rice (13%) (Figure A1, Appendix A). On the other hand, large areas of rubber (40 thousand ha) were replaced by forests as a result of the cabinet resolution on natural reserve land recall (Srisaowalak, 2010) that considering these rubber areas as the rubber-forest plantations after the recall. This explains the negative net change that we calculated for forests in Table 2.4. This implies that there was no net iLUC effect in this period, as a consequence of the above mentioned cabinet resolution. In summary, the iLUC effects of oil palm expansion resulted in a loss of cropland (17 thousand ha) rather than natural ecosystems (260 ha).

For the second period (2009-2012), we calculated a large increase in deforestation. The net change in forest area indicates that forests were frequently cleared for rubber development (41% of rubber area in 2012), followed by orchards (22%), and rice (15%). The loss of natural ecosystems in the second period is 36 times as large as in the first period.

Furthermore, we analysed the slopes of rubber and oil palm plantations to better understand conversion of forests either to rubber or oil palm. Rubber can be planted at relatively steep slopes (> 20 degrees; Figure A2 in the Appendix A). This is not the case for oil palm. Planting oil palm on slopes > 10 degrees increases the costs of good farm management to minimize soil erosion and nutrient leaching, and makes it more difficult to harvest oil palm fruits (RSPO, 2007). This could explain why in some regions more forest is converted to rubber than to oil palm.

We realized that rubber expansion associated with iLUC is not only limited to the Tapi river basin, but can also take place elsewhere, in particular the northern and north-eastern regions of Thailand that are in line with the government's campaign. For instance, the Department of Agriculture (DOA) promoted rubber development in the north and north-eastern regions from 2004 to 2013. This rubber promotion may be connected with the loss of rubber area (to oil palm plantations) in the south of Thailand, including the Tapi river basin. In these regions, DOA provided free rubber seedlings and technical supports to more than 140,000 farmers; resulting in more than 400,000 ha of rubber plantations (Boonnum and Chantuma, 2010; Chareonsuk, 2011). As mentioned earlier, iLUC effects related to rubber development in the north and north-east regions outside the Tapi river basin are not included in our analysis. The iLUC effect is estimated to have occurred in 3.2% of total area of the basin.

Table 2.4 Indirect land use change (iLUC) caused by the expansion of oil palm in rubber cultivation areas, calculated from the gross and net conversion of land use to rubber plantations during the periods 2000-2009 and 2009-2012 in the Tapi River Basin.

LUC (as a consequence of rubber expansion)	2000-2009			2009-2012		
	Converted to rubber (gross)[1], in ha	Converted to rubber (net)[2], in ha	iLUC effect from oil palm expansion (ha)[3]	Converted to rubber (gross)[1], in ha	Converted to rubber (net)[2], in ha	iLUC effect from oil palm expansion (ha)
Cropland						
- oil palm	23,313	-69,355	-	5,928	-5,542	-
- rice	13,915	11,535	11,535	3,537	3,387	3,387
- orchards	16,976	-5,211	-	5,719	4,961	4,961
- abandoned rice	7,842	5,301	5,301	2,674	2,542	2,542
Sub-total	62,047		16,836	17,858		10,890
Natural and unused land						
- forest	25,061	-15,201	-	9,552	9,150	9,150
- mangrove	-	-2	-		-	-
- Wetlands and peat land	459	257	257	23	23	23
- unused land	9,725	-5,817	-	4,916	4,248	-
Sub-total	35,246		257	14,491		9,173
Other						
- Water	2,061	-1,788		15	-57	
- Built-up area	6,047	-10,988		1,805	1,296	1,296
- Other agriculture land	5,485	1,295	1,295	1,445	958	958
Sub-total	13,593		1,295	3,265		2,254
TOTAL	110,886		18,388	71,228		22,317

[1] ***gross*** *= area converted to rubber. The gross values are taken from the spatial analysis by ArcGIS 10.0.*

[2] ***net*** *= area converted to rubber (**gross**) minus the area of rubber converted to other types of land use. Positive values of this net change are considered "the indirect land use change (iLUC) from oil palm expansion". A negative net change indicates that the area of rubber replaced by other land use types exceeds the area converted to rubber.*

[3] *iLUC from oil palm expansion is calculated as positive net change.*

2.3.4. Farmers' decisions on land use change

In the following, we summarized the results of the farmer interviews with three groups of farmers (Table 2.1). Detailed results are presented in the Appendix, in Tables A3, A4, A5.1 and A5.2.

Group 1- farmers who recently started oil palm cultivation

Almost all farmers reported that the age of their oil palm plantations were in the range of 3-15 years. These farmers started their oil palm plantations during the period 2002-2008, corresponding to the study period of our land use change analysis. From the interviews, rubber plantations were most frequently cleared for oil palm, followed by unused land and rice. However, oil palm expansion into degraded forests is also reported. The degraded forests were given to farmers free of charge under a responsibility of the Agricultural Land Reform Office (ALRO). The findings from the interview of group 1 strongly support the results of direct land use change analysis for the period 2000-2009. Most of the farmers decided to plant oil palm because of the profitability of the crop and considering the suitability of their land for oil palm. This result is supported by Nualnoom (2014) who states that farmers decided to switch from other crops, such as rice and rubber, to oil palm because oil palm provides better financial contributions and the suitability of their land for oil palm. Only a few farmers were not satisfied with oil palm because productivity had declined due to flooding. Another concern for farmers was the variability of palm oil, FFB prices and the recent reductions in prices. From the interviews, farmers usually burned the leftover biomass residues before planting oil palm. Inevitably, large emissions of air pollutants and greenhouse gases are emitted when burning the biomass (Kanabkaew and Kim Oanh, 2011; Permadi and Kim Oanh, 2012). Note that emissions of open burning biomass is not our main focus. However, we discussed the implication of open burning on air pollution in the discussion section (see section 4.1).

However, they did not intend to change oil palm for other crops at the time of interviews (July 2015), not even if the price of FFB would further decline. In view of the investment, they made in planting oil palms and in anticipation of better prices in the future. Most of the farmers had no plans for expansion, even if the FFB price would increase, because they lacked resources, or access to credits to buy new land for that purpose. Only four farmers (out of a total sample of 14) had sufficient access to capital and wanted to expand the oil palm area.

Group 2 - Farmers who recently started rubber cultivation

In group 2, the interviewed farmers mainly planted rubber during 2000-2005, which largely covers the period of our initial land use change analysis. The interviews confirm that rice fields were most often replaced by rubber plantations, followed by unused land. Clearing degraded forests (from ALRO) for rubber plantations was also reported during the interviews.

The farmer interviews support the result of the indirect land use change analysis for the period 2000-2009. The main reason for planting rubber is that the farmers' land are more suitable for rubber compared to other crops and favourable returns on investments in rubber in this period. Most farmers were satisfied with rubber, and mentioned that they could earn extra income from selling the rubber woods after the end of the lifetime of the plantation. Unstable price (both decreases and increases) had a small influence on the farmer's decisions to change their investments in rubber: mainly because of a lack of available land and credits. Some of them wished to increase their income by expanding the rubber areas.

Group 3 - farmers who recently started both oil palm and rubber cultivation, and switched in some plots from rubber to oil palm

The farmers' decisions and motivations to change land use in group 3 are similar to those in groups 1 and 2. Group 3 consists of only large-scale farmers who converted part of their rubber areas to oil palm. The main reason for this is that their lands are suitable for oil palm and they anticipated this crop to bring higher returns. Another reasons to expand their oil palm areas was the relative ease of oil palm management practices (i.e. a lower labour requirement and less plant diseases). Some farmers clearly indicated that they wanted to expand rubber plantations into either unused land or degraded forests from ALRO. Next, we compared the cost-income of oil palm and rubber for the year 2014: the net profits of oil palm were slightly higher than of rubber (see Table A5.2, Appendix). Note that cost-income of oil palm and rubber may vary among regions within the Tapi river basin and among different years.

2.3.5. Effects of land use change on ecosystem services

2.3.5.1.Food and non-food provisioning service

Fresh Fruit Bunch (FFB) production

The area of oil palm plantations in the Tapi river basin increased from 97,950 ha in 2000 to 200,191 ha in 2009 and to 220,115 ha in 2012. Our land use change analysis shows that the oil palm area in the Tapi river basin increased with approximately 102,000 ha between 2000 and 2009 and with 20,000 ha between 2009 and 2012. This expansion led to an increase in annual average FFB production of almost 1.92 million ton in the period of 2000-2009 and of 1.12 million ton in the period of 2009-2012 (Table 2.5).

Latex production

Table 2.6 shows that the rubber plantations decreased from 644,514 ha in 2000 to 554,544 ha in 2009. Oil palm expansion caused a decrease in rubber areas approximately of 90,000 ha between 2000 and 2009. As a result, annual latex production in the Tapi river basin decreased by approximately 121,000ton. Latex can usually be produced after 7 years of rubber cultivation. For the 2009 to 2012 period, we assumed that rubber plantations started in 2009 had not yet produced latex. This results in an increase in annual latex production of around 22,200 ton.

Rice production

Large areas of rice fields were replaced directly by oil palm and indirectly by rubber over the study periods because farmers generate lower profits from rice. In 2012, the net profit of rice, FFB and latex were about 4,900 THB/ha, 38,300 THB/ha and 34,100 THB/ha, respectively (OAE, 2013). The decrease in rice area resulted in a reduction in rice production of around 27,200 ton between 2000 and 2009 and around 17,600 ton between 2009 and 2012 in the Tapi river basin.

Fruit production

The net profit of fruits production (22,400 THB/ha) was lower than of FFB and latex productions (OAE, 2013). Thus, a number of orchard plantations were replaced directly by oil palm and indirectly by rubber over the study periods. There was a decrease of about 800 ha of orchard plantations from 2000 to 2009 (Table 2.5) and about 7,600 ha of orchard plantations from 2009 to 2012. In the period of 2000-2009, this reduction in orchard area led to a loss in fruit production in the basin approximately by 61,100 ton. In the period of 2009-2012, we assumed that orchard plantations started in 2009 had not yet produced fruits. We therefore calculated the loss in fruit production in the basin approximately by 67,800 ton.

Table 2.5 Effects of land use change on food and non-food provisioning services for different cropland in the Tapi river basin during the study periods.

Cropland / Product	Year/Study period	Total planted area (ha)	Annual average productivity[1] (ton/ha)	Annual production (ton)	Annual Production (ton)
Oil palm / FFB	2000	97,950	13.58	1,330,161	
	2009	200,191	16.22	3,247,098	
	2012	220,115	19.85	4,369,283	
	2000-2009				1,916,937
	2009-2012				1,122,185[a]
Rubber / Latex	2000	644,514	1.68	1,082,784	
	2009	554,544	1.57	870,634	
	2012	575,418	1.61	926,423	
	2000-2009				-212,149
	2009-2012				22,182[b]
Rice / Rice	2000	26,363	2.01	52,990	
	2009	8,750	2.94	25,725	
	2012	2,911	2.8	8,151	
	2000-2009				-27,265
	2009-2012				-17,574[c]
Orchards / Fruits	2000	50,249	6.75	339,181	
	2009	49,484	5.62	278,100	
	2012	41,879	4.25	177,986	
	2000-2009				-61,081
	2009-2012				-67,793[d]

A 'negative value' shows a loss or decreasing trend while 'positive value' shows a gain or increasing trend.
[1]*Crop productivity is from OAE* (OAE, 2011a)
[a] *Oil palm plantations are assumed to be producing FFB after 3-4 years* (OAE, 2011a). *New oil palm plantations in 2009 had produced FFB.*
[b] *Rubber plantations are assumed to be producing latex after 7 years* (OAE, 2011a). *New rubber plantations in 2009 had not produced latex.*
[c] *Rice fields are assumed to be producing rice after 180 days (twice a year)* (OAE, 2011a). *New rice fields in 2009 had produced rice.*
[d] *Orchards are assumed to be producing fruits after 5 years* (OAE, 2011a). *New orchard plantations in 2009 had not produced fruits.*

2.3.5.2.Biodiversity conservation

During the period 2000-2009, large areas of unused land (12 thousand ha) and forests (4 thousand ha) were directly cleared for oil palm plantations. In addition, a smaller area (< 850 ha) of wetlands and peatland (which cover only small parts of the basin) were affected. We did not record any conversions of forests and unused land as part of iLUC in this period, but we did found a small area of wetlands and peatland that was indirectly affected (290 ha). However, the effects on biodiversity strongly increased in the second period (2009-2012). Large areas of forests (~9000 ha) were converted or replaced by other crops, particularly rubber, with iLUC being much more important than dLUC. Given that forests are important habitats for many species (UNEP-WCMC, 2015), this implies that oil palm expansion in the period 2009-2012 caused a more serious impact on biodiversity loss than the expansion in earlier years. Moreover, we also noticed LUC inside protected areas. Khlong Phanom national park was subject to encroachment by oil palm plantations. Tai Rom Yen National park was subject to, in particular, encroachment by rubber plantations. These encroachments involved several 100s of ha and strongly increased in the second period, based on a comparison of our maps with those of the Royal Forest Department (RFD, 2016) indicating park boundaries.

Table 2.6 Effects of oil palm expansion on natural habitat loss, resulting from direct land use change (dLUC) and indirect land use change (iLUC) during the periods 2000-2009 and 2009-2012 in the Tapi river basin.

Natural ecosystems	2000-2009		2009-2012	
	dLUC	iLUC	dLUC	iLUC
	Loss of area (A_{eco}), in ha	Loss of area (A_{eco}), in ha	Loss of area (A_{eco}), in ha	Loss of area (A_{eco}), in ha
Forest	3,952	-	932	9,165
Mangrove	8	-	87	-
Wetlands and peat land	844	291	49	23
Unused land	11,777	-	3,419	-
Total	**16,581**	**291**	**4,487**	**9,188**

2.3.5.3.Carbon storage service

Land use types differ in their capacities to store and accumulate carbon from the atmosphere. Details on carbon stock pools for each land use type are provided in the Appendix, Table A1.

Table 2.7 shows that stored carbon in biomass, dead organic matter and soil can be released in large quantities when peat swamp forests, peatlands or forests are converted and drained. Converting rubber to oil palm also releases carbon. On the other hand, converting annual crops to oil palm results in net negative carbon emissions (i.e. sequestration), in the order of 41-60 ton C/ha on average, as the carbon storing capacity of oil palm is higher.

From 2000 to 2009, dLUC associated with expanding oil palm in the Tapi river basin resulted in about 7.2 million ton of carbon released into the atmosphere. However, iLUC led to the sequestration of carbon, with around 1.4 million ton of carbon, due to the conversion of annual cropland and unused lands to rubber plantations. The net effect therefore was a release of around 5.8 million ton of carbon. During the period 2009-2012, both dLUC and iLUC led to the release of carbon into the atmostphere. dLUC and iLUC led to emission of 0.3 million ton of carbon and 1.2 million ton of carbon, respectively. In this period, iLUC also led to carbon emissions since in this period a larger amount of forests were converted as part of iLUC. Note that the periods are of different length, i.e. 9 respectively 4 years. On an annual basis, carbon released into the atmosphre due to LUC amounted to 5.8/9 = 0.65 ton of carbon each year in the first period, and 1.5/4 = 0.38 ton of carbon each year in the second period. Note that the rate with which oil palm expanded in the first period is 12% per year, whereas in the second period this was only 2% per year. Hence, on a per hectare basis, these environmental impacts have strongly increased in recent years.

Table 2.7 Effects of land use change (dLUC and iLUC) on carbon storage service.

Land use type	Area of LUC, ha				Carbon Stock Change by land conversion to oil palm (ton carbon/ha)				Carbon stock change (ton carbon/basin)			
	2000-2009		2009-2012		Biomass	Dead organic matter	Soil carbon	Balance	2000-2009		2009-2012	
	dLUC	iLUC	dLUC	iLUC					dLUC	iLUC	dLUC	iLUC
Cropland												
- Oil palm	-			-	-				-	-	-	-
- Rubber	69,355	-	5,542	-	-96.77	-2.65	62.89	-37	2,533,764		202,463	
- Rice	3,186	13,071	2,131	3,396	47.62	0.00	46.88	94	301,078	1,235,099	201,337	320,919
- Orchards	3,111	-	3,433	4,961	41.39	-0.020	50.72	92	286,504	-	316,166	456,840
- Abandon rice*	5,980	12,853	2,675	2,564	47.62	0.00	46.88	94	565,102	1,214,552	252,789	242,244
Natural land												
- Forest	3,952	-	932	9,165	-119.06	-6.86	-5.51	-131	-519,367	-	-122,434	-1,204,494
- Mangrove	8	-	87	-	-69.92	0.00	48.70	-21	-166	-	-1,851	-
- Wetlands and peat land	844	291	49	23	-22.93	-27.65	-385.30	-436	-368,043	-126,748	-21,497	-10,199
- Unused land	11,777	-	3,419	-	43.66	-0.15	29.50	73	859,763	-	249,605	-

A 'negative value' shows a releasing stored carbon to the atmosphere while 'positive value' shows a storing and accumulating carbon from the atmosphere.

n.a. data is not available

* *assumed to be the same condition as rice field*

2.4. Discussion

2.4.1. Data uncertainties

Uncertainties associated with input data and ecosystem services modelling

There is a large uncertainty when modelling LUC. These uncertainties stem from both uncertainties in the input dataset (Dendoncker et al., 2008) and in the model (Ray et al., 2012). For the input dataset, we analysed land use change (dLUC and iLUC) based on available land use maps in 2000, 2009 and 2012 from the Land Development Department (LDD), Ministry of Agriculture and Cooperatives, Royal Thai government. These land use datasets were developed based on both satellite images for land use classification and site survey for ground-checking and for producing attribute data (Chanroj, 1999). According to a conversation with an LDD official, the uncertainty associated with the LDD land use maps is approximately 20%.

In our model, we quantify ecosystem services based on available statistics and literature. To model food and non-food provisioning service, statistics on crop yields, crop prices and costs from Office of Agriculture Office (OAE, 2013, 2011b, 2009) are used. The data represent an average value at provincial level. We then converted them from provincial to the basin level. This conversion leads to uncertainties. For the carbon storage service, we used carbon stocks data from the literature and there are uncertainties associated with assuming such values to be representative for the Tapi Basin, however we do not have local measurements. Hence, we are able to identify but not quantify the uncertainties in our model. We note that, in general, it seems to be difficult to analyse uncertainties in relation to ecosystem services assessment, given the shortage of data required to model ecosystem services – and the need for additional, local data to verify the models.

Farmers survey

We interviewed in total 37 farmers from Tham-Phannara and Thungyai districts in Nakhon-si-thammarat. We acknowledged that our sample is relatively small and may not be a good representation for the entire Tapi river basin. Nevertheless, our results from farmer interviews fit very well with our model outputs as they indicate that rubber plantations were mainly replaced by oil palm, whereas there is also conversion of unused land and rice fields. In addition, the farmer interview results are in agreement with the study of Nuannoom (2014) who interviewed farmers in Prasaeng and Bannaderm districts, Suratthani province (conducted in June 2012), which is part of the Tapi basin. He also found that farmers decided to switch their rubber and rice areas to oil palm because of higher returns on land and labour in oil palm compared to other crops and the suitability of their land for oil palm.

Integrated analytical approach for land use change

We modelled land use change caused by oil palm expansion using ArcGIS 10.0 based on the available land use datasets from the LDD. The model output maps provide insights in the extent to which types of land use changed as a result of oil palm expansion in the Tapi river basin including dLUC and iLUC. We believe that it is important, however, that in particular iLUC is not only analysed on the basis of spatial information. There are multiple processes, actors and types of land use change, and a causal relation between dLUC and iLUC can in our view not be established on the basis of modelling alone but also requires an understanding of why and how local actors decide upon LUC (cf. IFPRI 2009).

Implication of land use change on hydrology services

We think that the most important ecosystem services which could not be included in our analysis is the hydrological service provided by, in particular forests (Gilfedder et al., 2012; Hughes et al., 2012; Mustafa et al., 2012). Babel (2011) showed that the conversion of forests to oil palm plantations resulted in an increased surface runoff by about 13% and reduced base-flow by about 7% in Thailand. In contrast, the conversion of orchards and rubber plantations to oil palm, hardly decreased surface runoff and base-flow. Babel's study was carried out in the Klong Phlo watershed, where the biological and hydrological characteristics of this basin are similar to that of the Tapi basin (Haii, 2013). This means that, in particular, there is a risk that the conversion of forests to oil palm in in particular the second period has affected the hydrological service, potentially increasing flood risks in the basin. Further study is required, using hydrological modelling, to quantify these effects.

Implication of open burning on air pollution

Another main environmental issue, which is not adequately covered in the ecosystem services framework, relates to externalities of ecosystem use. A main issue in the Tapi river basin is open burning, which is a commonly applied by farmers to clear a new land before planting oil palm, leading to large emissions of air pollutants and greenhouse gases (Kanabkaew and Kim Oanh, 2011; Permadi and Kim Oanh, 2012). We present a preliminarily estimate of the annual emissions of burning residues after land conversion of rice to oil palm as an example. We used equations and emission factors from the study of Kanabkaew & Kim Oanh (2011) for annual emission rates. Our analysis shows that oil palm expansion in the period of 2000-2009 replaced 17,600 ha of rice fields. This conversion of rice to oil palm alone results in annual emissions of approximately 2,900 ton CO_2, 24 ton CH_4, 0.45 ton SO_2, 6 ton NOx, 232 ton CO, 17 ton NMVOC and 23 ton PM in the Tapi river basin. Hence, this is an important environmental effect of oil palm expansion, it should be studied in more detail and considered in policy making.

2.4.2. Policy recommendations

The policy setting.

According to government statistics, market prices of both FFB and latex increased over the past decade (2000-2013). The annual average price of FFB increased from 24,100 THB/ha in 2000 to 72,500 THB/ha in 2013. Meanwhile, the annual average price of latex increased from 33,500 THB/ha in 2000 to 119,100 THB/ha in 2013 (OAE, 2013, 2009). However, the market price alone seems to be an insignificant driving force for oil palm expansion and land use change in the Tapi river basin – more important are the availability of government support for land use change (in particular changing from rubber to oil palm), the interest of farmers to diversify, and the lower labour requirements of oil palm. The interviewed farmers generally indicated that price changes, within the currently encountered price range, had a small influence on farmer's decisions in changing either oil palm or rubber investment.

A national campaign to promote biodiesel production and consumption was initiated in 2005. However, at the initial stage the effects of this policy were insignificant. Later, in 2008, the Thai government adopted this policy requiring a replacement of all regular diesel with B2 biodiesel (a mixture of diesel with 2% biodiesel) (Kumar et al., 2013). Production of palm oil as biodiesel feedstock has been growing fast since then. The Thai government has continuously modified its policy and plans to increase the production and consumption of biodiesel. In 2012,the mandatory B5 rule (a mixture of diesel with 5% biodiesel) came into force. To achieve this goal, the Thai government promoted the expansion of oil palm area to a targeted 880,000 ha with targeted average yield at 20 ton/ha/year. (DEDE, 2012a; Preechajarn and Prasertsri, 2012). The farmer interviews confirmed that the farmer support that resulted from these policies was a major driver for the land use change in the Tapi river basin.

The national policies were also reflected in the provincial development plans. We studied the 2000-2012 development plans of three provinces in the Tapi river basin. These development plans promoted rubber and oil palm development (Krabi Admistrative, 2014; Nakhon-Si-Thammarat Adminitrative, 2014; Suratthani Adminitrative, 2014). Our farmer interviews show that the financial aid from Office of the Rubber Replanting Aid Fund, on average 100,000 THB/ha for a period of 5 years, had been granted to the farmers who switched their rubber plots to oil palm. This contributed to the rapid expansion of oil palm plantations in the Tapi river basin, confirming that government support is one of the main drivers for land use change.

Cultivation of oil palm has been increasing due to political interest in biofuels in Thailand. Currently, also second and third-generation biofuels are being considered. These include new energy crops (i.e. jatropha and micro algae) and technologies to convert from biomass to energy (i.e. pyrorysis) and Bio Hydrofined Diesel (DEDE, 2012a). However, full commercialization of these is not likely to occur in at least a decade around the world (Kumar et al., 2013) and their implications for mitigating land use change in the Tapi basin are likely to be small, at least in the time frame of the coming 10 to 20 years.

Negative effects of oil palm expansion can be reduced by stopping the conversion of new lands and increasing productivity

Annual average productivity of oil palm was 16 ton/ha in the period 2000-2009 and 20 ton/ha in the period 2009-2012 (OAE, 2013, 2009). Our analysis revealed that the annual expansion rate of oil palm was 12% for the period 2000-2009 and 2% for the period 2009-2012 (see section 3.1). In principle, increased productivity could be met with a smaller area of oil palm plantations. However, higher productivity could also increase the motivation and financial means of the farmers to convert even more land to oil palm.

We note that the current practice of expanding oil palm areas into cropland and other land use types is not consistent with sustainable palm oil production, because the available land in the Tapi river basin is limited and because the remaining forest resources are both limited as well as important for water regulation and other ecosystem services. If the current trends continue in the coming years, the production of other food crops (i.e. rice and orchards) will be so low that food security might become an issue in the basin. People may have to import, for instance, fruits into the basin from other regions. Inevitably, this will increase the price of fruits, with potential consequences for low income households. The drive for expanding oil palm production is also affecting national parks, with substantial encroachments of oil palm and rubber observed in two national parks in the Tapi basin (Khlong Phanom and Tai Rom Yen). We also note that, on a per hectare basis, the environmental impacts of converting land in the period 2009 to 2012 were much higher than in the period 2000 to 2009, meaning that further land conversion will increasingly bring negative environmental and economic effects. To minimize this risk, freezes on further land conversion, and promotion of the application of technologies and best practices that increase yields is recommended. Promoting the intensification of agricultural production should go hand in hand with environmental practices that minimize runoff of pesticides and fertilisers, such as reduced tillage and cover crops (Sharpley, 2016).

2.5. Conclusion

The Thai government has been promoting biodiesel since 2005. To meet its target, palm oil production considerably increased and oil palm plantations rapidly expanded. Land use change effects that resulted from the oil palm expansion cause environmental problems and deteriorate ecosystem services supply, especially when natural ecosystems are cleared. We analysed both direct and indirect land use change effects using spatial analysis in ArcGIS10.0 in combination with a farmer survey, and then quantified subsequent effects on the supply of selected ecosystem services (i.e. food and non-food provisioning service, carbon storage, biodiversity conservation). Our analysis focused on the Tapi river basin which is one of the main oil palm producing areas of the country.

Our analysis indicates that the pattern of land use change changed over time. In the period 2000-2009, approximately 80% of new oil palm area replaced cropland (i.e. rubber, rice, orchards, abandoned rice). Rubber was the main crop being replaced. In addition, natural ecosystems (i.e. forest, mangrove, wetland or peatland, unused land) were affected; this accounted for 16% of new oil palm area. iLUC in this period (as well as in the next) involved in particular the conversion of various land use types to rubber plantations. In the period 2009-2012, iLUC exceeded dLUC. Forests were cleared (39% of iLUC) to replace other crops (mainly rubber) that were converted to oil palm. Farmers' motivations for changing land use to oil palm include higher profits, the availability of government subsidies, and lower labour requirements compared to rubber.

Expanding oil palm plantations led to an increase in the annual average FFB production in the Tapi basin from 1,330,000 ton FFB/year in 2000 to 4,369,000 ton FFB/year in 2012. However, the production of a range of other crops (i.e. latex, rice and fruits) declined in the same period. Oil palm expansion also adversely affected carbon storage and biodiversity conservation in the Tapi Basin and, in particular in the second period, is likely to have affected the hydrology of the Tapi river. The encroachment of oil palm and rubber in national parks in the basin stands out as environmental effect. Worryingly, the clearance of natural forest for oil palm and rubber production strongly increased in the second period compared to the first period. Between 2009 and 2012, some two-thirds of the LUC (including dLUC and iLUC) involved loss of natural forests. This reflects that there is very little additional arable land available for oil palm in much of the Tapi basin. We therefore strongly recommend the government to stop promoting the conversion of additional land to oil palm. Instead, the government should aim to increase productivity in existing plantations.

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Chapter 3

Assessing environmental impacts of
palm oil production in Thailand

3. ASSESSING ENVIRONMENTAL IMPACTS OF PALM OIL PRODUCTION IN THAILAND

ABSTRACT

There are several concerns related to the increasing production of palm oil in Southeast Asia, including pollution, greenhouse gas emissions and land conversion. The RSPO (Roundtable on Sustainable Palm Oil) certification standard provides an incentive for reducing environmental impacts of palm oil production but to date, only few producers have been certified and studies on environmental implications of RSPO certification in Thailand are scarce. The objective of this study is to assess environmental impacts of palm oil production in Thailand. A case study is conducted in the Tapi River basin, accounting for 60% of palm oil production in Thailand. We developed a model to quantify effects of different management practices in plantations and mills producing Crude-Palm-Oil (CPO) – including non-RSPO, potential RSPO, and RSPO certified producers.

Our study shows that five activities contribute most to environmental impacts of CPO production; 1) burning fibres in boilers,2) use of fertilisers, 3) wastewater treatment and empty-fruit-bunch disposal, 4) gasoline use in weed cutters and 5) glyphosate use for weed control. Together these activities cause environmental impacts associated with global warming, ozone formation, acidification, and human toxicity problems. RSPO certified producers cause the lowest environmental impacts due to better waste management such as biogas production from wastewater. We found that environmental performance of the most environmental friendly mills considerably exceeds the RSPO standards, which may be related to the interventions of an environmental project in the Tapi basin.

Currently, only 11% of CPO in the Tapi River basin is produced by RSPO certified mills, and non-CPO certified mills produce around 60% of CPO. Most of environmental impacts of palm oil production in the basin are therefore caused by non-RSPO certified palm oil mills. We explored two alternative scenarios illustrating that if more mills in the basin would adopt best-practice CPO production processes in line with those group named “RSPO certified”, environmental impacts generated in the basin will be considerably lower.

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3.1. Introduction

The environmental impacts of palm oil have been increasing in many parts of the world (Choong and McKay, 2013) including Thailand, driven by the rapid expansion of the sector and a lack of environmental regulations in many of the areas where the crop is grown (Silalertruksa et al., 2012a; Silalertruksa and Gheewala, 2013; USAID, 2009). In many regions palm oil production is a major cause of land use change and deforestation, with major implications for biodiversity. In addition, there are pollution problems caused by palm oil production (Oosterveer, 2014). Assessing the environmental impacts of palm oil is important for a better understanding of the palm oil production sector in Thailand, and for further developing plans towards more sustainable production.

Palm oil production contributes to a number of environmental problems. For instance, emissions of greenhouse gases (GHGs) have been reported along the production chain (Bessou et al., 2014), in particularly methane (CH_4) emissions from wastewater in open ponds at the milling phase, and nitrous oxide (N_2O) emissions from nitrogen fertiliser application in the cultivation phase (Kaewmai et al., 2012; Silalertruksa and Gheewala, 2013). In addition, applying nitrogen and phosphorus fertilisers for maximizing oil palm yields causes eutrophication in surface waters (Achten et al., 2010; Bijay et al., 1995; Dumelin, 2009). Pleanjai et al.(2009) observed that high toxic herbicides, which are possibly harmful to human health and nearby watersheds, are used in oil palm plantations. Several air pollutants are generated during fuel combustion, such as particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs) and carbon monoxide (CO), which are harmful to human health and cause acidification, eutrophication and photochemical ozone formation problems (Achten et al., 2010; Dumelin, 2009).

The increasing environmental impacts of palm oil production result in a growing global concern and demand for palm oil products that are produced without harm to the environment and society. A global sustainability standard for the palm oil production, named Roundtable on Sustainable Palm Oil (RSPO), was established by multi-stakeholders to response on this growing concern and demand (RSPO, 2007; Von Geibler, 2013). RSPO is an emerging issue in Thailand. To date, only a small number of smallholder farmers and palm oil mills have been RSPO certified (Appalasamy, 2012a, 2012b; RSPO, 2012). Although RSPO is recognized as an important environmental management tool, there are only few studies on the environmental implications of palm oil production in Thailand. For instance, Patthanaissaranukool et al. (2013) and Kaewmai et al. (2012) focus on GHG emissions from palm oil mills but do not address other environmental impacts or the implications of RSPO certification.

The objective of this study, therefore, is to assess the environmental impacts of palm oil production in Thailand. To this end, we developed an environmental model to quantify the effects of different management practices in relation to the RSPO certification scheme. The Tapi River basin (Figure 3.1) is taken as a case study because more than half of palm oil production in Thailand is from this basin (DIT, 2012a, 2012b, 2011). Our results and conclusions may be useful for the development of additional policies aiming at a more sustainable palm oil production sector.

3.2. Methodology

3.2.1. Study area

About 60% of the total palm oil production in Thailand is from the Tapi River basin (Figure 3.1), and the basin contains 48 palm oil mills, over half the total number of mills in Thailand (DIT, 2012a, 2012b, 2011). The Tapi River basin is, therefore, selected as a case study to analyse the environmental impacts of palm oil production in relation to the RSPO certification scheme in Thailand. It is a main basin in the South of Thailand with area of 13,455 km^2, mainly covering three provinces; Surat Thani (69% of the basin), Nakhon Si Thammarat (17% of the basin), and Krabi (13% of the basin). About 350 smallholder farmers have been RSPO certified, managing 2,312 ha of plantation and producing about 43,385 tons (t) of fresh-fruit-bunch (FFB) per year (Appalasamy, 2012a, 2012b). There are only four RSPO certified mills that annually produce 936,000 t crude-palm-oil (CPO) and eight mills aiming to become RSPO certified that annually produce 2,520,000 t CPO (DIT, 2012a, 2012b, 2011).

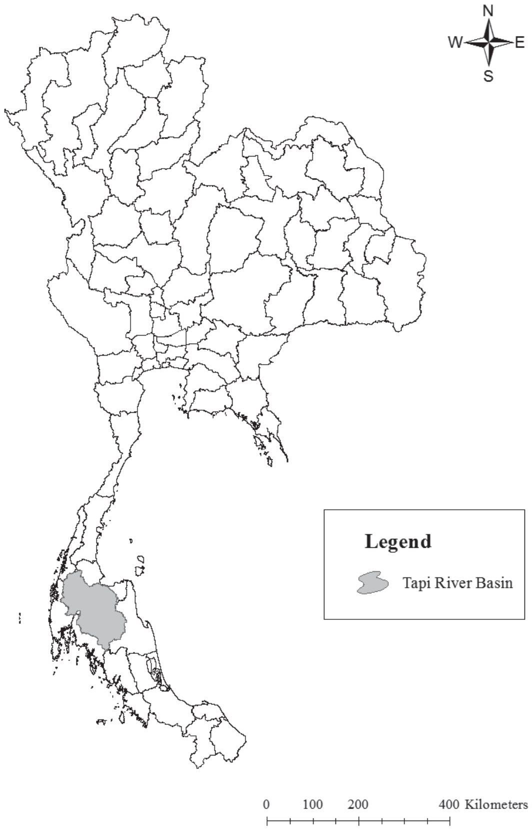


Figure 3.1 Location map of the Tapi River basin, in southern Thailand.

3.2.2. The palm oil production system

We defined our system of palm oil production (Figure 3.2) as consisting of two subsystems: oil palm plantations and palm oil mills, but excluded the effects of land use change. Activities taken into account included production, transportation and use of material inputs that are used in the palm oil production system (Figure 3.3). The overseas and domestic transportation of inputs were also considered. FFB produced from oil palm plantations are delivered to palm oil mills for extracting CPO from the palm fruits (Figure 3.2). Besides CPO, at palm oil mills, Palm-Kernel (PK) is produced as a co-product, and five types of waste (i.e. fibres, shells, decanter cakes and empty-fruit-bunch (EFB) and wastewater or palm-oil-mill-effluent (POME)) are generated.

The environmental impacts largely depend on how palm oil is produced. In this study, we assessed the environmental impacts caused by different management practices in relation to the RSPO certification scheme. To this end, we classified the CPO producers in the Tapi river basin into three categories, to which we referred as non-RSPO (N-RSPO), potential RSPO certified (P-RSPO), and RSPO certified (C-RSPO) producers. A description of three different study cases is presented in Table 3.1. Data were collected for these three groups of producers by literature review and through in depth interviews with 21 plantations and 2 mills. Based on farmer interviews, the majority of oil palm plantations in the Tapi river Basin were started less than 25 years ago. Palm-residue burning, typically taking place after 25 years, is not yet an issue in the Tapi River basin, and therefore not considered in this study. Our future scenarios assume that after 25 years replanting will take place without burning.

Table 3.1 Different practice of N-RSPO, P-RSPO and C-RSPO oil palm producers (plantations and mills)

Activity	N-RSPO[a]	P-RSPO[b]	C-RSPO[c]	Remark
Oil palm plantations				
Fertiliser management	Apply fertilisers according to the available nutrient budget	Apply fertilisers according to the available nutrient budget	- Apply according to the oil palm's needs - Leaf and soil analysis was conducted	Driven by RSPO P&C (Criteria 4.2)
Weed control	Regular removal of the weeds by using herbicides and weed cutting tool	Regular removal of weeds by using herbicides and weed cutting tool	- Regular removal of weeds manually together with weed cutting tool - Rarely use herbicides	Driven by RSPO P&C (Criteria 4.5 and 4.6)
Pest control	No information	No insecticide use was reported	- No insecticide use was reported - Some farmers apply the integrated pest management techniques, such as letting barn owl to control mice	
Transport of FFB	- Plantation to middleman - Middleman to mill	Plantation to mill	Plantation to mill	Driven by location of plantation
Palm oil mills				
FFB sourcing	100% from non-RSPO certified FFB	95% from non-RSPO certified FFB and 5% from potential RSPO certified FFB	63% from non- RSPO certified FFB, 5% from potential RSPO certified FFB and 32% from RSPO certified FFB	Driven by availability of RSPO certified FFB
%Oil extraction rate	17%	16%	18%	Driven by FFB quality
Use of renewable energy	Electricity from burning fibres	- Electricity from burning fibres - Electricity from captured biogas	- Electricity from burning fibres - Electricity from captured biogas	Driven by scheme set by Ministry of Energy and RSPO criteria5.4, 5.3 and 5.6
Wastewater treatment	Anaerobic lagoons	Biogas capture system	Biogas capture system	
Empty fruit bunch disposal	Open dumping	Open dumping	Mulching in the plantations	Driven by RSPO criteria 4.2, 5.3 and 5.6

a - Farmers and millers applying Business as Usual practices and not following the best practices in the RSPO Principle & Criteria (P&C).

b - Farmers and millers aiming to achieve RSPO certification and learning the best practices in the RSPO P&C.

c – RSPO certified farmers and millers that are following the best practices in the RSPO P&C.

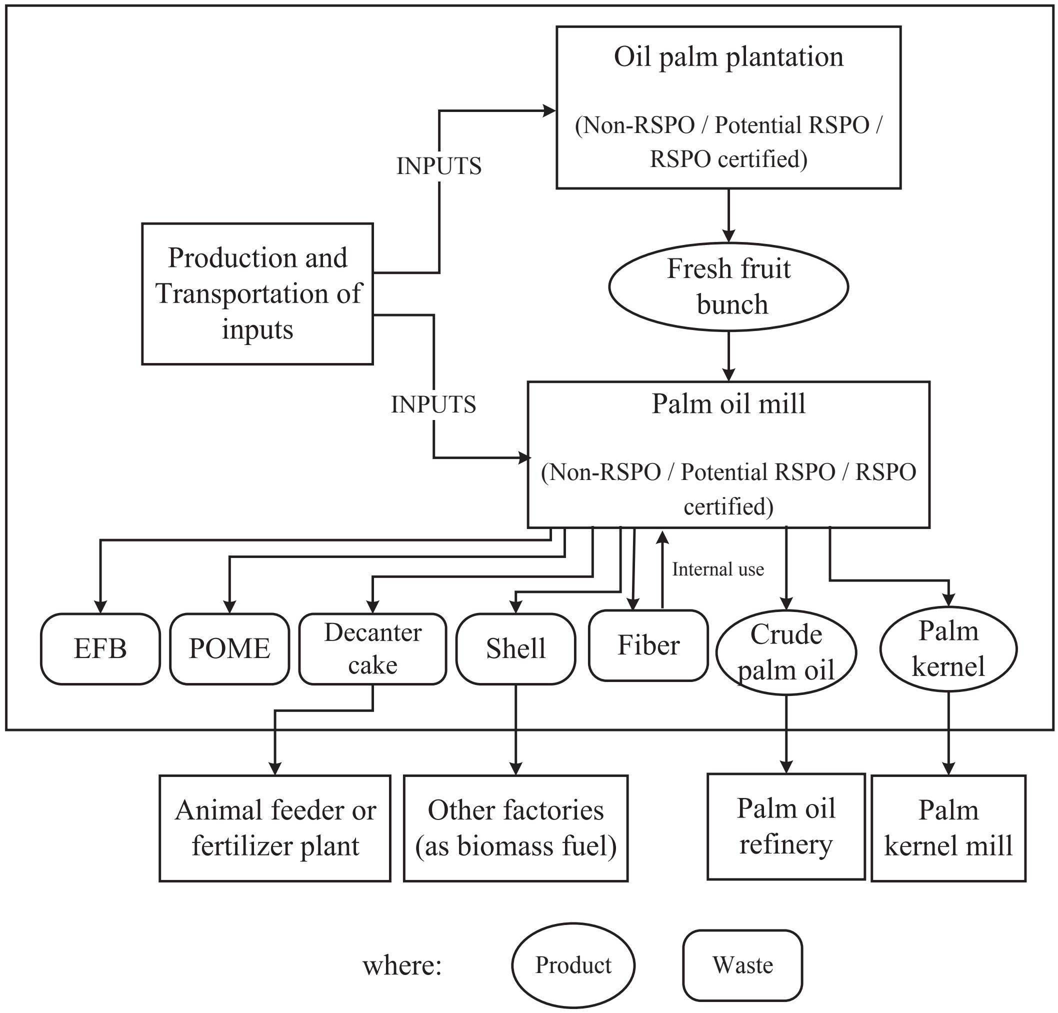


Figure 3.2 The system of palm oil production in the Tapi river basin, including oil palm plantations and palm oil mills that extract oil from fresh fruit bunches produced in the Tapi river basin. **EFB** = empty fruit bunch, and **POME** = palm oil mill effluent. Dotted lines are used for activities that are outside the scope of this study.

Based on the literature, six environmental impact categories were taken into account in this study (Figure 3.3). These impacts include global warming (GW), eutrophication (EP), acidification (AD), photochemical ozone formation (POF), human toxicity (HT), and freshwater ecotocixity (FE).

a. The oil palm plantations

We distinguished four main activities; soil preparation, fertiliser management, weed control and FFB transportation, are carried out in the oil palm plantations (Figure 3.3a). It starts with the soil preparation which uses tractors to turn over the soil and to dig holes for planting seedlings. It should be noted that the production of seedling were not considered in this study since its contribution share on the environmental impacts is considerably insignificant (GIZ, 2011).

Fertiliser management practice depends on maturity of the oil palm. High nutrients are required when the oil palm becomes mature. The lifetime of an oil palm plantation in Thailand is about 25 years. After about three to four years , FFB can be harvested for palm oil production for a period of around 22 years (Dallinger, 2011; Daniel and Gheewala, 2010; Pleanjai et al., 2009; Siangjaeo et al., 2011). In this study, we distinguished between two phases of oil palm production; 1) immature plantation (1 – 3 years) or non-productive period and 2) mature plantation (4 – 25 years) or productive period. The amount of fertilisers used over this period are summarized in Table 3.2.

Based on the interviews, we found that few insecticides are used in the plantations. Weed control is typically carried out every 3-4 months by using herbicides and weed cutting tools. Glyphosate, paraquat and cabarly are used. Only glyphosate was taken into account in this study as it is the most commonly used herbicide (Table 3.2). For the weed cutting tools, gasoline is required.

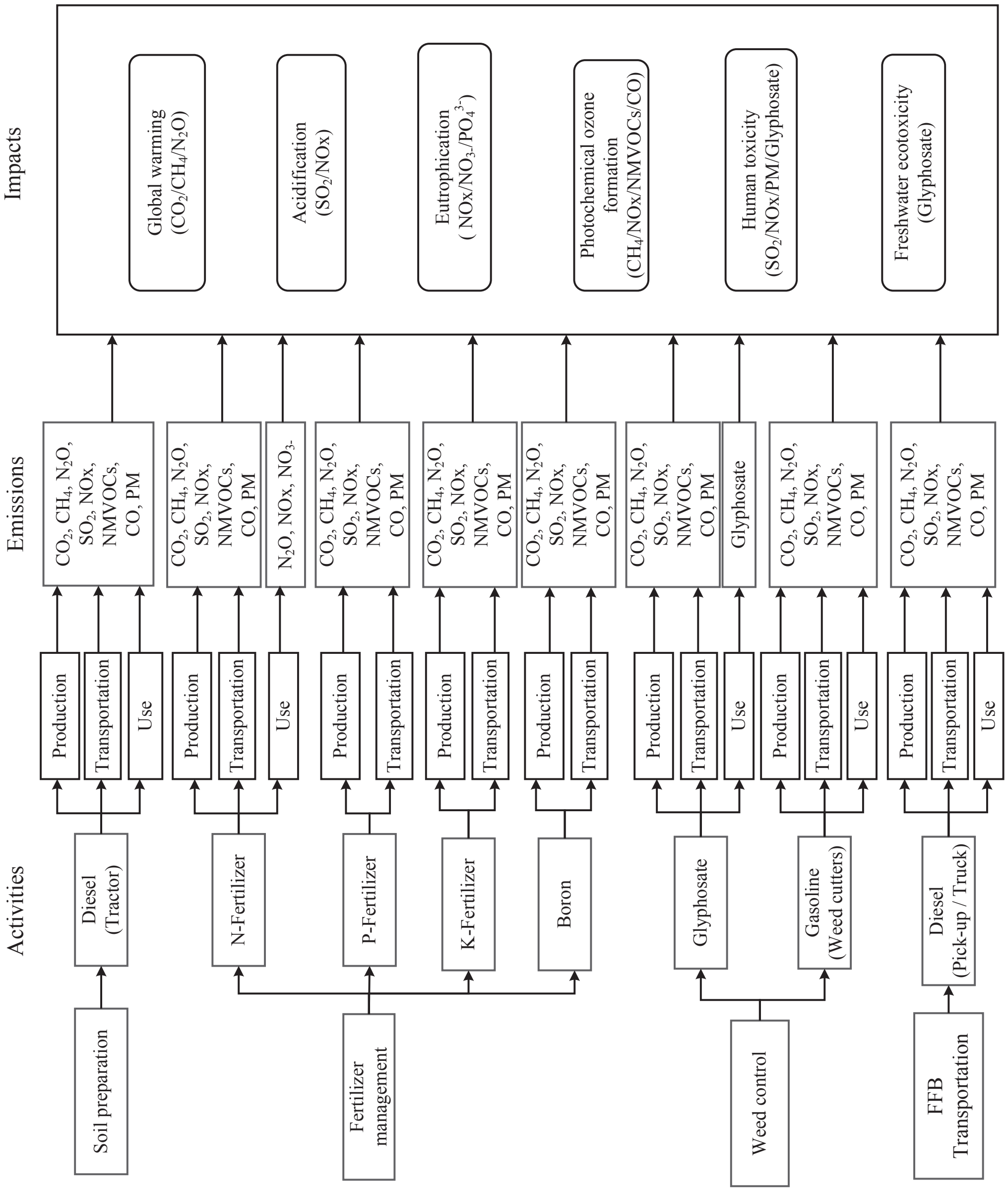
After harvest, famers deliver FFBs to either a nearby mill or to a middleman (ramp), who collects FFBs in pick-up trucks. This middleman system is unique for Thailand because 1) the majority of oil palm growers are smallholders without their own trucks to deliver large amounts of FFB to the mills, and 2) smallholder plantations are scattered and often far away from the mills.

b. The palm oil mills

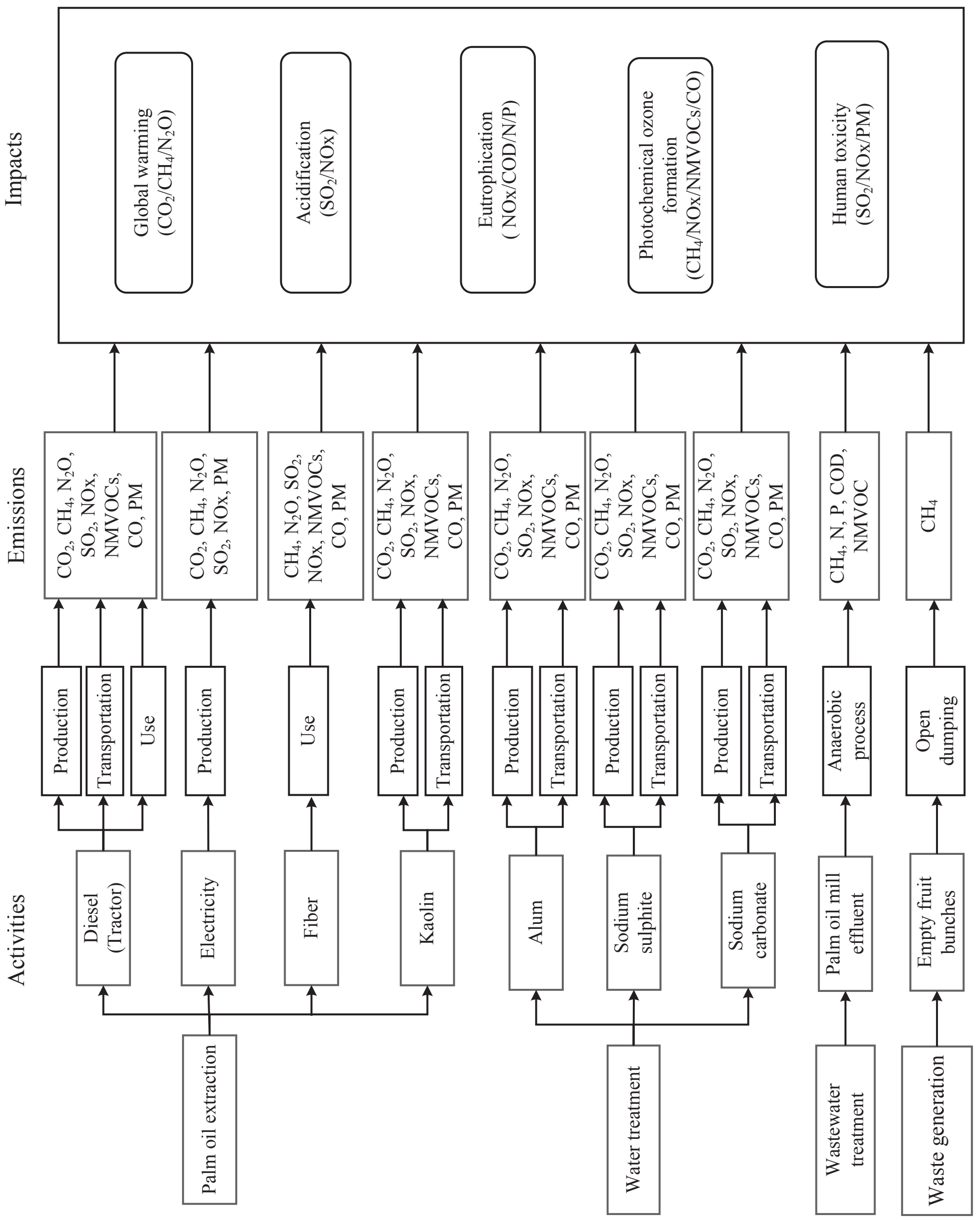
We distinguished between four main sub-units; palm oil extraction, water treatment, wastewater treatment and waste generation considered in the palm oil mill (Figure 3.3b). The oil extraction unit starts with diesel-fueled tractors loading the FFB into the oil extraction processes. During the oil extraction processing, CPO and nuts are generated. CPO is then purified and stored in tanks for sale, while nuts are cracked to produce PK. Kaolin is applied to separate shells from PK. Shells are collected and sold as biomass fuel. PK is further processed in a palm kernel mill to produce palm kernel oil which is outside our system boundary.

Decanter cake, EFB and fibres are waste products from the oil extraction unit. Decanter cakes have a relatively high oil and nutrient content. They are therefore used as a basis for animal feed or organic fertiliser. Apparently, there is no such user of EFB. As a result, large amounts of EFB are openly dumped within the mill area, causing CH_4 emissions. However, some recommendations on EFB utilization can be found in Malaysian literature, but this is not yet widely implemented in the Thai palm oil industry. For instance, Yoshizaki et al. (Yoshizaki et al., 2013) recommended to produce compost from EFBs by combining with POME anaerobic sludge. Besides composting, Chiew and Shimada (2013) revealed that EFBs can possibly be used for ethanol production, methane recovery, briquette production, biomass fuel for combined heat and power plants, medium density fibreboard production, and pulp and paper production. For fibres, they are internally reused in boilers as biomass fuel to internally produce steam and electricity. Electricity from the grid is then only used for starting-up. Biomass fuel could be viewed as carbon neutral since CO_2 emissions are sequestered for biological growth (IPCC, 2006a). Hence, we assumed that CO_2 emissions from burning fibres are neutralized by carbon stored during oil palm cultivation phase.

Large quantities of water are required for the oil extraction processes. Water used in mills is usually pumped from the Tapi River or its branches. This water needs treatment before use in boilers. Aluminum sulphate (Alum), sodium sulphite and sodium carbonate are applied in the water treatment units. Large amounts of POME are generated and treated by a series of open lagoons with potentially high CH_4 emissions. In some cases, treated POME is used as liquid fertiliser by surrounding plantations.



(a) oil palm plantation sub-system



(b) palm oil mill sub-system

Figure 3.3 Activities, pollutants, and potential environmental impacts that are relevant for the palm oil production system.

3.2.3. Data collection

Activity data (Table 3.2) related to the palm oil production system were derived from literature, farmer interviews, and mill visits. For the N-RSPO producers, the farm activity data were estimated from Patthanaissaranukool, et al.(2013) who collected data from 40 famers in the Tapi River basin, whereas the mill activity data was based on four mills studied by Kaewmai et al. (2012). For the P-RSPO and C-RSPO producers, activity data were derived from farmer interviews (10 P-RSPO farmers and 11 C-RSPO farmers), the mill visits (one P-RSPO mill and one C-RSPO mill) in Surat Thani and Krabi provinces, and weighted averages from Kaewmai et al. (2012) (two P-RSPO mills and one C-RSPO mill). We observed that our collected activity data are in the same range as in relevant studies (Bell et al., 2011; Chavalparit et al., 2006; Pleanjai et al., 2009; Pleanjai and Gheewala, 2009).

Due to difficulties in accessing data from mills and plantations, our samples were limited to total of 21 plantations and 2 mills. Nevertheless, our study provides a first comprehensive overview of environmental impacts from oil palm production in Thailand, of the differences in environmental performance between palm oil producers and of the potential for enhancing environmental performance by large scale adoption of best practices in the sector.

3.2.4. Functional unit and allocation

Typically, the palm oil mills produce not only CPO, but also PK as a co-product. In this study, CPO was the main focus as it is a main feedstock for food and biofuel production in Thailand. The functional unit was then set as “1 t CPO”. The production of 1 t CPO generates 293 kg of PK. Some emissions and environmental impacts were allocated to PK on the basis of a mass balance method by using allocation factors (CPO:PK) of 0.75:0.25, 0.77:0.23 and 0.80:0.20 for N-RSPO, P-RSPO and C-RSPO categories, respectively. The environmental impacts of PK production in the Tapi River basin are summarized in Appendix B5.1 and Appendix B5.2.

3.2.5. Mathematical formulation

We developed a model based on systems analysis approaches applied in other studies (Figueirêdo et al., 2012; B. G. Hermann et al., 2007; Jawjit, 2006; Jawjit et al., 2013, 2010, 2007; Neto, 2007; Pluimers, 2001). These studies combine analytical tools, such as a partial life cycle assessment, with scenario analysis to quantify emissions and environmental impacts. We used a similar approach for the palm oil production (Box 1).

In our approach, emissions are a function of activities and emission factors. The various activities in the palm oil production system give rise to several emissions of polluting compounds. To quantify emissions of 1 t FFB and 1 t CPO (Eqs. (3) and (4), Box 1), annual activity data were converted to activities per t FFB and CPO (Eqs. (1) and (2), Box 1). Emission factors ($EF_{\varepsilon,\alpha}$) used for quantifying emissions were mainly derived from internationally accepted sources, such as Intergovernmental Panel on Climate Change (IPCC), European Environment Agency (EEA) and the Eco-invent database (see Table B1 in Appendix B). Where available, Thailand-specific EFs were used. For instance, the EF for CO_2 was taken from data from electricity generation (EGAT, 2011) while EFs for SO_2, NOx and PM were from literature (Krittayakasem et al., 2011). To calculate emissions of the palm oil production system, emissions from oil palm plantations and from palm oil mills were aggregated according to proportion of FFB inputs in the mills (Eq. (5), Box 1). Based on collected data from the mill visits, about one-third of FFB supply in C-RSPO mills were from C-RSPO plantations (32%C-RSPO, 5% P-RSPO and 63% N-RSPO) while P-RSPO mills largely supplied FFB from N-RSPO plantations (95% N-RSPO and 5% from P-RSPO).

To calculate the potential environmental impacts (Eqs. (12), (13) and (14), Box 1), all emissions contributing to a certain environmental impact category were aggregated by using classification factors ($CF_{\mu,\varepsilon}$), which are specific for each potential impact category (Eqs. (9), (10) and (11), Box 1). The emissions of different GHGs, acidifying gases, eutrophying compounds, tropospheric ozone precursors and compounds that are toxic for humans and freshwater ecosystem can be expressed in terms of carbon dioxide equivalents (CO_2-eq), sulfur dioxide equivalent (SO_2-eq), phosphate equivalents (PO_4-eq), ehtylene equivalents (C_2H_4-eq) and chlorodibenzene equivalent ($C_6H_4C_{l2}$-eq), respectively. CFs were from the CML-IA database (CML, 2012), and presented in Table B2 in Appendix B. Next, the potential environmental impacts were multiplied by CPO production capacity ($Cap_{RSPO,Basin}$) for each RSPO category (Eq. (15), Box 1) to calculate the total environmental impacts of palm oil production in the Tapi River basin.

Box 1. Mathematic formulations of the model

Activity level:

$$A_{FFB\,\alpha,RSPO} = A_{\alpha,RSPO} / FFB_{RSPO} \quad (1)$$

$$A_{CPO\,\alpha,RSPO} = A_{\alpha,RSPO} / CPO_{RSPO} \quad (2)$$

Emission:

$$E_{FFB\;\varepsilon,\alpha,RSPO} = A_{FFB\,\alpha,RSPO} \times EF_{\varepsilon,\alpha} \quad (3)$$

$$E_{CPO\;\varepsilon,\alpha,RSPO} = A_{CPO\,\alpha,RSPO} \times EF_{\varepsilon,\alpha} \quad (4)$$

$$E_{Overall\;\varepsilon,\alpha,RSPO} = \sum_{RSPO} (E_{FFB\;\varepsilon,\alpha,RSPO} \times \%\,Source_{RSPO}) + E_{CPO\;\varepsilon,\alpha,RSPO} \quad (5)$$

$$E_{FFB\,\varepsilon,\,RSPO} = \sum_{\alpha} E_{FFB\,\varepsilon,\,\alpha,\,RSPO} \quad (6)$$

$$E_{CPO\,\varepsilon,\,RSPO} = \sum_{\alpha} E_{CPO\,\varepsilon,\,\alpha,\,RSPO} \quad (7)$$

$$E_{Overall\,\varepsilon,\,RSPO} = \sum_{\alpha} E_{Overall\;\varepsilon,\alpha,RSPO} \quad (8)$$

Impact:

$$M_{FFB\,\mu,\varepsilon,RSPO} = E_{FFB\,\varepsilon,RSPO} \times CF_{\mu,\varepsilon} \quad (9)$$

$$M_{CPO\,\mu,\varepsilon,RSPO} = E_{CPO\,\varepsilon,RSPO} \times CF_{\mu,\varepsilon} \quad (10)$$

$$M_{Overall\;\mu,\varepsilon,RSPO} = E_{Overall\;\varepsilon,RSPO} \times CF_{\mu,\varepsilon} \quad (11)$$

$$M_{FFB\,\mu,RSPO} = \sum_{\varepsilon} M_{FFB\,\mu,\varepsilon,RSPO} \quad (12)$$

$$M_{CPO\,\mu,RSPO} = \sum_{\varepsilon} M_{CPO\,\mu,\varepsilon,RSPO} \quad (13)$$

$$M_{Overall\;\mu,RSPO} = \sum_{\varepsilon} M_{Overall\;\mu,\varepsilon,RSPO} \quad (14)$$

$$M_{Basin} = \sum_{\mu} \left(M_{Overall\;\mu,\,RSPO} \times Cap_{RSPO,\,Basin} \right) \quad (15)$$

where:

$RSPO$ = index for RSPO certification scheme: C-RSPO, P-RSPO and N-RSPO

α = index for activity: production, transportation and use of all inputs used in the oil palm plantations (Fig. 3a) and the palm oil mills (Fig. 3b).

ε = index for pollutant emitted: CO_2, CH_4, N_2O, SO_2, NO_x, PO_4^{3-}, NO_3^-, COD, P, N, CO, NMVOCs, PM and glyphosate

μ = index for environmental impact considered: global warming, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater ecotoxicity

$\%\,Source_{RSPO}$ = % source of FFB in relation to $RSPO$

$A_{\alpha,RSPO}$ = level of activity α in relation to $RSPO$ (activity unit/year (y))

$A_{FFB\ \alpha,RSPO}$ = level of activity α for oil palm plantations in relation to $RSPO$ (activity unit/t FFB/y)

$A_{CPO\ \alpha,RSPO}$ = level of activity α for palm oil mills in relation to $RSPO$ (activity unit/ton (t) CPO/y)

$CF_{\mu,\varepsilon}$ = classification factor for impact μ due to emissions of compound ε (impact unit/kg of compound ε)

CPO_{RSPO} = CPO produced in relation to $RSPO$ (t CPO/y)

$Cap_{RSPO,\ Basin}$ = Palm oil mill capacity in relation to $RSPO$ (t CPO/y) in the Tapi River basin;

- N-RSPO = 5,304,000 t CPO/y
- P-RSPO = 2,520,000 t CPO/y
- C-RSPO = 936,000 t CPO/y

$E_{FFB\ \varepsilon,\alpha,RSPO}$ = emission of compound ε due to activity α for oil palm plantations in relation to $RSPO$ (kg pollutant /t FFB/y)

$E_{CPO\ \varepsilon,\alpha,RSPO}$ = emission of compound ε due to activity α for palm oil mills in relation to $RSPO$ (kg pollutant /t CPO/y)

$E_{Overall\ \varepsilon,\alpha,RSPO}$ = emission of compound ε due to activity α for overall palm oil production in relation to $RSPO$ (kg pollutant /t CPO/y)

$E_{FFB\ \varepsilon,\ RSPO}$ = total emission of compound ε for oil palm plantations in relation to $RSPO$ (kg pollutant /t FFB/y)

$E_{CPO\ \varepsilon,\ RSPO}$ = total emission of compound ε for palm oil mills in relation to $RSPO$ (kg pollutant /t CPO/y)

$E_{Overall\ \varepsilon,\ RSPO}$ = total emission of compound ε for overall palm oil production in relation to $RSPO$ (kg pollutant /t CPO/y)

$EF_{\varepsilon,\alpha}$ = emission factor of compound ε related to activity α (g of compound ε /kg of activity α)

FFB_{RSPO} = FFB produced in relation to $RSPO$ (t FFB/y)

$M_{FFB\ \mu,\varepsilon,RSPO}$ = impact μ for emissions of compound ε for oil palm plantations in relation to $RSPO$ (impact unit/t FFB/y)

$M_{CPO\ \mu,\varepsilon,RSPO}$ = impact μ for emissions of compound ε for palm oil mills in relation to $RSPO$ (impact unit/t CPO/y)

$M_{Overall\ \mu,\varepsilon,RSPO}$ = impact μ for emissions of compound ε for overall palm oil production in relation to $RSPO$ (impact unit/t CPO/y)

$M_{FFB\ \mu,RSPO}$ = total environmental impact μ for oil palm plantations in relation to $RSPO$ (impact unit/t FFB/y)

$M_{CPO\ \mu,RSPO}$ = total environmental impact μ for palm oil mills in relation to $RSPO$ (impact unit/t CPO/y)

$M_{Overall\ \mu,RSPO}$ = total environmental impact μ for overall palm oil production in relation to $RSPO$ (impact unit/t CPO/y)

M_{Basin} = total environmental impact from 3 types of $RSPO$ certification scheme in the Tapi River basin (impact unit/basin/y)

3.3. Results and discussion

3.3.1. Activity data

a. Oil palm plantations

Activity data ($A_{FFB\,\alpha,RSPO}$) from farmer interviews were categorized as Non-RSPO (N-RSPO), Potential RSPO certified (P-RSPO) and RSPO certified (C-RSPO) (see Table 3.2). In general, cultivating practices are similar for the three cases, except for weed control. Fertiliser use is in the same range. From interviewing RSPO certified farmers and checking their records, we observed that they were intensively trained on fertiliser management, farm management and integrated pest management (RSPO, 2012; Thongrak and Kiatpathomchai, 2011). This training program was developed to be in line with the RSPO P&C– principle 4 (RSPO, 2010). As a result, C-RSPO plantations used relatively small amount of fertilisers when compared with N-RSPO and P-RSPO plantations because they have learnt to fertilize according to the nutrient requirements of the oil palm . Best-practices of C-RSPO farmers result in a higher productivity (20.5 t FFB/ha) compared to P-RSPO and N-RSPO farmers ((21.2 and 19.2 t FFB/ha, respectively). P-RSPO farmers seem to use relatively high amounts of N-fertiliser (4.3 kg N/t FFB).

The interviewees did not report any use of insecticides. Herbicides (i.e. glyphosate) are applied in the plantations for weed control. Use of glyphosate (0.001 L/t FFB) and gasoline (0.07 L /t FFB) is relatively low in C-RSPO plantations as farmers manually removed weeds and left residues in the field in order to maintain soil moisture (Fairhurst and McLaughlin, 2009). Meanwhile, farmers in N-RSPO plantations used the highest gasoline (0.70 L/t FFB) and glyphosate (0.11 L/t FFB), which may be due to their lacked of knowledge on weed management.

After harvesting FFBs, P-RSPO and C-RSPO plantations directly deliver FFBs to their farming-partner mills as they are close to the mills. Pick-up trucks (carrying capacity 2.5 t) are commonly used for delivering FFBs with an accepted distance not greater than 10 km (4.84 km/t FFB for P-RSPO and 3.13 km/t FFB for C-RSPO). For farmers in N-RSPO plantations, there are two stages of FFB transportation as their plantations are located further away from the mills; (1) farmers deliver FFBs to middlemen (FFB transportation 1) by pick-up truck with a distance of 3.17 km/t FFB and (2) middlemen deliver FFBs to mills (FFB transportation 2). Sansompron (2011) reported that 10-wheel trucks (carrying capacity 25 t) are commonly used to carry FFBs from middlemen to mills with average distance of 50 km (2 km/t FFB).

b. Palm oil mills

Activity data ($A_{CPO\ \alpha, RSPO}$) from the mills are summarized in Table 3.2. C-RSPO mills perform better in terms of energy and resource efficiency and waste management which go well beyond the requirements for RSPO certification – principle 5 (RSPO, 2007). These mills can be seen as best-practice mills.

The oil extraction rate (OER) represents how much CPO can be extracted from the palm fruits. It is therefore commonly used to indicate the performance of the mills. A higher %OER is preferred because of a lesser FFB is needed and a lesser waste is generated. In the P-RSPO mills, %OER is calculated at 16, which is lower than for the other cases (17% for the N-RSPO mills and 18% for the C-RSPO mills). This leads to the highest FFB input (6.44 t FFB) and the highest waste generation (1,376 kg EFB/t CPO, 780 kg fibre/t CPO, and 218 kg decanter cake/t CPO). Technicians in the P-RSPO mills revealed that the price of FFB largely depends on its weight but not its quality so that smallholder farmers seem to neglect the quality of FFB. In addition, poor management by middlemen, such as watering on palm fruits and mixing up with sand, was observed to increase the weight of FFB. Quality of FFB is, therefore, an urgent and important issue that need to be addressed by relevant stakeholders (i.e. farmers, millers, middleman, and government) as it can reduce %OER and, as a result, the waste-related problems (cf. Dallinger (2011)).

For waste management, N-RSPO and P-RSPO mills lack an appropriate management for EFB. They openly dump (uncontrolled landfill condition) EFBs whereas no open dumping of EFBs was observed in C-RSPO mill during the visits. This is because C-RSPO mills are surrounded by large-scale plantations so that they could mulch EFBs in their plantations. Technicians in C-RSPO mills indicated that mulching EFBs in the plantations can result in a reduction of chemical fertiliser use and increase productivity in the long run as some nutrients still remain in EFBs and it keeps the soil moisture and increases soil fertility. This practice is also recommended by Fairhurst and McLaughlin (2009). Nevertheless, this practice is not yet common for N-RSPO and P-RSPO producers. This is because the surrounding plantations are small-scale plantations, owned by smallholder farmers without trucks to carry the EFBs.

For POME treatment, a biogas capture system is used in P-RSPO and C-RSPO mills. Captured biogas is then converted to power so that less electricity from the grid is needed. Electricity use in P-RSPO and C-RSPO mills is slightly less than in N-RSPO mills.

Table 3.2 Summary of the activity data for the oil palm plantations and palm oil mills

Process	Activity	N-RSPO[a,b]	P-RSPO[a,b,c,d]	C-RSPO[a,b,c,d]	Unit
Oil palm plantations					
Soil preparation	Diesel used in tractor	0.20	0.20	0.20	L/t FFB
Fertiliser management	N – Fertiliser	3.90	4.32	3.53	kg N/t FFB
	P - Fertiliser	2.90	2.15	1.31	kg P/t FFB
	K - Fertiliser.	10	8.45	13	kg K/t FFB
	Boron	-	0.38	0.17	kg/t FFB
Weed control	Glyphosate	0.11	0.02	0.001	L/t FFB
	Gasoline	0.70	0.32	0.07	L/t FFB
FFB transportation 1	Average distance	3.17	4.84	3.13	km/trip/t FFB
	Diesel used in pick-up truck	0.30	0.46	0.30	L/t FFB
FFB transportation 2	Average distance	2.00	-	-	km/trip/t FFB
	Total diesel used Truck	9.86	-	-	L/t FFB
Palm oil mills					
Oil extraction	FFB input	5.97	6.44	5.69	t/t CPO
	Diesel used for FFB loading	3.22	3.86	2.31	L/t CPO
	Electricity	3.97	2.93	2.86	kWh/t CPO
	Kaolin	12	15	11	kg/t CPO
Co-product	Palm kernel	336	298	246	kg/t CPO
	Water	4.51	4.81	2.55	m^3/t CPO
Water treatment	Alum	0.09	0.25	0.71	kg/t CPO
	Sodium sulphite	0.08	0.04	0.11	kg/t CPO
	Sodium carbonate	0.09	0.09	0.03	kg/t CPO
Wastewater treatment	Volume	4.55	3.81	3.64	m^3/t CPO
	COD inlet	85	70	70	kg COD/m^3
	COD before biogas Lagoon	-	65	70	kg COD/m^3
	COD after biogas Lagoon	-	11	5.72	kg COD/m^3
	COD outlet	2.13	2.40	1.70	kg COD/m^3
	Total N outlet	0.12	0.37	0.21	kg/m^3
	Phosphorous outlet	0.03	0.03	0.02	kg/m^3
Waste generation	Empty fruit bunch (EFB)	1,251	1,376	1061	kg/t CPO
	Decanter cake	174	218	175	kg/t CPO
	Fibre	549	780	391	kg/t CPO
	Shell	376	328	293	kg/t CPO

a – oil palm planation data were estimated from Patthanaissaranukool, et al.(2013)
b – palm oil mill data were estimated from Kaewmai et al. (2012)
c – oil palm planation data were derived from the farmer interviews
d – palm oil mill data were derived from the mill visits

3.3.2. Emissions from oil palm plantations and palm oil mills

a. Oil palm plantations

Table 3.3 shows emissions of 1 t FFB produced in the plantations ($E_{FFB\,\varepsilon,\,RSPO}$), while detailed emissions of individual compound are summarized in Table B3, Appendix B. We calculated that N-fertilisers play the most important role in the global warming (GW), acidification (AD), eutrophication (EP) and human Toxicity (HT) impacts with contributions of 67–80%, 31–45%, 92–96% and 47–68%, respectively. N_2O emissions from N-fertiliser use and CO_2 emissions from N-fertiliser production are main causes of GW impact. NO_3^- leaching and NOx emissions from N-fertiliser application contribute to EP, AD and HT impacts. Another important source of AD was the P-fertiliser, where SO_2 emissions from P-fertiliser production are predominant, contributing 34–46% of total AD impact. For weed control, gasoline use in weed cutters as it generates NMVOC and CO emissions and causes the Photochemical ozone formation (POF) impact (35–68%). Meanwhile, only the glyphosate use activity alone was considered for quantifying the freshwater eocotoxicity (FE) in this study.

As indicated in section 3.1 above, material inputs to C-RSPO plantations such as fertilisers, glyphosate and gasoline, are lower than in N-RSPO and P-RSPO plantations. This explains the lower emissions and environmental impacts in all categories, in particular for POF and FE. On the other hand, environmental impacts of N-fertiliser use in P-RSPO plantations are slightly higher than in N-RSPO and C-RSPO plantations due to differences in N-fertiliser use (Table 3.1). A majority of C-RSPO farmers remove weeds manually instead of using weed cutters. As a result, their POF impact from gasoline use (6.5 g C_2H_4eq/t FFB) is about 10 times lower than that in N-RSPO plantations (63 g C_2H_4eq/t FFB). For FFB transportation, diesel in N-RSPO plantations (17 g C_2H_4eq/t FFB) create the POF impact about 17 times higher than that in P-RSPO and C-RSPO plantations (about 1 g C_2H_4eq/t FFB). For other impact categories the difference was a factor of 6-10.

By comparing the C-RSPO with N-RSPO plantations, we can confirm that implementing best-practices would reduce emissions and environmental impacts of oil palm plantation by 99% in FE, 80% in POF, 38% in AD, 34% in HT, 21% in GW and 13% in EP.

Table 3.3 Aggregated emissions from oil palm plantation (unit per 1 t FFB).

Potential environmental impacts			Activity							
Impact category	Type of plantation	Total	Soil preparation	Fertiliser management				Weed Control		FFB transportation
			Diesel	N-fertiliser	P-fertiliser	K-fertiliser	Boron	Glyphosate	Gasoline	Diesel
Global Warming (GW) (as kg CO_2eq)	N-RSPO	57	0.07	38	4.62	5.45	-	1.10	1.93	5.37
	P-RSPO	53	0.07	42	3.43	4.43	0.04	0.19	0.89	1.36
	C-RSPO	45	0.07	34	2.09	7.20	0.02	0.01	0.20	0.88
Acidification (AD) (as g SO_2eq)	N-RSPO	235	3.31	73	108	18	-	3.81	3.60	25
	P-RSPO	186	3.31	81	80	15	0.24	0.67	1.67	4.80
	C-RSPO	146	3.31	66	49	24	0.11	0.05	0.37	3.11
Eutrophication (EP) (as g PO_4eq)	N-RSPO	144	0.82	132	2	2.67	-	0.26	0.36	5.95
	P-RSPO	152	0.82	146	1	2.17	0.06	0.05	0.17	1.16
	C-RSPO	125	0.82	119	1	3.53	0.03	0.00	0.04	0.75
Photochemical ozone formation (POF) (as g C_2H_4eq)	N-RSPO	93	0.75	6.55	1.91	2.81	-	0.94	63	17
	P-RSPO	42	0.75	7.24	1.16	2.28	0.04	0.17	29	1.35
	C-RSPO	18	0.75	5.92	0.70	3.71	0.02	0.01	6.46	0.87
Human toxicity (HT) (as g $C_6H_4Cl_2$eq)	N-RSPO	316	8.19	150	44	29	-	3.87	5.16	76
	P-RSPO	245	8.19	166	30	24	1.51	0.68	2.39	13
	C-RSPO	210	8.19	136	18	38	0.67	0.05	0.53	8.39
Freshwater ecotoxicity (FE) (as mg $C_6H_4Cl_2$eq)	N-RSPO	98	-	-	-	-	-	98	-	-
	P-RSPO	17	-	-	-	-	-	17	-	-
	C-RSPO	1.19	-	-	-	-	-	1.19	-	-

b. Palm oil mills

Emissions shown in the Table 3.4 are emissions per 1 t CPO produced in mills ($E_{CPO\,\varepsilon,\,RSPO}$), detailed emissions of individual compound are summarized in Table B4, Appendix B. Burning fibres is a main source of SO_2, NOx, NMVOC, CO and PM emissions, and contributes significantly to AD, EP, POF and HT impacts with contributions of 91-94%, 90-92%, 48-96%, and 94-95%, respectively. The P-RSPO mills generate relatively high volume of fibres. This implies that P-RSPO mills overuse and burn fibres. As a result, they produce larger emissions and environmental impacts than other cases in almost all categories, except for the GW impact. Note that we assumed CO_2 emissions from burning fibres are carbon-neutral, and that we do not include effects of land use change in our analysis.

POME treatment and EFB disposal are the main source of CH_4 emissions that largely contribute to the GW impact. They contribute ranging from 11% up to 87% of the total GW impact, depending on how POME and EFB are managed. In N-RSPO mills, POME is treated by a series of open lagoons under anaerobic condition (without CH_4 capture system) and EFB is openly dumped (uncontrolled anaerobic landfill). This results in great amount of CH_4 emissions (1,186 kg CO_2eq for POME and 1,130 kg CO_2eq for EFB). In P-RSPO mills, POME is treated by a biogas capture lagoon and EFB is openly dumped. As a result, they produce moderate amount of CH_4 emissions (161 kg CO_2eq for POME and 1,276 kg CO_2eq for EFB). The C-RSPO mills manage their POME and EFB in an appropriate way - POME is treated by biogas capture lagoon and EFB is taken back to mulch in the plantations (large-scale plantation). This results in avoiding CH_4 emissions up to 96% for POME treatment and 100% for EFB disposal in C-RSPO relative to N-RSPO mills.

The captured CH_4 (biogas) from POME treatment is used to generate electricity in P-RSPO and C-RSPO mills. Around 95% of generated electricity is exported to the grid and the remaining portion is internally used in the mills. As a result, emissions and environmental impacts of the electricity use in P-RSPO and C-RSPO mills are lower than in N-RSPO mills.

By comparing the C-RSPO with N-RSPO mills, we can confirm that following best-practices would avoid emissions and environmental impacts of palm oil mills by 97% in the GW, 62% in POF, 24% in EP, 24% in HT and 23% in AD.

Table 3.4 Aggregated emissions from crude palm oil mills (per 1 t CPO)

Potential environmental impacts			Activity								
Impact category	Type of mill	Total	Oil extraction				Water treatment			Wastewater treatment	Waste disposal
			Diesel	Electricity	Fibre	Kaolin	Alum	Sodium sulphite	Sodium carbonate	Palm oil mill effluent	Empty fruit bunch
Global Warming (GW) (as kg CO_2eq)	N-RSPO	2,332	0.82	1.94	11	2.17	0.04	0.08	0.07	1,186	1,130
	P-RSPO	1,458	1.00	1.47	16	2.82	0.10	0.05	0.07	161	1,276
	C-RSPO	62	0.62	1.49	8.29	2.06	0.30	0.12	0.03	49	-
Acidification (AD) (as g SO_2eq)	N-RSPO	716	40	3.19	661	8.63	0.59	2.29	0.22	-	-
	P-RSPO	1,030	49	2.42	965	10	1.69	1.28	0.21	-	-
	C-RSPO	552	30	2.45	503	7.55	4.98	3.31	0.09	-	-
Eutrophication (EP) (as g PO_4eq)	N-RSPO	126	10	0.50	114	0.99	0.02	0.02	0.02	0.69	-
	P-RSPO	181	12	0.38	166	1.06	0.05	0.01	0.02	0.85	-
	C-RSPO	96	7.55	0.38	86	0.78	0.14	0.03	0.01	0.57	-
Photochemical ozone formation (POF) (as g C_2H_4eq)	N-RSPO	1,325	9.07	0.18	632	0.70	0.01	0.02	0.10	360	323
	P-RSPO	1,345	11	0.14	922	0.86	0.03	0.01	0.10	46	364
	C-RSPO	502	6.91	0.14	481	0.63	0.10	0.03	0.04	14	-
Human toxicity (HT) (as g $C_6H_4C_{l2}$eq)	N-RSPO	1,934	99	4.75	1,819	11	0.30	0.50	0.22	-	-
	P-RSPO	2,794	122	3.60	2,655	12	0.82	0.27	0.21	-	-
	C-RSPO	1,474	76	3.64	1,383	8.68	2.42	0.70	0.08	-	-

3.3.3. Environmental impacts of the palm oil production

Figure 3.4 presents environmental impacts of overall palm oil production system, including eight groups of activities. The results are shown for CPO produced in three types of mills($M_{Overall\ \mu,RSPO}$), sourcing FFB from different types of plantations as indicated in Table 3.1.The lowest environmental impacts are calculated for CPO produced in C-RSPO mills. The results are most clear for the GW and POF impacts. On the other hand, CPO produced in P-RSPO mills shows the highest impacts on the EP, AD, and HT, mainly as a result of overuse and burn fibres in the palm oil extraction and excessive use of fertilisers in the plantations .

Oil extraction bar, dominated by fibre combustion, has a relatively large share in the HT impact (1,471 – 2,792 g $C_6H_4Cl_2$eq or 56-70% of total HT impact), POF (488 – 935 g C_2H_4eq or 38-62%), and AD (548 – 1,027 g SO_2eq or 36-50%). As indicated in section 3.2.b., P-RSPO mills overuse and burn fibres. As a result, they create larger environmental impacts than other cases.

The fertiliser bar in Figure 3.4 includes environmental impacts associated with N-, P-, K-fertilisers. The use of N-fertilisers is an important contributor to many environmental impact categories. It results in N_2O emissions that cause GW impact (222 – 228 kg CO_2eq), NOx emissions that cause AD (873 – 954 g SO_2eq or 46-59%) and HT (1,025 – 1,055 g $C_6H_4Cl_2$eq or 26-39%), and NO_3^- leaching that contributes to EP (640 – 660 g PO_4^{3-}eq or 77-86%).

Looking at the GW impact, a main contributor is not only N-fertiliser use but also POME treatment and EFB disposal in the mills. N-RSPO mills have a poor management for POME treatment and EFB disposal. They contribute 1,412 kg CO_2eq (47% of total GW impact) and 1,345 kg CO_2eq (45% of total GW impact) to the GW impact, respectively. On the other hand, C-RSPO mills have better management for POME treatment and EFB diposal. GHG emissions only come from open-ponds after biogas capture lagoon, accounting for 59 kg CO_2eq (19% of total GW impact). The N-fertiliser, therefore, becomes the main cause of the GW impact (72% of total GW impact) in C-RSPO mills. The P-RSPO mills have a biogas capture lagoon for POME treatment (192 kg CO_2eq) but they openly dump their EFBs (1,519 kg CO_2eq or 77% of total GW) which leads to substantial CH_4 emisisons. As a result, only 34% of CH_4 emisisons is avoided from biogas capture in P-RSPO mills relative to N-RSPO mills.

The weed control bar includes environmental impacts of glyphosate use and gasoline use in weed cutters in the plantations. The glyshosate use alone contributes to the FE impact while gasoline use largely contributes to the POF impact. In Figure 3.4, C-RSPO mills cause lower environmental impacts on POF and FE as they partly use FFBs from the C-RSPO plantations that apply smaller amounts of gasoline and glyphosate.

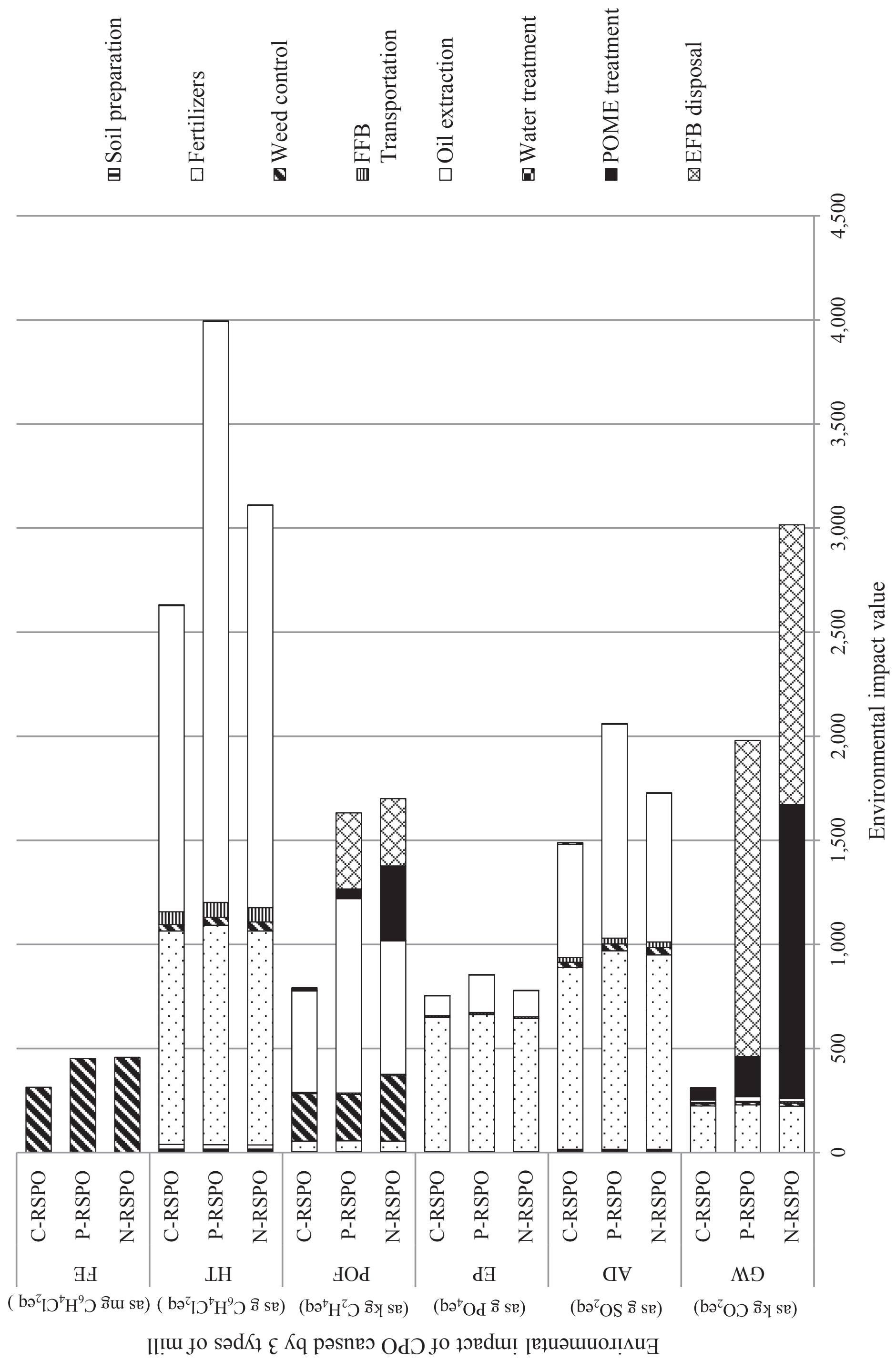


Figure 3.4 Environmental impacts of 1 t CPO produced by three types of mills. Impacts are shown for different groups of activities. See Table 3.1 for description of three types of mill and Figure 3.3 for activities related to the palm oil production.

3.3.4. Environmental impacts of palm oil production in the Tapi River basin

In the Tapi River Basin, currently 8.76 million t CPO is produced (DIT, 2012a, 2012b, 2011), of which 60% in N-RSPO mills, 29% in P-RSPO mills, and 11% in C-RSPO mills (Table 3.5). It should be noted that RSPO certified palm oil production is still limited in Thailand because the majority of oil palm plantations in Thailand are owned by smallholder farmers who lack knowledge and capital to cover for the relatively high costs of RSPO certification (Dallinger, 2011; Teoh, 2006).

Figure 3.5 shows the environmental impacts of palm oil production in the Tapi River basin by these three types of CPO producers (M_{Basin}).CPO produced by N-RSPO mills is dominating in the Tapi River basin. , their environmental impacts are accounted for 58 to 75% of the total environmental impacts. Even though the environmental impacts per t CPO was the lowest for C-RSPO mills (Figure 3.4), their current production capacity in the basin is relatively small. Improving production processes in N-RSPO plantations and mills would lead to a substantial reduction of environmental impacts in the basin. We explored two alternative scenarios to illustrate this: a Modest and an Ambitious Scenario. The scenarios assume an increased number of millers adopting best-practices in line with the mills that we labelled "C-RSPO" (Table 3.5). By increasing the number of C-RSPO mills, we assumed that also the number of C-RSPO plantations will increase as the C-RSPO mills obtain about one-third of their FFB from C-RSPO plantations (Table 3.1). In the Modest Scenario, we assumed that existing P-RSPO mills will follow best-practices of C-RSPO mills and half of existing N-RSPO mills will follow practices of P-RSPO mills. In the Ambitious Scenario, we assumed that all existing mills in the Tape River basin will follow best-practices of C-RSPO mills.

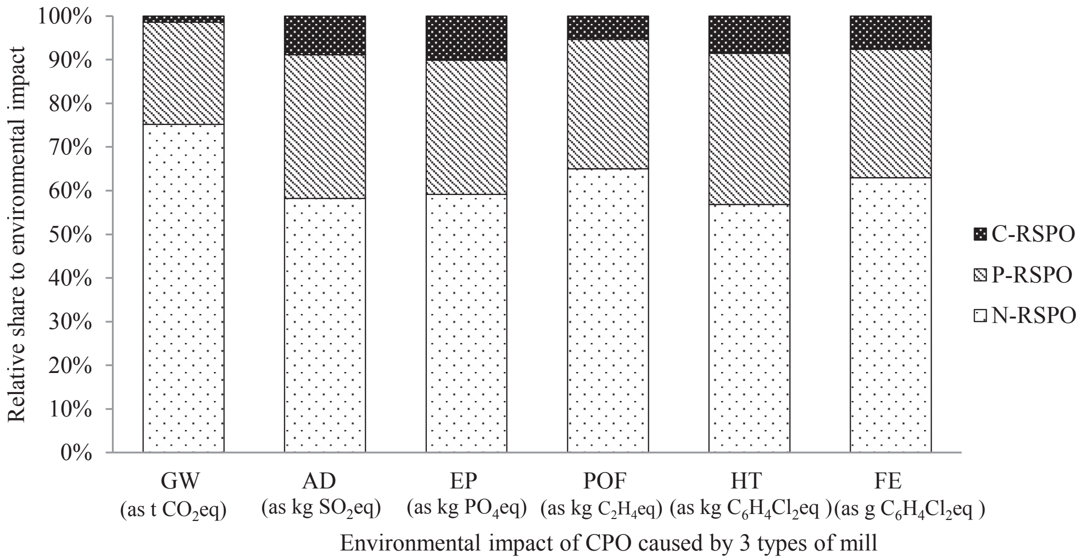


Figure 3.5 Relative share of CPO produced by the N-RSPO, P-RSPO and C-RSPO mills to the current environmental impacts of palm oil production in the Tapi River Basin. See Table 3.1 for description of the three types of mills and Table 3.5 for the production capacities.

Table 3.5 Description of two alternative scenarios

Scenario	N-RSPO	P-RSPO	C-RSPO (Best practice)
Current situation	60% of CPO produced in the basin (5.3 million t/basin).	29% of CPO produced in the basin (2.52 million t/basin).	11% of CPO produced in the basin (0.94 million t/basin).
Alternative scenario: Modest	30% of CPO produced in the basin (2.65 million t/basin).	30% of CPO produced in the basin (2.65 million t/basin).	40% of CPO produced in the basin (3.46 million t/basin).
Alternative scenario: Ambitious	-	-	100% of CPO produced in the basin (8.76 million t/basin).

Our scenario analysis shows that environmental impacts under the alternative scenarios are lower than for the current situation (Figure 3.6). In the Modest Scenario, only the GW and POF impacts are considerably lower (33% and 17%, respectively), while other impact categories are less than 10% lower than the current situation. CPO from P-RSPO mills contributes the highest environmental impacts to AD, EP, and HT, even higher than that in the N-RSPO mills, due to excessive use of N-fertilisers in plantations and overuse of fibres in mills. By assuming that half of existing N-RSPO mills become P-RSPO mills (see different practice of N-RSPO and P-RSPO in Table 3.1) this leads to an increase in environmental impacts. This explains the relatively small decrease in total environmental impacts in the basin for the Modest Scenario.

For the Ambitious Scenario, we calculated relatively a large reduction of environmental impacts for all categories; 87% reduction for GW, 17% for AD, 6% for EP, 50% for POF, 21% for HT, and 29% for FE. By assuming that all mills in the Tapi River basin are adopting the best-practices (in line with current C-RSPO mills), the environmental impacts are greatly reduced.

A question that we did not explore was the causality between RSPO certification and environmental performance. It may be that the most efficient producers that could easily obtain RSPO certification chose to become certified in view of the price premium for RSPO certified CPO. However, it is unsure if a similar environmental improvement would follow from more producers adopting the RSPO standard, since many of the environmental management system applied by best-practice operators are not required by RSPO. In addition, there are other approaches to enhance environmental performance. In Thailand there is another management tool for improving the environmental performance, called Thai Agricultural Standard for Good Agricultural Practice (GAP) for Oil Palm (ACFS, 2010). This standard is not widely implemented because it is not widely known by palm oil buyers and because there are few incentives for farmers to adopt this standard.

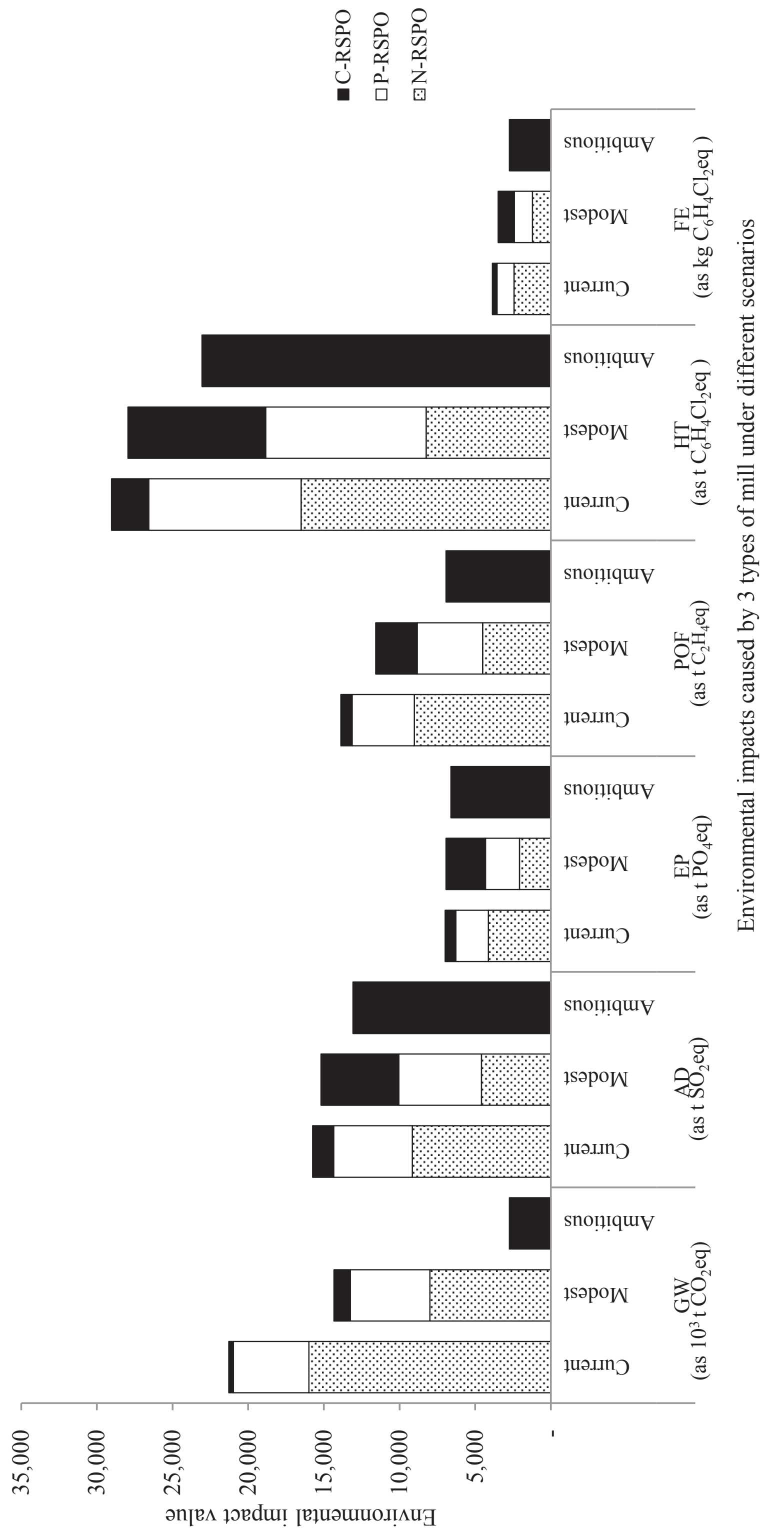


Figure 3.6 Comparative environmental impacts of CPO produced by the N-RSPO, P-RSPO and C-RSPO mills under different scenarios to the Tapi River Basin. See Table 3.1 for description of the three types of mills and Table 3.5 for description of three scenarios.

3.4. Conclusions

To date, only few smallholder farmers and mills have been RSPO certified in Thailand and there is a lack of information on the environmental impacts of CPO production and how these impacts could be reduced by certification. . Our objective was, therefore, to develop an environmental model to quantify the environmental impacts of the palm oil production in the Tapi River basin, Thailand. We considered the effects of different management practices in oil palm plantations and palm oil mills in our analyses; Non-RSPO (N-RSPO), Potential RSPO certified (P-RSPO) and RSPO certified (C-RSPO) palm oil production.

Our results show that there are five activities that contribute most to the environmental impacts of CPO production (Figure 3.4). Burning fibres in the boilers in mills is the main source of SO_2, NOx, NMVOC, CO and PM emissions and causes human toxicity problems (56-70% of the total toxicity impact), photochemical ozone formation (38-62%), and acidification (36-50%). The use of fertilisers in plantations is the main source of N_2O, NOx, NO_3^- and SO_2 emissions and causes global warming (upto 72%), eutrophication (77-86%), acidification (46-59%), and human toxicity (26-39%). Furthermore, wastewater treatment and empty-fruit-bunch disposal in mills are a main source of CH_4 emissions and cause global warming, with up to 47% and 45% of total global warming impact, respectively. Next, gasoline use in weed cutters is the main source of CO and NMVOC emissions and causes photochemical ozone formation (14-29%). Finally, glyphosate use for weed control leads to freshwater ecotoxicity problems.

Next, we compared environmental impacts of CPO produced from C-RSPO mills, P-RSPO mills and N-RSPO mills. Of these three types, the C-RSPO mills cause the lowest environmental impacts for all impact categories, especially for global warming and photochemical ozone formation. This results from best-practices in CPO production: efficient use of fertilisers, good quality of oil palm fruit for palm oil processing, and good waste management in mills. Implementing best-practices in the N-RSPO production chain would avoid 90% of the global warming, 14% of acidification, 3% of eutrophication, 53% of photochemical ozone formation, 15% of human toxicity and 32% of freshwater ecotoxicity problems caused by palm oil production (see Figure 3.4).

Most of environmental impacts of palm oil production for an entire Tapi River basin (Figure 3.5) are coming from CPO production in N-RSPO mills which are larger in number and have poor environmental performance. They contribute to 58-75% of the environmental impacts in the basin, followed by the P-RSPO (23 – 34%) and C-RSPO (≤10%) mills. We explored two alternative scenarios assuming that more mills in the Tapi River basin would adopt the best-practices that are currently applied by the group that we named "C-RSPO" (Table 3.5). In these scenarios, substantial improvements in environmental pressures on the basin are achieved.

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Chapter 4

Options to reduce environmental impacts of palm oil production in Thailand

4. OPTIONS TO REDUCE ENVIRONMENTAL IMPACTS OF PALM OIL PRODUCTION IN THAILAND

Abstract

There is an increasing demand for palm oil worldwide. In Thailand, oil palm is being promoted by the government but this expansion is associated with several environmental impacts. We identified 26 options for reducing the environmental impact of palm oil production in Thailand, and assessed their cost-effectiveness. Our analysis includes measures that can be taken in plantations as well as in palm oil mills. We analysed the effects of the options in terms of reducing greenhouse gas emissions, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater ecotoxicity. Our analysis shows that *empty fruit bunch (EFB) combustion, wet scrubbers* and *pre-heating fibre* are the most effective in reducing multiple impacts. Among these, *EFB combustion* results in the largest environmental improvement, but at relatively high costs. Several options are found to be not only effective, but also generate a positive net return. These include *cover crops, harvesting ripe fruits, mulching EFB, EFB composting, EFB pellets production, oil loss recovery from decanter cake* and *pre-heating fibre.* The most paying options are *mulching EFB, harvesting ripe fruits and cover crops*. Our results are relevant for the promotion of more environmental friendly oil palm production in Thailand.

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4.1. Introduction

Palm oil is a feedstock for food and biofuel. As a result, global demand for palm oil has been increasing; global palm oil production has more than doubled since 2005 (FAOSTAT, 2013). Also in Thailand the government promotes palm oil including for biofuel production (DEDE, 2012a). The production of palm oil, however, contributes to environmental problems, such as biodiversity loss and pollution caused by emissions of nutrients, air pollutants and greenhouse gases from plantations and palm oil mills (Saswattecha et al., 2015a, 2015b). This has led to a debate about whether and how palm oil can be sustainably produced.

In recent years, several options to reduce pollution have been introduced in the palm oil industry. Mostly, these are options to reduce greenhouse gas emissions. An example of this is biogas production from palm oil mill effluent (POME) (Kaewmai et al., 2013b; Pattanapongchai and Limmeechokchai, 2011; Poh and Chong, 2009). Other examples include conversion of empty fruit bunches (EFB) to biocomposts (Schuchardt et al., 2008, 2002) and power generation from EFB combustion (Arrieta et al., 2007; Chiew and Shimada, 2013; Patthanaissaranukool et al., 2013). However, options to reduce other environmental impacts, such as acidification and eutrophication, are not well studied. Moreover, studies on the cost-effectiveness of these options are scarce.

The purpose of this study is to identify options for reducing the environmental impacts of palm oil production in Thailand, and to assess the cost-effectiveness of these options. Thailand is selected as a case study because it is the third largest palm oil producer worldwide. Therefore, improving palm oil production in Thailand may have important implications. This will lead to an overview of cost-effective environmental improvement options for the palm oil industry in Thailand. We focused on environmental impacts caused by emissions of pollutants from existing oil palm plantations and oil palm mills. Land use change aspects are not considered in our paper. We focused on measures that can be taken at the level of individual mills or plantations (but see for instance Saswattecha et al., (2016) for more information on land use change impacts of oil palm production in Thailand). Our analysis can assist the palm oil sector to improve production processes in plantations and mills.

4.2. Methodology

4.2.1. Palm oil production in Thailand

Palm oil production includes two sub-systems: oil palm plantations and palm oil mills (Figure 4.1).

Oil palm plantations

To cultivate oil palm, land needs to be prepared by levelling, ploughing and digging holes for planting seedlings. Fertilisers are generally applied. Usually no insecticides are used, but herbicides such as glyphosate are used in the plantations for weed control. Fresh fruit bunches (FFB) can be harvested every 15-20 days and are delivered to palm oil mills to extract crude palm oil (CPO).

Palm oil mills

The oil extraction includes FFB unloading, sterilization, threshing, fruit digestion, pressing, purification and CPO storage. Besides CPO, palm kernel (PK) is produced as a co-product and further processed in the palm kernel mill (not considered in our study). Water use is high in palm oil extraction, and about 60% of the water ends up in POME (Kaewmai et al., 2012; Patthanaissaranukool et al., 2013). POME is typically treated by a series of open lagoons which emit relatively large amounts of methane (CH_4). This is particularly the case in small-scale palm oil mills (with a capacity of <45 ton FFB/hr). In recent years, biogas capture systems, reducing CH_4 emissions, have become more feasible and affordable. These are often applied in medium-scale (capacity 45-60 ton FFB/hr) and large-scale (capacity > 60 ton FFB/hr) palm oil mills. An estimated 60% of all mills in Thailand currently apply biogas capture systems.

Solid waste generated by palm oil mills includes shells, decanter cake, EFB and fibre. In the following, we describe the typical waste management in Thai palm oil mills.

Shells (high heating value) and *decanter cake* (high nutrient content) are usually sold to other factories as fuel and animal feed, respectively.

EFB is only partly used. About 40% of the EFB produced in Thailand is dumped in the open air and not used (DEDE, 2012b). Many studies recommend to use EFB as a feedstock for: mulching (Heriansyah, 2011; Schuchardt et al., 2008; Vries, 2012; Yoshizaki et al., 2013), composting for mushroom cultivation (Sudirman et al., 2011), biogas production (DEDE, 2007), power generation (ABO, 2010; Chavalparit et al., 2006; DEDE, 2007; Patthanaissaranukool et al., 2013) producing pellets (Reeb et al., 2014; TÜV NORD CERT GmbH, 2012). Approximately one-third of EFB is used for mulching in plantations, while almost 30% is used for combustion and mushroom cultivation (estimated from Papong et al. (2004) and DEDE (2012b)).

Fibre is internally used in boilers to produce steam for sterilization. Note that water used in boilers is often from rivers and needs to be treated before use.

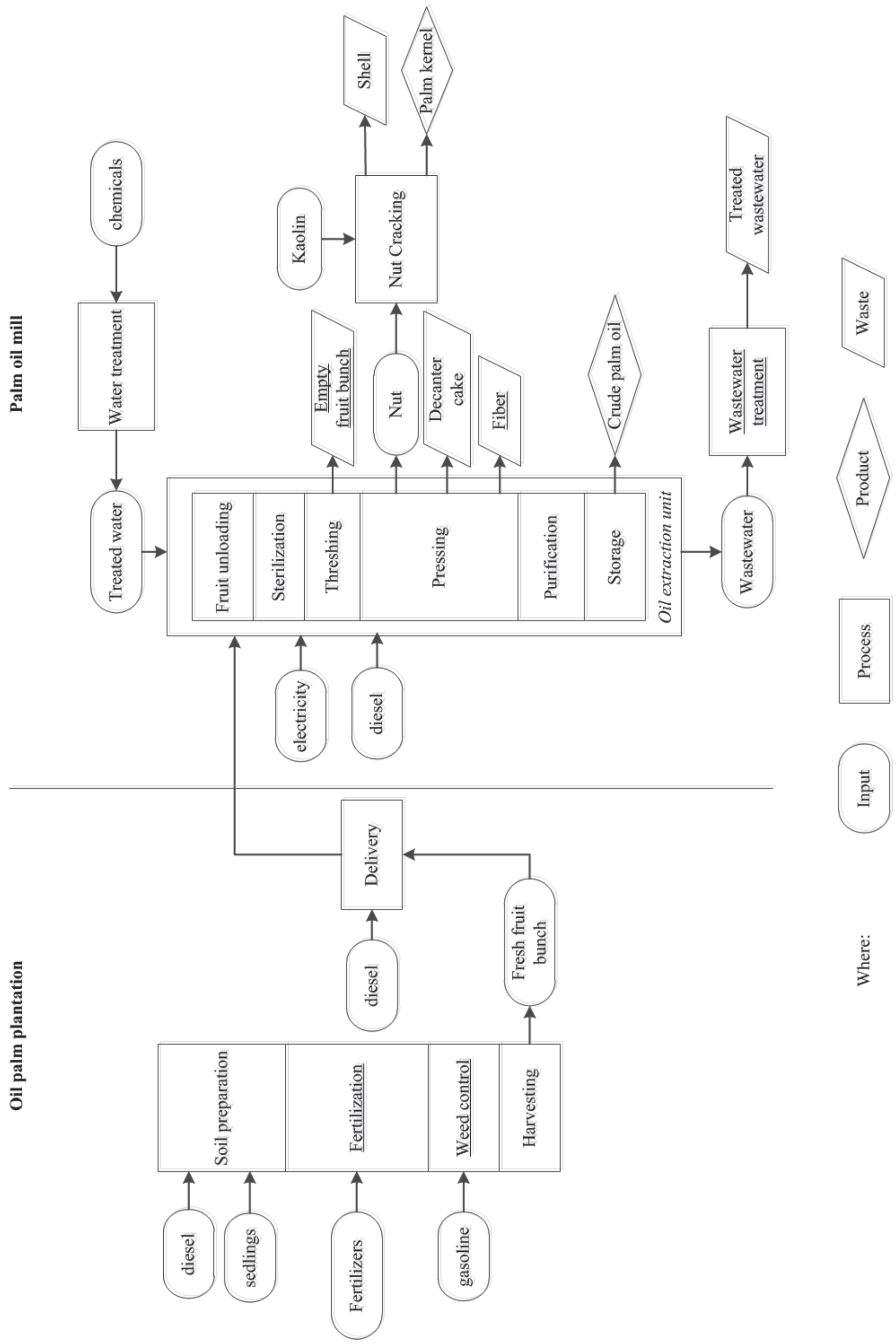

Figure 4.1 Process diagram of palm oil production underlying this study. Underlined are the main causes of environmental problems (Saswattecha et al. (2015b)).

4.2.2. Model description

In an earlier study, we developed a model to assess the environmental impact of palm oil production in the Tapi river basin in Thailand (Saswattecha et al., 2015b). Here we used this model to assess the effects of options to reduce environmental impacts for Thailand as a whole. Six environmental impact categories are analysed in the model; global warming potential (GWP), acidification (AD), eutrophication potential (EP), photochemical ozone formation (POF), human toxicity (HT) and freshwater ecotoxicity (FE). In our earlier study (Saswattecha et al., 2015b), emissions and environmental impacts of palm oil production were identified. We assumed that activities that contribute at least 85% of total emissions of palm oil production are significant sources of emissions and must be managed. These selected activities are presented in Table 4.1. We identified options to reduce these environmental impacts. We quantified their effectiveness to reduce environmental impact, and their cost-effectiveness (see section 2.2.2).

4.2.2.1.Model equations

Model equations are modified from our previous study (2015b) and Jawjit et al. (2007), as presented in Box 1. Options are affecting either activity levels ($rf_{\alpha, i}$) or emission factors ($rf_{\varepsilon,\alpha, i}$) or yield ($if_{y,\alpha, i}$) (see Table C1-C3, Appendix C). Activity levels (A_{α}) depend on options (Eq 2, Box 1) while emissions depend on activities, emission factors and reduction factors of options (Eq 3, Box 1). Some options improve yields (Eq 1, Box 1) and other options release emissions of other pollutants as well as a side-effect when applied (Eq 4, Box 1). For instance, applying selective catalytic reduction and selective non-catalytic reduction for nitrogen oxides (NOx) control increase nitrous oxide (N_2O) emissions by 10-20% of NOx reduced (Kim, 2013; Martín et al., 2007). Next, we summed emissions from relevant activities and emissions released as side-effect to estimate total emissions (Eq 5, Box 1). To calculate the potential environmental impacts, emissions were aggregated by using classification factors ($CF_{\mu,\varepsilon}$), which are specific for each potential impact category (Eqs. 6 and 7, Box 1).

The total annual costs *(C)* of options is a function of investment cost (CI_i), operating cost (CO_i) and variable cost (CV_i) (Eqs 8-11, Box 1). In CI_i , the interest rate (q) and lifetime of reduction option (LT_i) are considered. Detailed information on CI_i , CO_i , CV_i and lifetimes of reduction options are provided in Table C1 and C2 (Appendix C). For the interest rate, we used an annual average of minimum retail rates in 2015 (6.5%) from the Krungthai bank (BOT, 2016). Operating costs may include maintenance and administrative costs. Variable costs are a function of Y and A_{α} in the reference case as explained below. We accounted for possible increases and decreases in production and costs of activities when reduction options are applied.

Some options generate additional income through yield improvement or selling additional products. For instance, biogas capture systems (to produce electricity from CH_4) can generate income from selling electricity to the grid. We accounted for such co-benefits through CV_i. In some cases, the benefits exceed the costs of implementation of options. In such cases *C* is negative. We considered options with a negative value of *C* as "paying" options.

Next, we calculated the cost-effectiveness ($CE_{i,M\mu}$) of options (Eq 12, Box1), i.e. the costs per avoided unit of environmental impact. Options that reduce the environmental impact by less than 5% relative to the reference case are not included in the cost-effectiveness analysis.

Table 4.1 Overview of activities in palm oil production that contribute most to the different environmental impact categories. The table lists options that explain at least 85% of the environmental impacts (based on Saswattecha et al. (2015b)).

Environmental impact	Sub-system	Activities	Pollutants	Relative share in total emission (%)***
Global warming potential (GWP)	Plantations	Fertilisers *- N-fertiliser use*	 N_2O	 3%
	Mills	POME treatment EFB treatment	CH_4 CH_4	47% 45%
Acidification (AD)	Plantations	Fertilisers *P-fertiliser production** *N-fertiliser use* *N-fertiliser production**	 SO_2 and NOx NOx SO_2	 29% (27% of SO_2 and 2% of NOx) 13% 6%
	Mills	Burning fibre	NOx and SO_2	38% (25% of NOx and 13% of SO_2)
Eutrophication (EP)	Plantations	Fertilisers *- N-fertiliser use*	 NO_3^- and NOx	 78% (70% of NO_3^- and 8% of NOx)
	Mills	Burning fibre	NOx	15%
Photochemical ozone formation (POF)	Plantations	Weed control *- Gasoline use*	NMVOC and CO	18% (15% of NMVOC and 3% of CO)
	Mills	Burning fibre POME treatment EFB treatment	NMVOC, CO and NOx CH_4 CH_4	37% (21% of NMVOC, 15% of CO and 1% of NOx) 21% 19%
Human toxicity (HT)	Plantations	Fertilisers *N-fertiliser use* *P-fertiliser production** *N-fertiliser production**	 NOx NOx, PM and SO_2 NOx and PM	 18% 6% (2.5% of NOx, 2% of PM and 1.5% of SO_2) 5% (3% of NOx and 2% of PM)
	Mills	Burning fibre	NOx and PM	58% (34% of NOx and 24% of PM)
Freshwater ecotoxicity (FE)	Plantations	Weed control *- Glyphosate use***	 Glyphosate	 100%

* *Environmental impact of the production of fertilisers is not considered in this study.*
** *Glyphosate is commonly used in Thai oil palm cultivation. We did not consider other herbicides.*
*** *These figures are derived from the Non-RSPO certified case in our early study* (Saswattecha et al., 2015b).

Box 1. Mathematic formulations

Yield: $Y_i = Y_{ref} \times (1 + if_{y,i})$ (1)

Activity: $A_\alpha = A_{ref,\alpha} \times (1 - rf_{\alpha,i})$ (2)

Emission: $E_{\varepsilon,\alpha} = A_\alpha \times EF_{\varepsilon,\alpha} \times (1 - rf_{\varepsilon,\alpha,i})$ (3)

$ES_{\varepsilon,i,\alpha} = A_\alpha \times EFS_{\varepsilon,i,\alpha}$ (4)

$E_\varepsilon = \sum_\alpha E_{\varepsilon,\alpha} + \sum_\alpha ES_{\varepsilon,i,\alpha}$ (5)

Impact: $M_{\mu,\varepsilon} = E_\varepsilon \times CF_{\mu,\varepsilon}$ (6)

$M_\mu = \sum_\varepsilon M_{\mu,\varepsilon}$ (7)

Cost: $C = \sum_{i \in n} (CI_i + CO_i) + CV_i$ (8)

$CI_i = I_i \times q / [1 - (1+q)^{-LTi}]$ (9)

$CO_i = I_i \times f_i$ (10)

$CV_i = (Y_{ref} - Y_i) \times P + \sum_\alpha (A_\alpha - A_{ref,\alpha}) \times P_\alpha$ (11)

Cost-Effectiveness: $CE_{i,M\mu} = \dfrac{C_i}{M_{\mu,ref} - M_\mu}$ (12)

where:

α	=	index for activity: production, transportation and use of all inputs used in the oil palm plantations and the palm oil mills.
ε	=	index for pollutant emitted: CO_2, CH_4, N_2O, SO_2, NO_x, PO_4^{3-}, NO_3^-, COD, P, N, CO, NMVOCs, PM and glyphosate
μ	=	index for environmental impact considered: global warming, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater ecotoxicity
i	=	index for reduction option
ref	=	reference case assuming no yield improvement and reduction options are applied
A_α	=	level of activity α in alternative cases (activity unit/ton CPO/year)
$A_{ref\ \alpha}$	=	level of activity α in the reference case (activity unit/ ton CPO/year)
C	=	total annual cost of reduction options ($/ton CPO/year)
C_i	=	annual cost of reduction option i ($/ton CPO/year)
$CE_{i,M\mu}$	=	Cost-effectiveness of option i for specific environmental impact ($/ton impact avoided/ton CPO/year)
$CF_{\mu,\varepsilon}$	=	classification factor for impact μ due to emissions of compound ε (impact unit/kg of compound ε)
CI_i	=	annual investment costs of reduction options ($/ton CPO/year)
CO_i	=	annual operation and maintenance costs of reduction options ($/ton CPO/year)
CV	=	variable costs of all applied reduction options ($/ton CPO/year)
E_ε	=	total emission of compound ε in alternative cases (kg pollutant / ton CPO /year)

$E_{\varepsilon,\alpha}$	=	emission of compound ε due to activity α in alternative cases (kg pollutant /ton CPO/year)
$EF_{\varepsilon,\alpha}$	=	emission factor of compound ε related to activity α (g of compound ε /kg of activity α)
$EFS_{\varepsilon,i,\alpha}$	=	emission factor of compound ε released as side-effect of the application of reduction option i aimed to reduce emission of another compound
$ES_{\varepsilon,i,\alpha}$	=	emission of compound ε released as side-effect of the application of reduction option i aimed to reduce emission of another compound
I_i	=	investment cost of reduction option i
$if_{y,i}$	=	yield increase factor by reduction option i (fraction)
LT_i	=	lifetime of reduction option i (year)
M_{μ}	=	total impact μ in alternative cases (impact unit/ton CPO/year)
$M_{\mu,\varepsilon}$	=	impact μ for emission of compound ε in alternative cases (impact unit/ton CPO/year)
$M_{\mu,ref}$	=	total impact μ in the reference case (as ton CO_2eq, SO_2eq, PO_4^{3-} eq, C_2H_4 eq, $C_6H_4Cl_2$ eq)
P	=	price of product (FFB or CPO) ($ / kg product)
P_{α}	=	price of activity α ($ / activity unit)
q	=	interest rate (% /100 /year)
f_i	=	fixed percentage of investment in maintenance of reduction option i (fraction)
$rf_{\alpha,i}$	=	reduction factor for activity α by reduction option i (fraction)
$rf_{\varepsilon,\alpha,i}$	=	reduction factor for emission ε due to activity α by option i (fraction)
Y_i	=	yield after application of option i (yield unit/year)
Y_{ref}	=	yield in the reference situation (yield unit/ year)

4.2.2.2. Reference case

The effects of environmental improvement options are quantified relative to a reference case. We defined this reference as a situation in which none of the proposed options to reduce environmental impact are implemented. Details on management practices and activity data of palm oil production in the reference case are presented in Table 4.2.

Table 4.2 Management practices and activities in palm oil production in the reference case (based on Saswattecha et al. (2015b)).

Process	Management practice	Activity	Amount*	Unit
Oil palm plantations				
Soil preparation	Land is prepared by using a tractor/macro	Diesel used in tractor	0.20	L/ton FFB
Fertiliser management	Fertilisers are applied according to available budget	N – Fertiliser	3.90	kg N/ton FFB
		P - Fertiliser	2.90	kg P/ton FFB
		K - Fertiliser.	10	kg K/ton FFB
Weed control	Weeds are removed using herbicides and a weed cutter	Glyphosate	0.11	L/ton FFB
		Gasoline	0.70	L/ton FFB
FFB transportation 1	Harvested FFB is transported from oil palm plantations to collecting sites by farmers or middlemen using a pick-up truck	Average distance	3.17	km/trip/ton FFB
		Diesel used in pick-up truck	0.30	L/ton FFB
FFB transportation 2	Collected FFB is delivered from collecting sites to palm oil mills by middlemen using a 10-wheel truck	Average distance	2.00	km/trip/ton FFB
		Total diesel used Truck	9.86	L/ton FFB
*Palm oil mills***				
Oil extraction	None of oil recovery measure is implemented	FFB input	5.97	ton/ton CPO
		Diesel used for FFB loading	3.22	L/ton CPO
		Electricity	3.97	kWh/ton CPO
		Kaolin	12	kg/ton CPO
Water treatment	Treating water before using in the boiler	Water	4.51	m^3/ton CPO
		Alum	0.09	kg/ton CPO
		Sodium sulphite	0.08	kg/ton CPO
		Sodium carbonate	0.09	kg/ton CPO
Wastewater treatment	Anaerobic open ponds	Volume	4.55	m^3/ton CPO
		COD inlet	85	kg COD/m^3
		COD outlet	2.13	kg COD/m^3
		Total N outlet	0.12	kg/m^3
		Phosphorous outlet	0.03	kg/m^3
Solid waste	Open dumping	Empty fruit bunch	1,251	kg/ton CPO
	Sell as animal feed	Decanter cake	174	kg/ton CPO
	Burn in boilers (internal reuse)	Fibre	549	kg/ton CPO
	Sell as biomass	Shell	376	kg/ton CPO

* *This is derived from non-RSPO certified (N-RSPO) case in the study of Saswattecha et al.* (2015b). *We selected the N-RSPO case most CPO is produced as in N-RSPO in the Tapi river basin as well as for Thailand.*

** *Besides crude palm oil (CPO), the palm oil mills produce palm kernel as a co-product: 336 kg/ton CPO.*

4.3. Options to reduce the environmental impact

4.3.1. Effectiveness of options

The most important sources of emissions are fertiliser use, weed control, burning fibre, POME treatment and EFB treatment (Table 4.1). In total, 26 options in 11 groups are analysed. Table 4.3 shows an overview of these options. Details on these options (e.g. descriptions and reduction factors) are provided in Appendix C (Tables C1- C3).

Table 4.3 Summary of options to reduce emissions and environmental impacts of palm oil production in Thailand.

Group	Option	Description	Primary Effect		Side-effect		Reference
			Level	Effect	Level	Effect	
Oil palm plantations							
Optimising fertilisers use	Apply optimum dose of fertilisers	Fertilisers are applied according to crop demand.	Activity	Reduce N-fertiliser	-	-	Kroeze and Mosier (2000)
	Apply slow-release fertilisers	Reducing nutrient input by using slow-release fertilisers.			-	-	
FFB yield improvement	Harvesting ripe fruits	Harvesting FFB when it is ripe.	Yield	Increase FFB	-	-	AgriSource (2005)
Weed control	Cover crops	Weed suppression by planting cover crops in between sods.	Activity	Reduce glyphosate and gasoline	Yield	Increase FFB	Samedani et al.(2014)
Palm oil mills							
POME treatment	Biogas capture system	Converting open lagoons into biogas capture systems.	Emission	Reduce CH_4	-	-	Kaewmai et al. (2013b)

Group	Option	Description	Primary Effect		Side-effect		Reference
			Level	Effect	Level	Effect	
	Bioreactor plus upgrading biogas plant	Converting open lagoons into bioreactor equipped with upgrading biogas unit where the CH_4 content of biogas is increased, and other gases (e.g. H_2S, CO_2, and H_2O) are removed.			-	-	Pattanapongchai and Limmeechokchai (2011)
EFB treatment	Mulching EFB	A single-layer pile of EFB is placed in the inter-rows.	Activity	Avoid untreated EFB	Activity	Reduce fertilisers use	Heriansyah (2011)
					Yield	Increase FFB	
					Emission	Increase N_2O, NOx and NO_3^-	
	EFB composting plant	EFB is chopped into smaller pieces and piled up to heaps for composting. Then, POME is added to chopped EFB in open windrows which are turned regularly by a turning machine.			-	-	Schuchardt et al. (2008, 2002), Singh et al. (2010) and Stichnothe and Schuchardt (2011)
	EFB combustion	EFB is combusted in a direct-fired power generator to produce electricity which is sold to the grid.			Emission	Avoid NOx and SO_2	ABO (2010), Arrieta et al. (2007), Chiew and Shimada (2013) and Patthanaissaranukool et al. (2013)
						Increase CO, VOC and PM	
	EFB pellets production	EFB is converted to solid pieces that can be used as a biofuel.			-	-	Chavalparit et al. (2006) and Chiew and Shimada (2013).

Group	Option	Description	Primary Effect		Side-effect		Reference
			Level	Effect	Level	Effect	
	EFB ethanol production	Cellulose and hemicellulose in EFB are converted ethanol.			-	-	Chiew and Shimada (2013), Piarpuza¡n et al. (2011) and Tan et al. (2010)
	EFB gasification	Biomass in EFB is converted to gaseous fuel in a fluidized bed biomass gasifier.			Emission	Increase PM	Asadullah (2014), Lahijani and Zainal (2011a), Mohammed et al. (2011a, 2011b) and Ogi et al. (2013)
NOx control for fibre combustion	Low-NOx burner	Decreasing the air in the primary combustion zone to avoid NOx formation.	Emission	Remove NOx	-	-	EPA (1999), Trozzi et al. (2013) and US-DOE (1996)
	Selective catalytic reduction	Injection of ammonia in the flue gas. The mixture of ammonia and flue gas passes through a catalyst where the NOx are converted to dinitrogen and water vapour.			Emission	Increase N_2O	EPA (2003a) and Trozzi et al. (2013)
	Selective non-catalytic reduction	Injection of ammonia or urea in the flue gas to convert NOx into dinitrogen and water vapour without use of catalyst.					EPA (2003b) and Trozzi et al. (2013)
	Non-thermal plasma	A process that uses ozone to reduce pollutants in a reaction chamber.			-	-	EPA (2005a, 2005b, 1999)
SO_2 control for fibre combustion	Wet scrubber	Flue gas is flowed upward and contacted with limestone droplets in a chamber. Limestone converts NOx and SO_2 to form calcium sulphate and ammonium nitrate.		Remove SO_2	Emission	Reduce PM, NOx and VOC	EPA (2003c) and Trozzi et al. (2013)
VOC control for fibre combustion	Thermal incinerator	VOC is oxidized and converted to CO_2 and water using high temperature at sufficient time to reach a complete combustion stage.		Remove VOC	Emission	Reduce PM and CO	EMIS (2015) and EPA (2003d)

Group	Option	Description	Primary Effect		Side-effect		Reference
			Level	Effect	Level	Effect	
PM control for fibre combustion	Cyclones	PM is removed by centrifugal and inertial forces.		Remove PM	-	-	EPA (2003e).
	Baghouse	PM is passing through a tightly woven fabric. This causes PM to be collected on the fabric.			-	-	EPA (2003f)
	Electrostatic precipitator	PM is given an electrical charge by electrodes and forced to the collector walls. Then, collectors are knocked to dislodge PM to be collected.			-	-	EPA (2003g)
Boiler efficiency improvement	Pre-heating fibre	Fibre is transported on a belt while the hot drying gas (mixture of flue gas and air) is passing by to dry the fibre. Combustion temperature are now optimized and fibre consumption will be decreased.	Activity	Reduce burning fibre	-	-	DEDE (2007)
Oil extraction improvement	Oil recovery from decanter cake	Oil loss in decanter cake is recovered by adjustment of decanter inlet feed-rate and sludge density and temperature.	Yield	Increase CPO	-	-	(DEDE, 2006).
	Oil recovery from fibre	Oil loss in decanter cake is recovered by adjustment of equipment operation & control.			-	-	(DEDE, 2006)
	Oil recovery from POME	Oil loss in POME is recovered by improvement operational efficiency of sludge handling in the settling tank (i.e. feed-rate and temperature adjustment).			-	-	(DEDE, 2006)
	Oil recovery from EFB	EFB is first chopped and then pressed to recover the oil loss through EFB shredder and EFB press. Pressed EFB is ready to use as fuel.			Yield	Increase palm kernel	(DEDE, 2006)

4.3.1.1. Options to reduce greenhouse gas (GHG) emissions

We identified 17 options to reduce GHG emissions in oil palm mills. Of these, nine options primarily aim at reducing GHG emissions while other options aim to reduce other pollutants or increase yields. On the other hand, *Selective catalytic reduction* and *Selective non-catalytic reduction*, meant to reduce NOx emissions, lead to an increase in N_2O emissions as a side-effect. However, these emissions of N_2O are small and account for less than 1% of the total GHG emissions in the reference case.

The options in the group of EFB management are most effective in reducing GHG emissions (Figure 4.2). They result in reductions ranging between 27% and 85% relative to the reference case. Among these options, EFB combustion is found to be the most effective. Also *Biogas capture systems* (23%) and *Bioreactors plus upgrading biogas plants* (23%) are highly effective. These options can avoid CH_4 emissions from untreated EFB and POME.

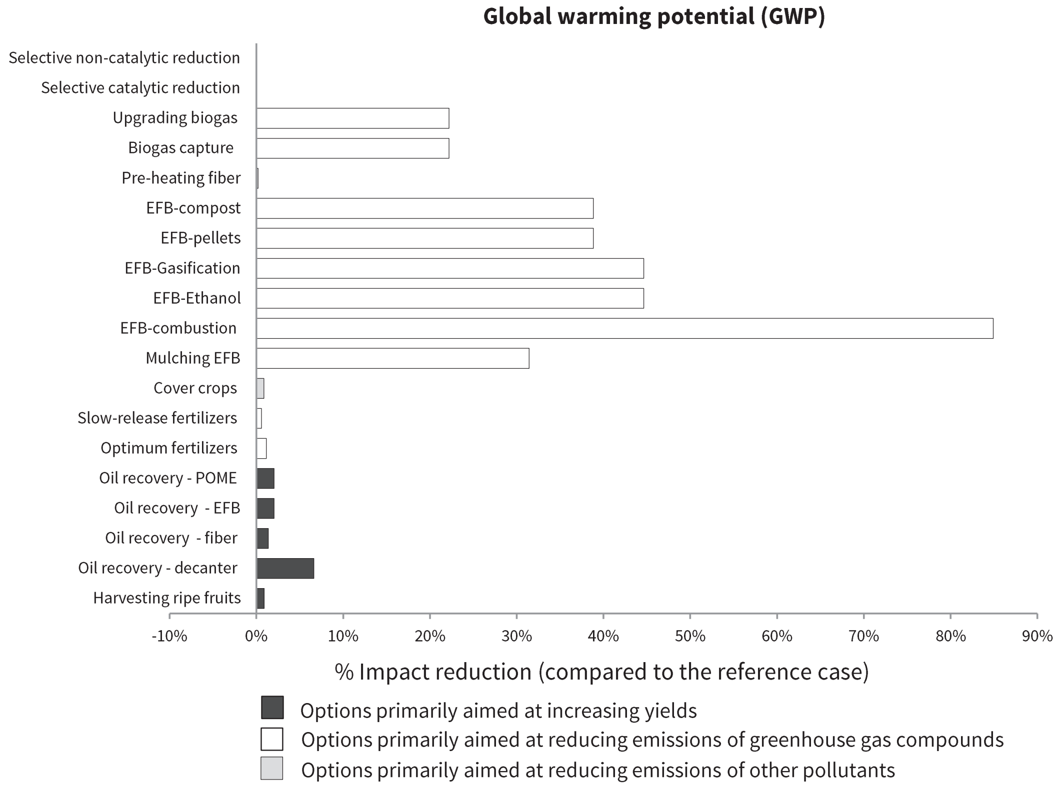

Figure 4.2 Effectiveness of options to reduce the global warming potential of palm oil production (% reduction relative to the reference case). See Table 4.2 for a description of the options. The breakdown of environmental impacts of individual options is presented in Table Table C4 (Appendix C).

4.3.1.2. Options to reduce emissions of acidifying compounds

We identified 15 options that can reduce acidification. Only eight of these options primarily aim to reduce emissions of acidifying compounds. *Mulching EFB* increases emissions (75% relative to reference case) because the extra N-input from mulched EFB causes NOx emissions.

EFB combustion is the most effective option to reduce acidifying emissions and results in large reductions (Figure 4.3). In facts, this option aims to avoid CH_4 emissions from untreated EFB by converting EFB to electricity. This electricity is partially replacing electricity from the grid. As a result, it avoids NOx and SO_2 emissions from fossil fuel combustion. Other options that are relatively effective include *Wet scrubbers, Non-thermal plasma, Selective catalytic reduction* and *Pre-heating fibre*. These options reduce emissions by 20-28% relative to the reference case. *Wet scrubbers, Non-thermal plasma* and *Selective catalytic reduction* remove NOx and SO_2 emissions from the flue gas when burning fibre. Meanwhile, *Pre-heating fibre* reduces the activity of burning fibre which is the most important source of acidifying emissions in the palm oil mills.

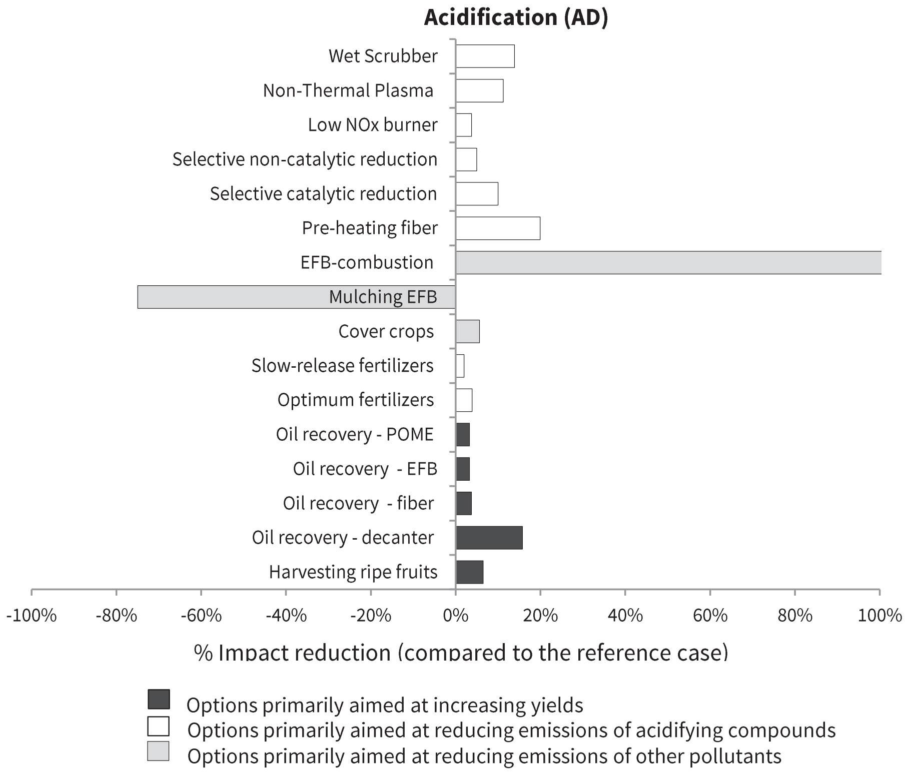

Figure 4.3 Effectiveness of options to reduce acidification of palm oil production (% relative to the reference case). See Table 4.2 for a description of the options. The breakdown of environmental impacts of individual options is presented in Table C4 (Appendix C).

4.3.1.3. Options to reduce emissions of eutrophying agents

We identified 15 options that can reduce eutrophication (EP). Only eight options primarily aim to reduce emissions of eutrophying compounds. *Mulching EFB* increases emissions to a large extent because of the extra N-inputs from mulched EFB and the associated NO_3^- and NOx emissions.

From these 15 options, *EFB combustion* is the most effective and may reduce emissions by 79% relative to the reference case (Figure 4.4). It can substitute some electricity otherwise taken from the grid and thus avoid emissions of NOx. In addition, *Oil recovery from decanter cake* and *Apply optimum dose of fertilisers* may reduce emissions considerably, by 16-21% in relative to the reference case. *Oil recovery from decanter cake* can reduce eutrophication because it increases CPO yields. Moreover, *Applying optimum dose of fertilisers* also reduces EP through a reduction in fertiliser N-inputs and this reducing the associated NO_3^- and NOx emissions. *Wet scrubbers*, *Selective catalytic reduction* and *Non-thermal plasma* are somewhat less effective, and may reduce eutrophying emissions from burning fibre by 10-13% relative to the reference case.

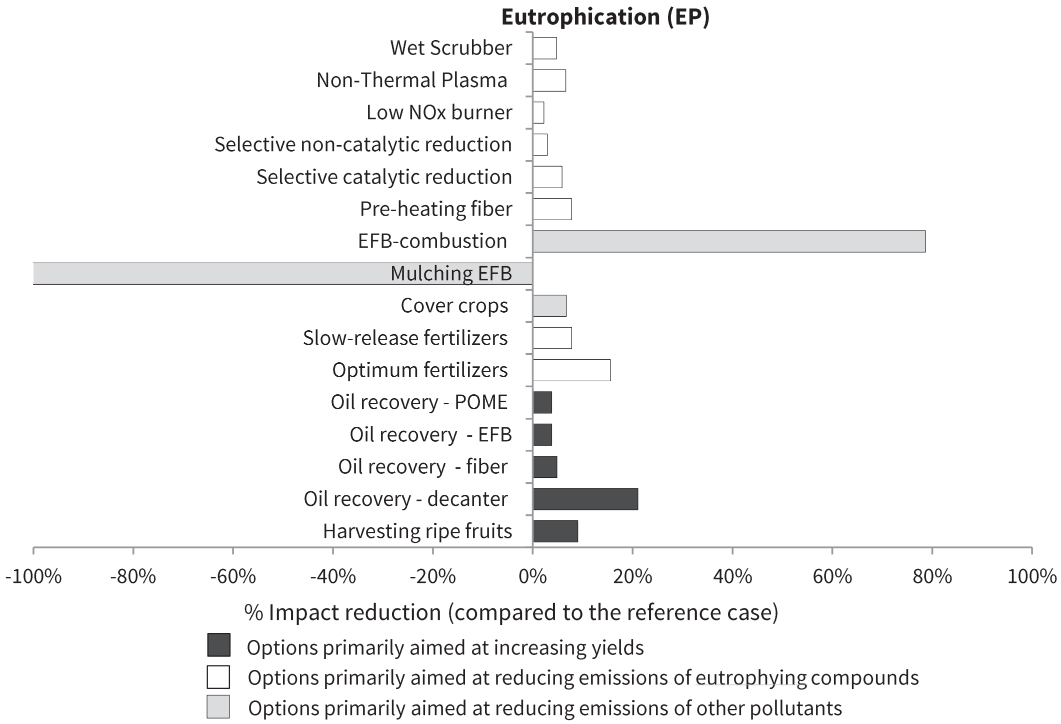

Figure 4.4 Effectiveness of options to reduce eutrophication of palm oil production (% relative to the reference case). See Table 4.2 for a description of the options. The breakdown of environmental impacts of individual options is presented in Table C4 (Appendix C).

4.3.1.4. Options to reduce emissions of photochemical ozone formation (POF) precursors

We identified 23 options effecting emissions of POF precursors (i.e. CH_4, CO and VOC). Of these, 18 primarily aim to reduce POF and four reduce POF as a side-effect. We found only one option that increases POF emissions as a side-effect: *EFB combustion*, which increases POF by 75% relative to the reference case.

Using a *Thermal incinerator* is the most effective option, with a 34% reduction when compared to the reference case (Figure 4.5). Second most effective options are in the EFB treatment group, *Pre-heating fibre* and using *Wet scrubbers* which have relatively high effectiveness (16-19% relative to the reference case). EFB treatment can avoid the production of untreated EFB which is an important source of CH_4. *Pre-heating fibre* can reduce the use of fibre which is important source of VOC, CO, CH_4 and NOx. Whilst, *Wet scrubbers* can remove VOC and NOx emissions from fibre combustion in boilers.

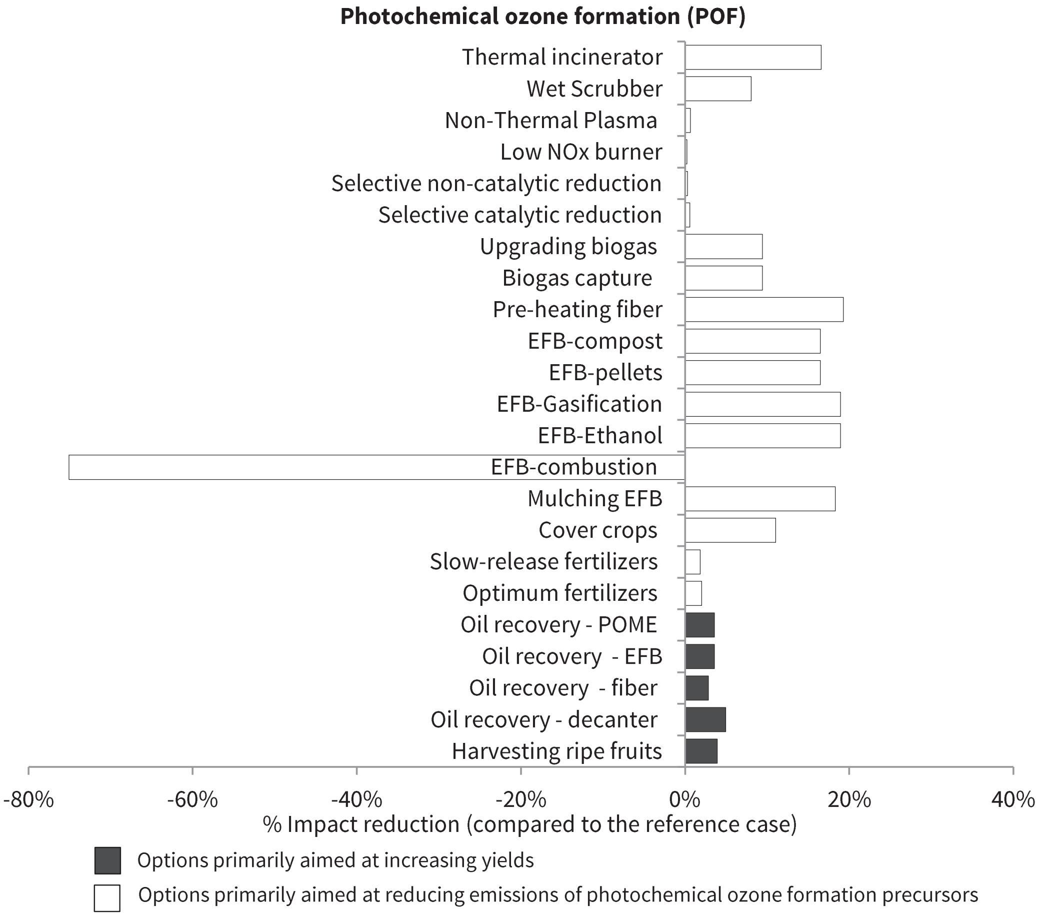

Figure 4.5 Effectiveness of options to reduce photochemical ozone formation of palm oil production (% relative to the reference case). See Table 4.2 for a description of the options. The breakdown of environmental impacts of individual options is presented in Table C4 (Appendix C)

4.3.1.5.Options to reduce emissions of human toxifying compounds

We identified 21 options effecting emissions of human toxifying compounds. We found two options that increase human toxicity (HT) as a side-effect: *Mulching EFB* and *EFB gasification,* which increase HT by 135% and 12% relative to the reference case, respectively. *Mulching EFB* increases NOx emissions while *EFB gasification* increases PM emissions.

From these 19 options, *EFB combustion* is the most effective option, with a reduction 92% reduction when compared to the reference case (Figure 6). It primarily aims to reduce CH_4 emissions from untreated EFB but it also avoids NOx and SO_2 emissions. Second most effective options are *Wet scrubbers, Non-thermal plasma* and *Pre-heating fibre* which have relatively high effectiveness (30-42% relative to the reference case). *Wet scrubbers* can effectively remove SO_2, NOx and PM emissions. *Non-thermal plasma* can remove only NOx emissions. For *Pre-heating fibre,* it reduces HT impact by reducing the use of fibre in boilers. As a result, it can avoid emissions of SO_2 NOx and PM.

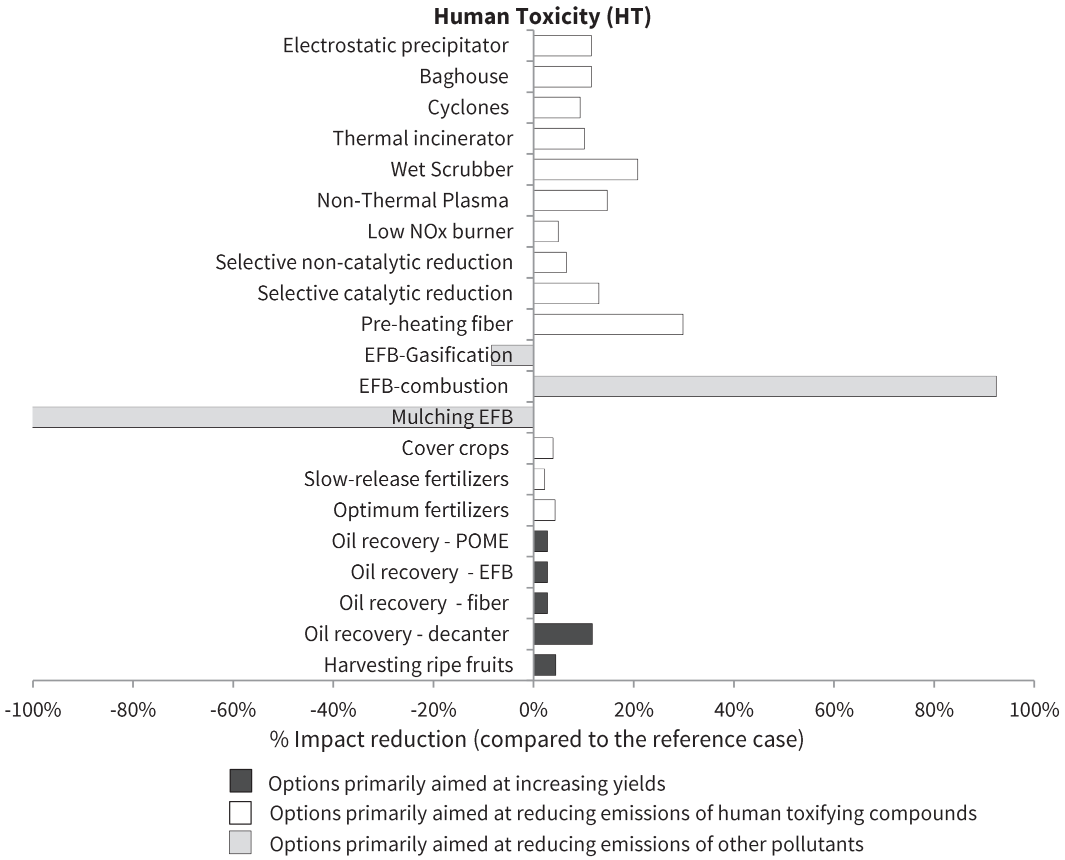

Figure 4.6 Effectiveness of options to reduce human toxicity of palm oil production (% relative to the reference case). See Table 4.2 for a description of the options. The breakdown of environmental impacts of individual options is presented in Table C4 (Appendix C).

4.3.1.6. Options to reduce emissions of freshwater ecotoxicity (FE) compounds

We identified seven options to reduce FE. Of these, only *Cover crops* primarily aim to reduce emissions of FE. It is the most effective option (52% reduction relative to the reference case) because it can both reduce the use of glyphosate (FE compounds) and can increase FFB yields (side-effect) after implementation. Other effective options are *Oil recovery from decanter cake* (25%), *Mulching EFB* (12%) and *Harvesting ripe fruits* (11%) because they increase yields (Figure 4.7).

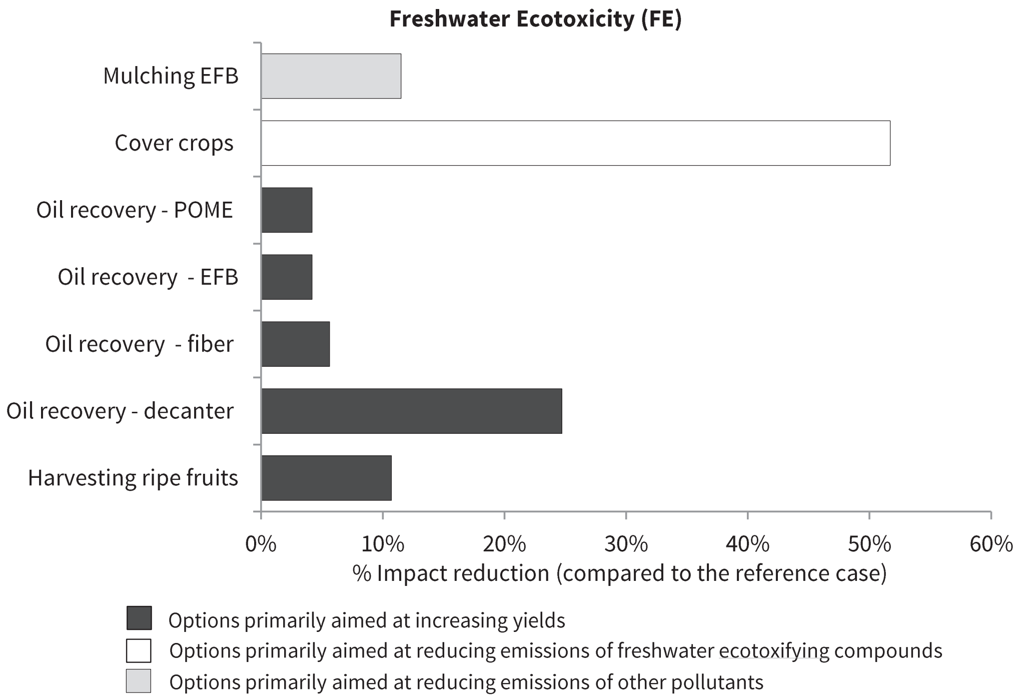

Figure 4.7 Effectiveness of options to reduce freshwater ecotoxicity of palm oil production (% relative to the reference case). See Table 4.2 for a description of the options. The breakdown of environmental impacts of individual options is presented in Table C4 (Appendix C).

4.3.2. Costs of reduction options

Next, we calculated the costs of implementing the reduction options on the basis of investment costs, operation and maintenance costs, and variable costs (see Box 1). For some options the costs exceed the benefits, while for others the benefits exceed the costs (Table 4.4 and 4.5).

For 26 options we calculated that benefits are smaller than the cost as a result of relatively high investment and operating costs. This is the case for, for instance, *EFB Combustion* (117 $/ton CPO/year), *Apply slow-release N-fertiliser* (88 $/ton CPO/year) and *EFB ethanol production* (27 $/ton CPO/year). Only options reducing NOx, SO_2, VOC and PM control from fibre combustion do not provide financial benefits. Nevertheless, their annual costs are relatively low (0.3 – 5 $/ton CPO/year).

For 10 options the benefits exceed the costs. We referred to these as paying options (i.e. they generate a positive return on investment). *Mulching EFB* is the most profitable paying option (-249 $/ton CPO/year), followed by *Harvesting ripe fruits* (-92 $/ton CPO/year), *Cover crops* (-61 $/ton CPO/year) and *Oil recovery from decanter cake* (-42.0 $/ton CPO/year). Benefits of *Mulching EFB* are mainly from the cost saving for fertiliser reduction (197 $/ton CPO/year) and income from increased FFB (100 $/ton CPO/year). Meanwhile, benefits of *Cover crops, Harvesting ripe fruits* and *Oil recovery from decanter cake* are from income from increased yields (Table 4.4 and 4.5).

Table 4.4 Costs of implementing the options to reduce the environmental impact of oil palm plantations. See Box 1 for equations, and Table 4.2 for a description of options. Detailed information on costs are provided in Table C5 in the Appendix C.

Group of options	Options	Description	Annual costs ($/ton CPO/year)			
			Investment costs (CI)[a]	Operation and maintenance costs (CO)[b]	Variable costs (CV)[c]	Total costs (C)[d,*]
Optimising fertilisers use	Apply optimum dose of fertilisers	Fertilisers	-	-	-1.8	2.64
		Labour	-	-	<-0.1	
		Education/Training	4.5	-	-	
	Apply slow-release fertilisers	Slow-release fertiliser	-	-	87.6	87.6
		Labour	-	-	<-0.1	
Weed control	Cover crops	Glyphosate	-	-	-0.9	-61.3
		Labour	-	-	-0.3	
		Yield increase (FFB)	-	-	-64.6	
		Education/Training	4.5	-	-	
FFB yield improvement	Harvesting ripe fruits	Yield increase (FFB)	-	-	-92.3	-92.3

** Negative values indicate that benefits exceed costs.*
- Not applicable.
a – Investment cost (CI) is calculated using equation 9, Box 1.
b – Operation and maintenance cost (CO) is calculated based on equation 10, Box 1.
c – Variable cost (CV).is calculated using equation 11, Box 1.
d – Net cost (C) is calculated using equation 8, Box 1.

Table 4.5 Information on associated costs for reduction options related to the palm oil mills. Detailed information on cost are provided in Table C6, Appendix C.

Group of options	Options	Description	Annual costs ($/ton CPO/year)			
			Investment cost (CI)[a]	Operation and maintenance cost (CO)[b]	Variable cost (CV)[c]	Total cost (C)[d,*]
POME treatment	Biogas capture system	Covered lagoon technology, including power generation unit	8.2	5.8	-	10.2
		Income from selling electricity	-	-	-3.8	
	Bioreactor plus upgrading biogas plant	Bioreactor plus upgrading biogas technology, including power generation unit	7.5	5.8	-	10.7
		Electricity increase	-	-	-2.6	
EFB treatment	Mulching EFB	Labour	-	-	6.8	-248.6
		Transportation to the plantations	-	-	41.2	
		Fertilisers	-	-	-196.7	
		Yield increase (FFB)	-	-	-269.2	
	EFB composting plant	EFB composting plant	2.0	1.9	-	-1.5
		EFB-compost	-	-	-5.3	
	EFB combustion	EFB combustion plant	61.3	34.6	-	124.5
		Transportation of EFB	-	-	44.7	
		Electricity	-	-	-16.1	
	EFB ethanol production	EFB ethanol plant	258.7		-	27.2
		EFB-ethanol	-	-	-231.5	
	EFB pellets production	EFB pellets plant	9.3	25.3	-	-9.8
		EFB- pellets	-	-	-44.4	
	EFB gasification	EFB gasification plant	0.9	0.5	-	0.4
		Electricity	-	-	-1.0	
NOx control for fibre combustion	Non-thermal plasma	Non-thermal plasma technology	3.6	0.9	-	4.5
	Selective catalytic reduction	Selective catalytic reduction technology	2.5	1.5	-	0.9

Group of options	Options	Description	Annual costs ($/ton CPO/year)			
			Investment cost (CI)[a]	Operation and maintenance cost (CO)[b]	Variable cost (CV)[c]	Total cost (C)[d,*]
	Selective non-catalytic reduction	Selective non-catalytic reduction technology	1.9	1.1	-	3.0
	Low-NOx burner	Low-NOx burner technology	0.6	0.4	-	1.0
SO_2 control for fibre combustion	Wet scrubber	Wet scrubber technology	0.5	0.4	-	0.9
VOC control for fibre combustion	Thermal incinerator	Thermal incinerator technology	0.3	<0.1	-	0.3
PM control for fibre combustion	Cyclones	Cyclones technology	0.4	0.2	-	0.5
	Baghouse	Baghouse technology	0.3	0.1	-	0.4
	Electrostatic precipitator	Electrostatic precipitator technology	1.1	0.6	-	1.7
Boiler efficiency improvement	Pre-heating fibre	Belt conveyor, including civil works	<0.1	<0.1	-	-3.8
		Saved- fibre	-	-	-3.9	
Oil extraction improvement	Oil recovery from decanter cake	Yield increase (CPO)	-	-	-42.0	-42.0
	Oil recovery from fibre	Yield increase (CPO)	-	-	-7.6	-7.6
	Oil recovery from POME	Yield increase (CPO)	-	-	-3.8	-3.8
	Oil recovery from EFB	EFB shredder	0.2	<0.1	-	-3.4
		EFB press[e]	0.2	<0.1	-	
		Yield increase (palm kernel)	-	-	-<0.1	
		Yield increase (CPO)	-	-	-3.8	

[*] Negative values mean the benefits exceed the costs after implementing the options.
- Not applicable.
a Investment cost (CI) is calculated using equation 9, Box 1.
b Operation and maintenance cost (CO) is calculated based on equation 10, Box 1.
c Variable cost (CV).is calculated using equation 11, Box 1.
d Net cost (C) is calculated using equation 8, Box 1.
e Annual costs are assumed to be the same as the EFB shredder.

4.3.3. Cost-Effectiveness of reduction options

The cost-effectiveness (*CE)* is defined as the costs per avoided unit of environmental impact (see Box 1). The lower the CE, the more cost effective the options are. CEs are only calculated for options that can reduce the environmental impact by more than 5% relative to the reference case. We realise that absolute impacts are also relevant for decision making, in particular for impact categories to which palm oil production contributes to a relatively small extent (and where the 5% threshold leads to relatively minor environmental benefits). For reasons of simplicity and consistency, we apply a 5% threshold throughout, but we reflect on this assumption in the discussion section below. The most effective options are not necessarily the most cost-effective options. High investment and operating costs can explain why some options that are highly effective in reducing pollution, are not very cost effective. For instance, *EFB Combustion* is not very cost effective (i.e. *CE* is high) even though it is the most effective option in all impact categories.

Paying options are more cost-effective than non-paying options. Paying options like *Cover crops, Mulching EFB, Harvesting ripe fruits, Oil recovery from decanter cake, Pre-heating fibre, EFB composting plant* and *EFB pellets production* are the most cost-effective in reducing a broad range of environmental impact categories (Table 4.6). Most of these options result in yield improvement, and as a result in reducing multiple impacts. For instance, *Oi loss recovery from decanter cake* is a cost-effective option for all categories, except for POF. *Cover crops* is cost-effective option to reduce AD, EP, POF and FE. Meanwhile, *Mulching EFB* is a cost-effective option to reduce GWP, POF and FE but it increases AD and EP. *Pre-heating fibre,* can reduce fibre combustion which is important source of NOx, SO_2, CO, VOC and PM emissions. Thus, it is cost-effective for many impact categories, except for GWP and FE. Meanwhile, *EFB composting plant* and *EFB pellets production,* are aiming to reduce CH_4 emissions. They are cost-effective only for reducing GWP and POF.

Table 4.6 Cost-effectiveness of reduction options categorized by impact category, including global warming potential (GWP) acidification (AD), eutrophication (EP), human toxicity (HT) and freshwater ecotoxicity (FE).

Group of options	Options	Cost-effectiveness (CE)*					
		GWP ($/kg CO_2eq avoided/ton CPO/year)	AD ($/g SO_2eq avoided/ton CPO/year)	EP ($/g PO_4^{3-}eq avoided/ton CPO/year)	POF ($/g C_2H_4eq avoided/ton CPO/year)	HT ($/g $C_6H_4Cl_2$eq avoided/ton CPO/year)	FE ($/mg $C_6H_4Cl_2$eq avoided/ton CPO/year)
Optimising fertilisers use	Apply optimum dose of fertilisers	N	N	0.02	N	N	N
	Apply slow-release fertilisers	N	N	1.48	N	N	N
Weed control	Cover crops	N	-0.63	-1.20	-0.33	N	-0.27
FFB yield improvement	Harvesting ripe fruits	N	-0.82	-1.34	N	N	-1.97
POME treatment	Covered lagoon	0.01	N	N	0.06	N	N
	Bioreactor plus upgrading biogas plant	0.02	N	N	0.06	N	N
EFB treatment	Mulching EFB	-0.26	I	I	-0.80	I	-4.94
	Composting plant	-0.001	N	N	-0.01	N	N
	Combustion	0.05	0.03	0.21	I	0.04	N
	Ethanol production	0.02	N	N	0.08	N	N
	Pellets production	-0.01	N	N	-0.03	N	N
	Gasification	0.0003	N	N	0.001	I	N
NOx control for fibre combustion	Non-Thermal Plasma	N	0.01	0.04	N	0.005	N
	Selective catalytic reduction	I	0.01	0.04	N	0.005	N
	Selective non-catalytic reduction	I	0.02	0.06	N	0.01	N
	Low-NOx burner	N	0.01	N	N	0.003	N
SO_2 control for fibre combustion	Wet Scrubber	N	0.002	0.01	0.003	0.001	N
VOC control for fibre combustion	Thermal incinerator	N	N	N	0.0006	0.0005	N
PM control for fibre combustion	Cyclones	N	N	N	N	0.001	N
	Baghouse	N	N	N	N	0.0005	N
	Electrostatic precipitator	N	N	N	N	0.002	N
Boiler efficiency improvement	Pre-heating fibre	N	-0.01	-0.06	-0.01	-0.004	N

Group of options	Options	Cost-effectiveness (CE)*					
		GWP ($/kg CO_2eq avoided/ton CPO/year)	AD ($/g SO_2eq avoided/ton CPO/year)	EP ($/g PO_4^{3-}eq avoided/ton CPO/year)	POF ($/g C_2H_4eq avoided/ton CPO/year)	HT ($/g $C_6H_4Cl_2$eq avoided/ton CPO/year)	FE ($/mg $C_6H_4Cl_2$eq avoided/ton CPO/year)
Oil extraction improvement	Oil recovery from decanter	-0.21	-0.15	-0.26	N	-0.11	-0.39
	Oil recovery from fibre	N	N	N	N	N	-0.31
	Oil recovery from POME	N	N	N	N	N	N
	Oil recovery from EFB	N	N	N	N	N	N

N = No effect. This option is not included in the cost-effectiveness analysis because it has a small (< 5%) or no effect on reducing environmental impacts or emissions of pollutants (see Figure 4.2 and Table C4, Appendix C).

I = Increase. This option is not considered cost-effective because it increases the environmental impacts or emissions of pollutants (see Figure 4.2 and Table C4, Appendix C).

**Cost-effectiveness (CE) is calculated using equation 12, Box 1.*

4.4. Discussion

4.4.1. Practical implementation of proposed options

In total, we analysed 26 options. Some of proposed options in this study have already been implemented in the Thai palm oil industry. For instance, around 60% of palm oil mills in Thailand have already installed a *Biogas capture system* (Ayachanan, 2015). Such large-scale implementation is driven by the renewable energy policy promoted by the Thai government (DEDE, 2012a). However, there are some limitations on connection and distribution lines to the grid that limit the widespread application of this option (Dallinger et al., 2013). Note that we did not consider this limitation in this study. *EFB combustion* is also a part of this policy. However, the number of EFB power plant increases at a slow rate because high investment and operating costs. In addition, local people have not fully accepted *EFB combustion* as it contributes to air pollution problems (Dallinger et al., 2013). To mediate in such situations, environmental impact assessment using stakeholder participation approach is required. Apparently, the costs for acquiring EFB (i.e. EFB material and transportation) have been increasing due to a high competition from other biomass power plants (Dallinger et al., 2013). To deal with this problem, a proper zoning for EFB-power plant is recommended to control the EFB-price in correspondence to the demand and less cost of transportation.

Some proposed options are practical in Malaysia and Indonesia, such as *Mulching EFB, EFB composting plant* and *EFB pellets production,* but not for Thailand. *Mulching EFB* is widely implemented in Malaysia and Indonesia because large-scale plantations are prevalent there. This is unlike Thailand, where more than 70% of plantations belong to smallholders (Dallinger, 2011). Handling EFB from the mills to smallholder plantations is a main problem as they do not own a truck to carry large volume of EFB. Moreover, spreading a-single layer of EFB throughout the plantations requires intensive labour which is more expensive than labour cost for chemical fertilization. Altogether, *Mulching EFB* in the smallholder plantations is likely to be impractical in Thailand under the current value chain. To encourage *Mulching EFB* in Thailand, building a partnership between a mill and smallholder famers is recommended. This way, the mills could provide support in EFB-transportation and laying EFB, while smallholder farmers could deliver FFB to the mill. However, *Mulching EFB may have* negative side-effects on N_2O, NOx and nitrate emissions. Therefore, it is recommended to (1) optimise the amount of EFB used in mulching, and (2) minimise the runoff during mulching.

Some options, such as *Harvesting ripe fruits* and *Oil recovery from wastes* require low costs for implementation. Only changes in management practices are needed. However, they are still not widely implemented in Thailand. For *Harvesting ripe fruits*, farmers lack motivation and incentives to harvest the ripe fruits because of an unfavourable FFB pricing system which relies only on the weight of the FFB not their quality. Therefore, a new FFB pricing system that relies on quality (oil content) is highly recommended. Research on a tool to measure oil content in fruits by the Kasetsart University is in the pipeline (Ayachanan, 2015). This would facilitate the introduction of a new FFB pricing system. *Oil recovery from wastes* has been implemented only in the large-scale mills but is more difficult to implement in small-scale and medium-scale mills. This is because operators in these mills have a more limited knowhow to efficiently recover the oil losses from wastes. To address this issue, performance of oil recovery among small-scale and medium-scale mills should be benchmarked so that they could learn from each other as well as keep improving their performance. Alternatively, international sustainability standards, such as the Roundtable of Sustainable Palm Oil (RSPO), could be helpful in this context as RSPO encourages practitioners to improve their practices towards best management practices.

Some of the proposed options are still under research and development, such as the *Bioreactor plus upgrading plant, EFB ethanol production* and *EFB gasification.* If these options can be improved to a commercial scale in the near future, the Thai palm oil industry could become a source of renewable energy and it would considerably reduce the environmental impacts of palm oil production in the country.

In our cost-effectiveness analysis, a minimum of 5% reduction is used as a threshold for selection of the options. Thus options that reduce the environmental impact by less than 5% relative to the reference case are not included in the cost-effectiveness analysis. The 5% threshold that we used is arbitrary, and a simplification. We realize that by doing this we could be ignoring options that reduce emissions by only a few percent but still have a large (local) impact. We realize that companies may be interested in the absolute environmental benefits of an investment. Nevertheless, when considering transaction costs (Hein and Blok, 1995), such as costs for decision making and monitoring investments, we assume that companies in general may not be interested in investments that have minor benefits.

4.4.2. Strengths and limitations of our study

The strength of our study is that it can evaluate options to reduce the environmental impacts of palm oil production in Thailand, while taking account different environmental problems and the cost-effectiveness of reduction options. The cost-effectiveness analysis that we applied builds upon Jawjit et al. (2007) who applied this approach in the eucalyptus-based kraft pulp industry. Neto (2007) applied it to aluminium pressure die casting. We believe our study to be the first study in Thailand to evaluate the effects of options to reduce the environmental impacts of palm oil production.

Since the cost-effectiveness analysis requires a lot of information, such as reduction potentials, investment and operating costs, the weaknesses of our study include missing data and uncertainties in the assumptions. Data from other regions and different climate zones are used in the calculations when specific data for Thailand are lacking. For instance, the reduction factors for *Apply optimum dose of fertilisers* and *Apply slow-release fertilisers* are derived from a temperate climate. Sample data on investment and operating costs of *Thermal incinerator* and *Non-thermal plasma* are based on pilot plants in the United State of America. In some cases, there are uncertainties in the assumptions. For instance, the yield increase factors for *Cover crops, Mulching EFB* and *Harvesting ripe fruits* are derived from either empirical studies or based on few samples. In reality, actual increase in FFB yields may differ when implemented in Thailand. Removal efficiencies (or reduction factors) of pollution control devices for fibre combustion depend on many factors (i.e. type of industry, size of factory and technology). Therefore, the actual reduction in emissions may differ when applying these devices in the palm oil mills. Moreover, we realised that the input data used in our analysis have their uncertainties. For instance, reduction factors used for *Wet scrubbers* and *Thermal incinerator* are reported as ranges in the literature (see Table A3). In such cases we selected the most appropriate value from the range for our analysis. We did perform a full quantitative uncertainty analysis. Although this would be interesting, we consider it outside the scope of our analysis. It should be noted that many of our input data are from sources reporting single values without their uncertainty ranges.

Our cost-effectiveness analysis of individual reduction options provides useful information to decision makers for the design of environmental management strategies. For instance, a decision maker who focuses on reducing greenhouse gases may pay more attention to reduction options from groups of EFB and POME treatment (Figure 4.2). Our model allows the users to analyse any environmental problems of interest. For instance, based on economic grounds, a palm oil producer may choose the most cost-effective options from each impact category (Table 4.5). Different environmental management strategies would lead to different combinations of options. We recommend future studies to analyse consequences of such combinations of options.

4.5. Conclusion

Many nations, including Thailand, promote the use of biodiesel to mitigate climate change. This results in a fast increase in palm oil production. We identified options to reduce the associated environmental impact, and assessed their cost-effectiveness. We did this for six environmental impact categories: global warming, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater ecotoxicity.

In a previous study, we assessed the environmental impact of palm oil production in Thailand (Saswattecha et al., 2015b). Based on this, we determined the key sources of emissions. These are the use of N fertiliser, weed control, burning of fibre, treatment of palm oil mill effluent (POME) and empty fruit bunch (EFB) management. We identified options to reduce these environmental impacts. In total, we described 26 different options in 11 groups: minimizing fertiliser use, weed control, FFB yield improvement, POME treatment, EFB treatment, NOx control, SO_2 control, VOC control, PM control, boiler efficiency and oil extraction improvement.

The most effective options differ among impact categories. Our effectiveness analysis shows that options in the groups of EFB and POME treatment are the most effective (23-85% reduction relative to the reference case) in reducing global warming impact as they can reduce CH_4 emissions. Among these, EFB is found to be the most effective. *EFB combustion*, *wet scrubbers, non-thermal plasma, selective catalytic reduction* and *pre-heating fibre (*20-238% reduction relative to the reference case) are effective in reducing acidification. This is because they reduce SO_2 and NOx emissions from combustion processes. For eutrophication, *EFB combustion, oil recovery from decanter cake, apply optimum dose of fertilisers* (16-79% reduction) are the most effective options, as they reduce NO_3^- and NOx emissions. In addition*, thermal incinerators, pre-heating fibre*, and all options in the EFB treatment group (except for *EFB combustion*) are effective (16-34% reduction) in reducing photochemical ozone formation. Human toxicity problems can be most effectively reduced by *EFB combustion, wet scrubber, non-thermal plasma* and *pre-heating fibre* (30-92% reduction), because they either reduce emissions of fibre combustion or reduce the use of fibre. For freshwater ecotoxicity, *cover crops, oil recovery from decanter, mulching EFB* and *harvesting ripe fruits* are effective options (11-52% reduction). *Cover crops* are the most effective option as it can both reduce freshwater ecotoxicity compounds and increase FFB yields while other options only increase FFB yields. To this end, we found that *EFB combustion, Wet scrubbers* and *Pre-heating fibre* are the most effective in reducing multiple impact categories as they can remove or avoid NOx emissions which contributes to acidification, eutrophication and human toxicity.

The costs of the effective options listed above mostly exceed the benefits. For instance, EFB combustion requires considerably high investment and operating costs (*C* = 117 $/ton CPO/year). Nevertheless, for some options the benefits exceed the costs. This is the case for *Mulching EFB* (*C* = -249 $/ton CPO/year) and *Harvesting ripe fruits* (*C* = -92 $/ton CPO/year). We considered these options so-called "paying options". There are 10 paying options identified. Seven of these are effective options (i.e. reducing the environmental impact by more than 5% relative to the reference case). These include *oil loss recovery from decanter cake*, *pre-heating fibre, EFB composting, EFB pellets production, cover crops, mulching EFB* and *harvesting ripe fruits.* These options can reduce multiple impacts at the same time. For example, *oil loss recovery from decanter cake* is effective in reducing impacts in all categories, except for photochemical ozone formation. Meanwhile, *mulching EFB* is effective in reducing global warming, photochemical ozone formation and freshwater ecotoxicity but it increases acidification and eutrophication.

Palm oil mills generate large amounts of EFB. Therefore, several technologies for EFB management are analysed in this study (i.e. mulching, composting, combustion, gasification, pellets production and ethanol production). Both direct effect and side-effects of these options are included. For instance, in EFB combustion, we not only accounted for direct effect on CH_4 avoidance from untreated EFB but also takes the side-effects on avoiding (i.e. CO_2, NOx and SO_2) and increasing emissions (i.e. VOC, CO and PM) into consideration when connected the generated electricity to the grids. Among these options, the most effective option is *EFB combustion* and the most cost-effective is *Mulching EFB*.

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Chapter 5

Non-CO_2 greenhouse gas emissions from palm oil production in Thailand

5. NON-CO_2 GREENHOUSE GAS EMISSIONS FROM PALM OIL PRODUCTION IN THAILAND

ABSTRACT

The global demand for palm oil has been increasing during the past two decades. As a result, there has been an expansion of oil palm plantations and palm oil production, in particular in South East Asia. This contributes to a number of environmental problems. In this study, we focus on non-CO_2 greenhouse gas emissions from palm oil production in Thailand, the third largest palm oil producing country in the world. Carbon dioxide (CO_2) is typically emitted during fuel combustion in production processes. In addition, methane (CH_4) and nitrous oxide (N_2O) are emitted during palm oil production. We quantified current and future emissions of CH_4 and N_2O based on future projections for palm oil production in Thailand. Our analysis distinguishes between emissions from oil palm plantations and palm oil processing mills. Our study shows that nitrogen fertilisers are the main source of N_2O emissions, while CH_4 is emitted mainly from inappropriate management of empty fruit bunches and wastewater management. We also analysed the effect of possible options to reduce emissions of CH_4 and N_2O, illustrating the potential for emission reduction in the future.

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5.1. Introduction

The demand of palm oil for food and biofuel industries has been increasing. As a result, environmental impacts associated with palm oil production (Kaewmai et al., 2012; Oosterveer, 2014) have become a crucial issue in Southeast Asia, South America, and Africa (Silalertruksa and Gheewala, 2013; USAID, 2009). Several studies reveal that palm oil production contributes to a broad range of environmental problems, including global warming, biodiversity loss, eutrophication, acidification, and photochemical ozone formation. The use of nitrogen (N) and phosphorus (P) fertilisers in oil palm plantations causes global warming impact and eutrophication in surface waters (Achten et al., 2010; Bijay et al., 1995; Dumelin, 2009). The use of herbicides poses risks for human health and nearby water bodies (Pleanjai et al., 2009). Fuel combustion generates several air pollutants that contribute to human toxicity, acidification, eutrophication and photochemical ozone formation problems (Achten et al., 2010; Dumelin, 2009; US-EPA, 2012). This is also the case for Thailand.

To mitigate the environmental impacts of palm oil production, assessing the environmental impacts of palm oil production is therefore an essential element for gaining a better understanding of Thai palm oil production. Kaewmai et al. (2012) indicated that non-CO_2 greenhouse gases have a relatively large share in the total global warming impact of oil palm production in Thailand. In this study, we therefore focus on non-CO_2 greenhouse gases, including methane (CH_4) emissions from waste management in the palm oil processes, and nitrous oxide (N_2O) emissions when applying the nitrogen fertilisers in the oil palm plantations (Kaewmai et al., 2012; Silalertruksa and Gheewala, 2013).

The global demand for environmental and social friendly palm oil products has been increasing in order to cope with the environmental impacts associated with the palm oil production. The Roundtable on Sustainable Palm Oil (RSPO), a global sustainability standard for palm oil production, was established by multiple stakeholders in response to the increasing demand for sustainably grown palm oil (RSPO, 2007). Since RSPO is an emerging issue in Thailand, only few Thai smallholder farmers and palm oil mills have, to date, been RSPO certified (DIT, 2011; RSPO, 2012). Studies on the environmental impacts of palm oil production in relation to the RSPO certification in Thailand are limited. For instance, Patthanaissaranukool et al. (2013) and Kaewmai et al. (2012) focused on greenhouse gas emissions from palm oil mills but did not address the implications of RSPO. This may be related to RSPO criteria (RSPO P&C) not including specific requirements for reducing greenhouse gas emissions along the production chains of palm oil.

The objective of this study is to analyses current and future emissions of CH_4 and N_2O, associated with palm oil production in Thailand, and the potential effects of emission reduction options. We quantified emissions under different management practices in the Tapi River basin. This area is taken as a case study area because more than half of the palm oil production in Thailand takes place in this basin (DIT, 2012a, 2011; MOI, 2012). Our study contributes to a better understanding of the global warming impact of oil palm production in Thailand. As such, it can help to identify pathways for sustainable palm oil, that also account for the other environmental impacts of palm oil production (Saswattecha et al., 2015).

5.2. The processes of crude palm oil production in the Tapi river basin

In this section we describe the processes of crude palm oil (CPO) production in the Tapi river basin that are considered in our analysis (Figure 5.1). CPO is produced from fresh fruit bunches (FFB) in mills. In Thailand, most of the fresh fruit bunches come from small oil palm plantations. Our descriptions are based on literature, interviews and site visits (Saswattecha et al., 2015b).

5.2.1. Oil palm plantations

In oil palm plantations (Figure 5.1), the soil is prepared only once before planting oil palm seedlings. Tractors are used for ploughing to turn over the soil and to dig holes for planting seedlings. It should be noted that the production of seedlings is not considered in this study since its share in the environmental impact is relatively low (GIZ, 2011).

Fertilisers are usually applied according to the oil palm cycle, higher fertilisers when oil palms become mature. The lifetime of oil palms in Thailand is about 25 years. Oil palm fruits can be harvested after about three or four years of cultivation for palm oil production (Dallinger, 2011; Daniel and Gheewala, 2010; Pleanjai et al., 2009; Siangjaeo et al., 2011). In this study, we differentiated the life cycle of oil palm into a non-productive (1 – 3 years) and productive (4 – 25 years) period. An annual average for fertiliser use over 25 years is used for the calculations in our analysis.

Based on interviews, no use of insecticides in the plantations was reported. Weed control is performed every 3-4 months using herbicides (i.e. Glyphosate, paraquat and cabarly) and weed cutting tools. Glyphosate is the most commonly used herbicide and we include only this herbicide in our analysis. Gasoline is required when using the weed cutting tools.

In Thailand, the majority of oil palm growers are smallholders without their own trucks to deliver large amounts of FFB to the mills and their plantations are often far away from the mills. After harvest, famers deliver FFB to either nearby mills or middlemen who collect FFBs and subsequently sell these to mills.

5.2.2. Palm oil mills

Palm oil production starts from unloading the FFB from trucks to the oil extraction unit to generate CPO and nuts. Next, CPO is purified and stored in tanks while nuts are cracked to produce Palm Kernel (PK). Shells from nut cracking process are collected and sold as biomass fuel and PK is further processed in palm kernel mills to produce palm kernel oil which is outside our system boundary (Figure 5.1).

Wastes from the oil extraction units, such as decanter cake, fibres, and Empty Fruit Bunches (EFB), are usable. For instance, decanter cake can be used as a basis for animal feed or organic fertiliser factories as it contains relatively high oil and nutrient content. Fibres are internally reused in boilers (biomass fuel) to produce steam and electricity in the mills. Electricity from the grid is only used for starting-up. Many studies indicate opportunities for EFB use, such as composting (Chiew and Shimada, 2013; Singh et al., 2010; Yoshizaki et al., 2013), use as fuel for electricity generation (Chavalparit et al., 2006; Chiew and Shimada, 2013; Patthanaissaranukool et al., 2013) or as substrate for mushrooms (DOAE, 2011; Sudirman et al., 2011). However, in practice it is difficult to use EFB generated from all mills in the basin. A large amount of EFB is currently not used. As a result, large amounts of EFB are dumped without a proper care.

The oil extraction processes require a large quantity of water. The mills usually pump water from the Tapi River or its branches and treat water before use in boilers by aluminum sulphate (Alum), sodium sulphite (oxygen scavenger) and sodium carbonate (anti-scaling agent). As a result, large amounts of wastewater or Palm-Oil-Mill-Effluent (POME) are generated. Nowadays, there are two types of POME treatment; 1) a series of open lagoons without biogas capture systems with potentially high CH_4 emissions and 2) a biogas capture system (biogas capture unit and followed by open lagoons). The captured biogas (CH_4) is used to generate power. In Thailand, small and medium scale mills mostly use a series of open lagoons without biogas capture systems while large scale mills treat POME using biogas capture systems. Treated POME is usually stored and dried in open lagoons. In some cases, treated POME is used as liquid fertiliser in surrounding plantations.

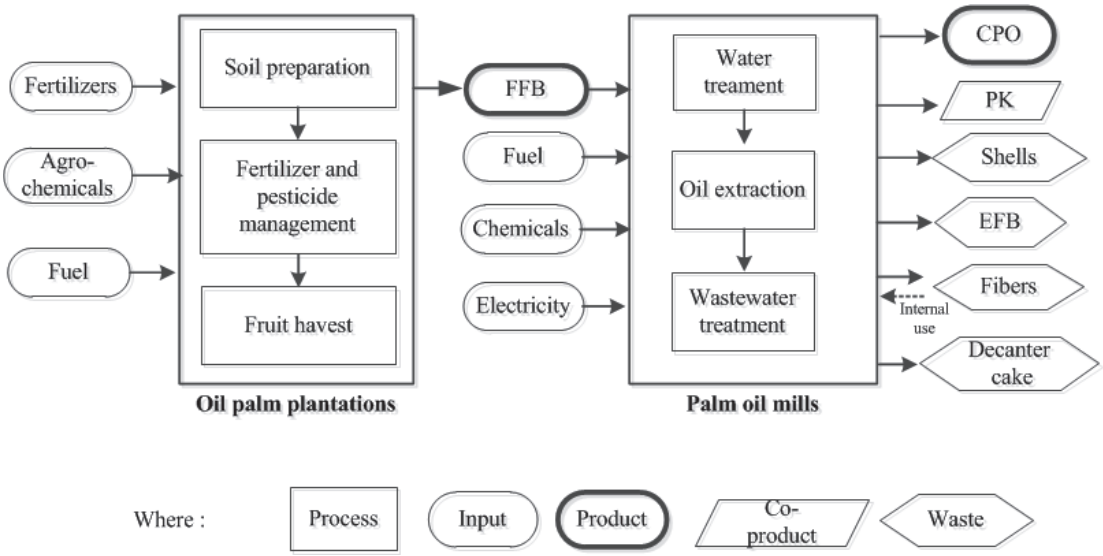

Figure 5.1. Schematic overview of crude palm oil production in the Tapi river basin.

5.3. Management practices in relation to RSPO certification regimes

In this study, we distinguished between three management regimes: Non-RSPO certified (N-RSPO), Potential RSPO certified (P-RSPO) and Certified RSPO producers (C-RSPO) as listed below. For more information on these three groups we refer to Saswattecha et al. (Saswattecha et al., 2015b).

- N-RSPO - Farmers and millers applying Business as Usual practices and not following the best practices in the RSPO Principle & Criteria (P&C). Farmers have limited resources to buy and apply fertilisers. Oil palm plantations are located far away from the palm oil mills. FFB delivery by middlemen is, therefore, required. POME is treated in open lagoons, and EFB is untreated.
- P-RSPO - Farmers and millers aiming to achieve RSPO certification and learning the best practices in the RSPO P&C. Farmers adopt some best practices in the RSPO P&C and are in the transition to become RSPO certified. Farmers have can afford to buy fertilisers. Oil palm plantations are close to palm oil mills so that FFB delivery by middlemen is not needed. POME is treated by biogas capture system, while EFB is untreated.
- C-RSPO – Farmers and millers being RSPO certified. These are producing FFB and CPO by following best practices that are in line with or beyond RSPO P&C. Oil palm plantations are close to palm oil mills so that FFB deliver by middlemen is not needed. POME is treated by biogas capture system. EFB is mulched in the oil palm plantations.

In the following we describe these three types with respect to their management practices for crude palm oil production.

5.3.1. Oil palm plantations

Farm activity data were derived from Patthanaissaranukool et al. (2013) for the N-RSPO case and farmer interviews for P-RSPO (10 farmers) and C-RSPO (11 farmers) cases. The farm data may not perfectly represent the actual situation but we consider the data good enough for the purpose of our study. In general, the cultivating practices are similar for the three cases, except for weed control. In Thailand, the majority of oil palm growers are smallholder farmers (we refer to it as N-RSPO case) who lack knowledge of fertiliser management and, in some cases, also lack access and budget for good quality fertilisers. In the N-RSPO plantations, we observed that farmers apply fertilisers as follows: 3.9±1.0 kg N/ton FFB, 2.9±0.9 kg P/ton FFB and 10.4±3.9 kg K/ton FFB. No use of boron (supplementary nutrient) was reported. From interviews, we concluded that RSPO certified farmers are trained in fertiliser management, farm management and integrated pest management, which is in line with the RSPO P&C– principle 4 (RSPO, 2010) and have access to good quality fertilisers at a reasonable price, supported by a joint project co-implemented by the Office of Agricultural Economics (OAE) and the German International Cooperation (GIZ) (RSPO, 2012; Thongrak and Kiatpathomchai, 2011). Hence, they are able to manage fertilisers according to the nutrient requirements of oil palm. This training results in relatively low fertiliser use in the C-RSPO plantations (3.5±1.2 kg N/ton FFB; 1.3±1.5 kg P/ton FFB; 13.7±12.5 kg K/ton FFB; 0.2±0.9 kg boron/ton FFB) when compared with N-RSPO and P-RSPO plantations. The potential certified RSPO farmers in the P-RSPO plantations are in a process of learning and changing their fertilizing behavior to maximize FFB fields as well as to be able buy fertilisers; this explains why they seem to use relatively high fertilisers, particularly for N fertiliser (4.3±1.9 kg N/ton FFB) but also for other fertilisers: 2.2±1.9 kg P/ton FFB; 8.5±4.2 kg K/ton FFB; 0.4±0.1 kg boron/ton FFB). It should be noted thatthe effect of increased fertiliser application on FFB yield takes place after a few years.

For weed control, herbicides (in particular glyphosate) are applied in the plantations. The interviewees indicated that there is no use of insecticides. Use of glyphosate (0.001±0.024 L/ton FFB) and gasoline (0.07±0.50 L/ton FFB) in C-RSPO plantations is relatively low as farmers manually remove weeds and use glyphosate only when necessary. On the other hand, the farmers in N-RSPO plantations use larger amounts of gasoline (0.70±0.20 L/ton FFB) and glyphosate (0.11±0.01 L/ton FFB) which is likely related to a lack knowledge on weed management.

After harvesting, the P-RSPO and C-RSPO farmers directly deliver FFB to the partner-mills by pick-up trucks (carrying capacity 2.5 ton) with average distances not exceeding 10 km (4.8±4.6 km/ton FFB for P-RSPO and 3.1±5.6 km/ton FFB for C-RSPO) as their plantations are close to mills. For the N-RSPO plantations, farmers usually deliver FFB to middlemen using pick-up trucks with a distance of 3.2±3.2 km/ton FFB as their plantations are located further away from mills. These middlemen deliver FFB to the mills by 10-wheel trucks (carrying capacity 25 ton) with an average distance of 50 km (2 km/ton FFB) (2011). This implies emissions associated with 2 km of transport are allocated to each ton of FFB.

5.3.2. Palm oil mills

Mill activity data were derived from Kaewmai et al. (2012) for N-RSPO and P-RSPO cases and mill visits for C-RSPO case (2 mill visits). In palm oil mills, the oil extraction rate (in percentage, %OER) is commonly used to indicate mill performance. It shows the efficiency of extracting crude palm oil out of the palm fruits. A higher %OER is preferred, because then less FFB is needed, and less waste is generated. Our results indicate that the %OER is higher in C-RSPO mills (%OER = 18±0.1), than in N-RSPO mills (%OER = 17) and P-RSPO mills (%OER = 16). As a result, the P-RSPO mills have the highest FFB use (6.44 ton FFB/ton CPO) while producing most waste (1,376 kg EFB/ton CPO, 780 kg fibre/ton CPO, and 218 kg decanter cake/ton CPO). Technicians in the P-RSPO mills explained that the FFB price is typically based on weight, and not on quality. This is an incentive for smallholder farmers to cut unripe fruits with low oil content (low quality) to deliver to the mills. Furthermore, the middlemen, who collect and deliver FFB to the mills, spray water on the palm fruits and sometimes even add sand to increase the weight of FFB. These poor management practices of famers and middlemen deteriorate the quality of the fruits. It is clear that using low quality of FFB can reduce %OER and, as a result, increase waste-related problems.

Waste management in mills, particularly for EFB, is generally poor, as indicated during site visits and interviews. EFB is often openly dumped (uncontrolled landfill condition) in the N-RSPO and P-RSPO mills, whereas no open dumping of EFB was observed in the C-RSPO mills during the visits. This is because the RSPO certified mills (C-RSPO) are surrounded by large-scale company plantations so that they could manage to mulch all EFBs in their plantations. This practice is considered as recycling nutrients and in line with the RSPO P&C and also recommended by Fairhurst and McLaughlin (2009). It is, however, not yet widely implemented in the N-RSPO and P-RSPO mills, as their surrounding plantations are small-scale plantations, owned by smallholder farmers without trucks to transport the EFBs.

Wastewater or POME treatment in N-RSPO mills results in relatively high emissions (Volume = 4.6 m^3/ton CPO; COD_{inlet} = 85 kg/m^3; COD_{outlet} = 2 kg/m^3). They still use a traditional series of open lagoons (anaerobic condition) releasing large amounts of CH_4 emissions. Meanwhile, the P-RSPO (Volume = 3.8 m^3/ton CPO; COD = 70 kg/m^3 ; COD $removal_{biogas\ unit}$ = 54 kg/m^3 ; COD_{outlet} = 2 kg/m^3) and C-RSPO mills (Volume = 3.6±0.6 m^3/ton CPO; COD_{inlet} = 70±2.3 kg/m^3; COD $removal_{biogas\ unit}$ = 65±2.4 kg/m^3 ; COD_{outlet} = 1.7±0.6 kg/m^3) use biogas capture system to treat POME and then use biogas generators to produce power from biogas and sell to the grid.

For more details on activity data that are used in the calculations to quantify emissions of non-CO_2 greenhouse gases from plantations and mills in the Tapi River basin we refer to Saswattecha et al. (2015b).

5.4. Estimating emissions

In our approach, emissions are a function of activities and emission factors. We calculate emissions of non-CO_2 greenhouse gases from oil palm plantations (E_{FFB}) and palm oil mills (E_{CPO}) as follows:

$$\text{Emissions from plantations } (E_{FFB}) = \text{Activity } (A) \times \text{Emission Factor } (EF) \quad (1.1)$$

$$\text{Emissions from mills } (E_{CPO}) = \text{Activity } (A) \times \text{Emission Factor } (EF) \quad (1.2)$$

Activity data (*A*) and Emission Factors (*EF*) used for quantifying emissions were derived from Saswattecha et al. (Saswattecha et al., 2015b). The EFs are mainly derived from internationally accepted sources, such as the Intergovernmental Panel on Climate Change (IPCC), European Environment Agency (EEA) and the Eco-invent database (see Table D1, Appendix D). Next, the estimated emissions are converted to "CO_2-equilavents" using global warming potentials from IPCC.

In case of wastewater treatment without biogas capture, we calculated CH_4 emissions based on the amount of COD removal. Meanwhile, COD removal after biogas capture is used for wastewater treatment with biogas capture. Non-CO_2 emissions from EFB management depends on how it is disposed of. EFB is fully reused in the C-RSPO case so that we assume no CH_4 emissions. On the other hand, EFB is dumped in the open in the N-RSPO and P-RSPO cases. The associated CH_4 emissions are calculated as a function of the amount of EFB generated.

To calculate total emissions from palm oil production ($E_{T,\ RSPO}$), emissions from the oil palm plantations and from the palm oil mills were aggregated (Eq.2).

$$\text{Total Emissions } (E_T) = (E_{FFB} \times \%\text{FFB supply}) + E_{CPO} \quad (2)$$

From the mill visits we concluded that about one-third of FFB supply in C-RSPO mills is from C-RSPO plantations and almost two-thirds from N-RSPO plantations, while FFB supply in the P-RSPO mills is largely (95%) from N-RSPO plantations. For FFB supply in the N-RSPO mills, we assume that 100% is from N-RSPO plantations.

Next, the aggregated emissions are multiplied by CPO production capacity (*Cap*) to calculate the total emissions of palm oil production in the Tapi River basin (Eq. 3).

$$\text{Emissions in the Tapi River basin } (E_{Tapi}) = E_T \times Cap \quad (3)$$

The production capacity (*Cap)* in the Tapi River basin was derived from personal communication with mill operators and data from the Department of Internal Trade (DIT, 2012a, 2012b, 2011). N-RSPO mills produce 5,304,000 ton CPO/year, P-RSPO mills 2,520,000 ton CPO/year, and C-RSPO mills 936,000 ton CPO/year.

In palm oil mill processing, not only CPO is produced but also PK as a co-product. Our result shows that the production of 1 ton CPO generates 293 kg of PK. As CPO is a main feedstock for food and biodiesel production in Thailand we only consider emissions of CPO in this study. Part of the non-CO_2 greenhouse gas emissions are allocated to PK on the basis of a mass balance (CPO: PK) of 0.75:0.25, 0.77:0.23 and 0.80:0.20 for N-RSPO, P-RSPO and C-RSPO categories, respectively. Allocation can be based on different assumptions. Here we allocate based on mass for reasons of transparency and because all required information for this approach was available. Alternatives would be allocating based on energy or economic values. These are more complex approaches. Our mass based approach is commonly used, like for instance bySubramaniam et al. (2010) and Kaewmai et al. (2012). It would be interesting to test the sensitivity of the results for other allocation procedures in future studies.

5.5. Emissions of non-CO_2 greenhouse gases

5.5.1. Emissions from oil palm plantations (E_{FFB})

Nitrogen fertilisers, mainly associated with N_2O emissions, are the largest source of non-CO_2 greenhouse gas emissions, contributing by more than 95% to total emissions from all types of plantations (see aggregated emissions in Table 5.1 and disaggregated emissions in Table D2, Appendix D).

As indicated in section 3, farmers in the C-RSPO plantations use relative small amounts of N-fertilisers, while farmers in P-RSPO plantations seem to use much larger amounts. As a result, C-RSPO plantations have lowest emissions of non-CO_2 GHG, and P-RSPO plantations highest (Table 5.1).

Comparing C-RSPO with N-RSPO plantations indicates that implementing best-practices in RSPO P&C can reduce non-CO_2 greenhouse gas emissions from oil palm plantations by 10%. However, there are also good agricultural practices being promoted by the National Bureau of Agricultural Commodity and Food Standards (ACFS – TAS 5904-2010) which may stimulate farmers to follow good practices (ACFS, 2010).

Table 5.1 Emissions of non-CO_2 greenhouse gases from oil palm plantations in the year 2012.

Activity (*A*)	Non-CO_2 GHG Emissions from Oil palm plantations [1] (g CO_2eq/ton FFB)[2]		
	N-RSPO	P-RSPO	C-RSPO
Diesel - soil preparation	8	8	8
Mineral - N	25,872	28,633	23,397
Mineral - P	161	119	73
Mineral - K	494	402	653
Boron	-	1	1
Glyphosate	65	11	1
Gasoline - weed cutting	36	16	4
Diesel - FFB transport	40	8	5
Total	**26,676**	**29,199**	**24,140**

[1] E_{FFB} *calculated using equation 1*

[2] *The emissions of non-CO_2 greenhouse gases are expressed in CO_2-equivilents following the IPCC Guidelines for National Greenhouse Gas Inventories, using GWP values of 298 for N_2O and 25 for CH_4. See Saswattchea et al.*(2015b) *for details.*

5.5.2. Emissions from palm oil mills (E_{CPO})

POME treatment and EFB disposal, mainly associated with CH_4 emissions, are the main sources of non-CO_2 greenhouse gas emissions (see aggregated emissions in Table 5.2 and disaggregated emissions in Table D3, Appendix D). These CH_4 emissions account for 11-85% and 49-88% of total non-CO_2 greenhouse gas emissions, respectively, depending on how these waste materials are managed.
As indicated in section 3, N-RSPO mills treat POME by open (anaerobic) lagoons and openly dump EFB in the mill area. This results in higher emissions than for C-RSPO mills, that properly treat POME by biogas capture technology and manage EFB by mulching in their surrounding plantations. RSPO certified mills produce lowest non-CO_2 GHG emissions. Our results indicate that the practices of the RSPO certified mills have the potential to reduce CH_4 emissions from N-RSPO mills by 96% (for POME) to 100% (for EFB) (Table 5.2). Note that the practice of producing biogas from POME is considerably driven by the clean development mechanism, not by RSPO certification. This indicates that the practices in mills in the C-RSPO group go beyond RSPO certification requirements.

The captured CH_4 from POME treatment is used to generate electricity in the P-RSPO and C-RSPO mills. 95% of the generated electricity is exported to the grid and the remaining 5% are used in the mill. This electricity from biogas could eventually substitute the electricity supply from the grid during the plant start-up. As a result, emissions from electricity use in the P-RSPO and C-RSPO mills are lower than the N-RSPO mills.

Fibre is internally used in boilers for stream production and electricity generation. It may not be a significant source of non-CO_2 greenhouse gas emissions, but it is a significant source of other pollutants contributing to , for instance, acidification, smog formation and human toxicity (Saswattecha et al., 2015b).

Comparing C-RSPO with N-RSPO mills indicates that implementing best-practices could reduce non-CO_2 greenhouse gas emissions from oil palm mills in the Tapi basin by 98%.

Table 5.2 Emissions of non-CO_2 greenhouse gases from palm oil mills in the year 2012.

Activity (*A*)	**Non-CO_2 GHG Emissions - Palm oil mills[1] (g CO_2eq/ton CPO)[2]**		
	N-RSPO	**P-RSPO**	**C-RSPO**
Diesel - FFB loading	92	113	70
Electricity	271	206	208
Burning fibre	10,904	15,918	8,292
Kaolin	90	117	85
Alum	1	4	11
Sodium sulphite	4	2	5
Sodium carbonate	6	6	2
POME treatment	1,185,961	161,107	49,181
EFB disposal	1,129,683	1,275,578	-
Total	**2,327,012**	**1,453,050**	**57,855**

[1] E_{CPO} *calculated using equation 1*

[2] *The emissions of non-CO_2 greenhouse gases are expressed in CO_2-equivilents following the IPCC Guidelines for National Greenhouse Gas Inventories, using GWP values of 298 for N_2O and 25 for CH_4. See Saswattchea et al.*(2015b) *for details.*

5.6. Emissions from palm oil production (E_T)

Total non-CO_2 greenhouse gas emissions from palm oil production as calculated using equation 2 are shown in Figure 5.2. Emissions are presented for production of CPO by non-RSPO certified producers (N-RSPO), potential RSPO certified producers (P-RSPO) and RSPO certified producers (C-RSPO). Of these three types of producers, the C-RSPO producers who implement the best practices that go well beyond the RSPO P&C produce lowest non-CO_2 greenhouse gas emissions.

We found that there are three large sources of emissions: disposal of empty fruit bunches (EFB disposal), palm oil mill effluent treatment (POME treatment), and mineral N fertilisers (N-Fertiliser) (Figure 5.2). The relative share of these three sources varies among the type of mills, mostly depending on how POME and EFB are managed. In case of N-RSPO mills with no appropriate waste management, 48% and 46% of emissions are from POME treatment and EFB disposal, respectively. In P-RSPO mills, POME is treated by biogas capture systems so that the EFB disposal becomes the main contributor (81% of total emissions). Since POME and EFB are properly managed in the C-RSPO mills, N-fertiliser is the main source of emissions, contributing by 67% to total emissions.

To identify solutions for reducing non-CO_2 greenhouse gas emissions from CPO production, we therefore focused on these three sources. Reduction options are analysed and described in Emission reduction options section.

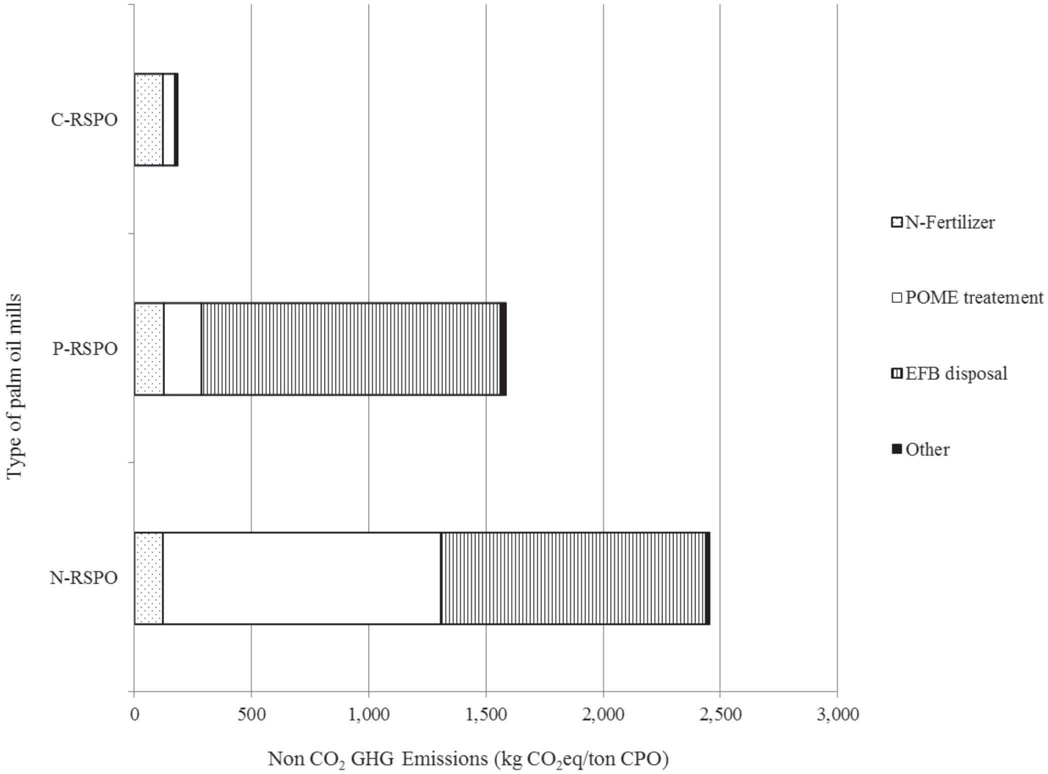

Figure 5.2 Emissions of non-CO_2 greenhouse gases from palm oil production by different types of mills in the Tapi river basin (See Tables 1 and 2 for a list of other sources).

5.7. Emission reduction options

5.7.1. Oil palm plantations – N-fertiliser management

Fertilisers are the largest source of non-CO_2 greenhouse emissions from plantations. Nitrogen inputs to soils increase microbial production of N_2O. This is a process that is difficult to control. The more nitrogen is available for nitrifying and denitrifying bacteria, the more N_2O will be produced. The most effective way to reduce these emissions is by increasing the N use efficiency of oil palm production. This can be achieved by proper management of agricultural fields, and effective fertilization strategies. Precision fertilization and soil analyses are ways to increase the N efficiency. The RSPO certified plantations use less fertiliser N than the other plantations, indicating there are opportunities for improvement in the Tapi river basin. However, the difference between certified and non-certified farms is relatively small, indicating that it is not easy to reduce fertiliser N application without yield loss.

5.7.2. Palm oil mills – Wastewater and Empty Fruit Bunch management

Large amounts of Palm-Oil-Mill-Effluent (POME) and Empty-Fruit-Bunches (EFB) are released after the production of Crude-Palm-Oil (CPO) (See Table 5.2). POME can be converted into environmental friendly produces through a variety of biological and physicochemical treatments such as anaerobic digestion treatment, composting, physicochemical treatments and membrane filtration. For the analysis of the effectiveness of the options (Table 5.3), anaerobic digestion was selected because it is the most suitable option to transform organic waste into biogas. This option leads to the most efficient recycling of waste and is increasingly applied in palm oil mills world-wide.

Anaerobic digestion is considered as a cost-effective solution for the treatment of organic waste since it effectively captures CH_4 emissions from effluent generated during CPO production. Captured biogas can be used as a renewable energy for mill operations such as fuel in a boiler, generation of steam and electricity. Moreover biogas could generate electricity that can be used internally or sold to the national electric grid (Chavalparit, 2006; Poh and Chong, 2009; Yoshizaki et al., 2013).

Non-RSPO certified mills use open ponding system for wastewater treatment. These, release relatively large amounts of methane (CH_4). Non-CO_2 GHG emissions from N-RSPO mills are 186 ton CO_2eq/ton CPO and from C-RSPO mills 0.49 ton CO_2eq/ton CPO (Table 5.2). This is mainly the result of options implemented in C- RSPO mills reducing CH_4 emissions from POME by 96% (Table 5.3).

Emissions from EFB can be reduced in at least three ways: mulching, pellet production and burning. These options have been applied in different RSPO members (in Malaysia, Indonesia and Colombia) in order to reduce GHG emissions (RSPO, 2013b). Nevertheless, more options to reduce emissions from EFB several measures are recommended, such as gasification, pyrolysis, ethanol production, fibreboard (Asadullah, 2014; Chiew and Shimada, 2013; Tan et al., 2010; Uemura et al., 2013), but they have not yet transformed to a commercial scale and widely implemented in Thailand.

Mulching consists of spreading empty fruit bunch (EFB) across the field, usually in a single layer. The type of mulching depends on plantations characteristics (in particular soil conditions and age of the palm). For instance, if there are immature palms (1-3 years) the EFB should be spread out 0.2 to 1.5 m away from the palm base (Hansen et al., 2012; Heriansyah, 2011). During the mill visits, no dumped EFB was observed in the C-RSPO mills. This implies that 100% of the EFB that is generated is used. In this study we, therefore, assumed a 100% reduction in EFB production if mulching is applied (Table 5.3).

Pellet production mainly includes the conversion of EFB to uniform and solid pieces that can be used as a fuel. One of the advantages of this option is that it provides an easy way to transport EFB as well to handle it and store it. Also, it increases the combustion quality since there is a reduction in moisture content increasing the energy content or calorific value. This makes burning EFB more effective (Chiew and Shimada, 2013; Kerdsuwan and Laohalidanond, 2011). For pellet production, it is assumed it can reduce the volume of EFB by 100% (Table 5.3).

There are different ways to burn EFB. This study only considers using a boiler. Thermo-chemical and biological processes are excluded from the analysis. Burning in boilers may reduce non-CO_2 GHG emissions by 99% (Table 5.3). Two assumptions were made. Firstly, burning EFB is assumed to reduce the total volume of EFB produced during the production of 1 ton of CPO by 100%. Secondly, methane (CH_4) and nitrous oxide (N_2O) emissions are calculated due to the biomass burning activity.

Table 5.3. Potential reduction factors for emissions, activity levels (only for EFB options) and greenhouse gas emissions for the selected reduction options in mills.

Waste generation	Option	Reduction factor (fraction)		Reference case		Activity level after the option is applied (kg EFB/ton CPO)	Emissions after the option is applied (kg CO_2 eq/ton CPO)
		Emission	Activity level	Emission (kg CO_2eq/ton CPO)	Activity level (kg/ton CPO)		
POME	Anaerobic digestive system*	0.96	n.a	1,186	n.a	n.a	47
EFB	Mulching*	n.a	1	1,130	1,251	0	n.a
	Pellet**	n.a	1	1,130	1,251	0	n.a
	Burning**	0.99	n.a	1,130	1,251	n.a	11

n.a: not applicable
** This is an option that has already been implemented in the RSPO certified mills*
*** This is an alternative option that has not yet been implemented in any mills in this study*

Anaerobic digestion may reduce non CO2 GHG emissions from POME by 96%. On the other hand, the best options that would help to reduce emissions emitted from EFB are mulching and pellet production.

In the following, only reduction options that are currently applied in the C-RSPO mills implementing best practices are selected for further analyzing the future trends.

5.8. Future trends

5.8.1. Description of scenarios

Figure 5.2 indicates that improving the production processes in the N-RSPO plantations and mills in the Tapi river basin could reduce non-CO_2 greenhouse gas emissions in the basin. Based on available information, we, therefore, explored two alternative scenarios assuming an increase in the number of millers adopting the best practices of the mills that we named as "RSPO certified". Increasing numbers of RSPO certified mills, will increase the number of RSPO certified plantations because the RSPO certified plantations supply about one third of the FFB input to RSPO certified mills. In addition, it would reduce the distance of FFB transportation from plantations to mills to some extent, such as no FFB deliver by middlemen is needed when a N-RSPO farmer becomes a C-RSPO farmer. It must be noted that the reduction in distance is not always resulted from adopting the best practices in RSPO certification. We named these two alternative scenarios as the *Modest* and the *Ambitious* Scenario. They differ from the current situation as follows.

(1) Current situation

- Non-RSPO certified mills are dominating in the Tapi River basin with a CPO production capacity of 5,304,000 ton CPO/year or 60% of total CPO production in the basin, followed by P-RSPO mills (2,520,000 ton CPO/year or 29%) and C-RSPO mills (936,000 ton CPO/year or 11%). This information was derived from personal communication and data from Department of Internal Trade (DIT, 2012a, 2012b, 2011).
- Current management practices of these three types of mills are 1) None of reduction options are used in the N-RSPO mills, 2) Anaerobic digestion or Biogas capture is used for POME treatment in the P-RSPO mills and 3) Anaerobic digestion or Biogas capture is used for POME treatment and mulching is used for EFB disposal in the C-RSPO mills.

(2) Modest Scenario

In the Modest Scenario, we assumed that existing P-RSPO mills will follow best practices of C-RSPO mills and half of the existing N-RSPO mills will follow practices of the P-RSPO mills.

- CPO produced by the N-RSPO mills decreases to 2,650,000 ton CPO/year or by 30% whereas P-RSPO and C-RSPO mills produce more: 2,650,000 ton CPO/year (30%) and 3,460,000 ton CPO/year (40%), respectively.
- The increasing number of P-RSPO and C-RSPO mills leads to more mills applying reduction options for POME treatment (Biogas capture) and EFB disposal (Mulching).

(3) Ambitious Scenario

In the Ambitious Scenario, we assumed that all existing mills in the Tapi River basin would follow best practices in line with the mills that we labelled RSPO certified.

- All CPO produced in the Tapi river basin is from C-RSPO mills with a CPO production capacity of 8,760,000 ton CPO/year.
- All mills in the Tapi river basin apply reduction options for POME treatment (Biogas capture) and EFB disposal (Mulching).

5.8.2. Scenario analysis

We quantified emissions of non-CO_2 greenhouse gases to the Tapi river basin following the equation 3. The current emissions are largely from N-RSPO mills, accounting for 76% of total emissions in the basin. This is because these mills are dominating in the basin (60% of total CPO production in the basin). The scenario analysis shows that emissions of non-CO_2 greenhouse gases from the Tapi river basin under the alternative scenarios (Modest and Ambitious) are lower than that in the current situation (Figure 5.3). In the Modest Scenario, non-CO_2 greenhouse gas emissions are about one-third lower than in the current situation. For the Ambitious Scenario, we calculated a considerably larger reduction in non-CO_2 greenhouse gas emissions (91% reduction when compared with the current situation). By assuming that all mills in the Tapi River basin are adopting the best-practices as in current C-RSPO mills, emissions of non-CO_2 greenhouse gases could be greatly reduced.

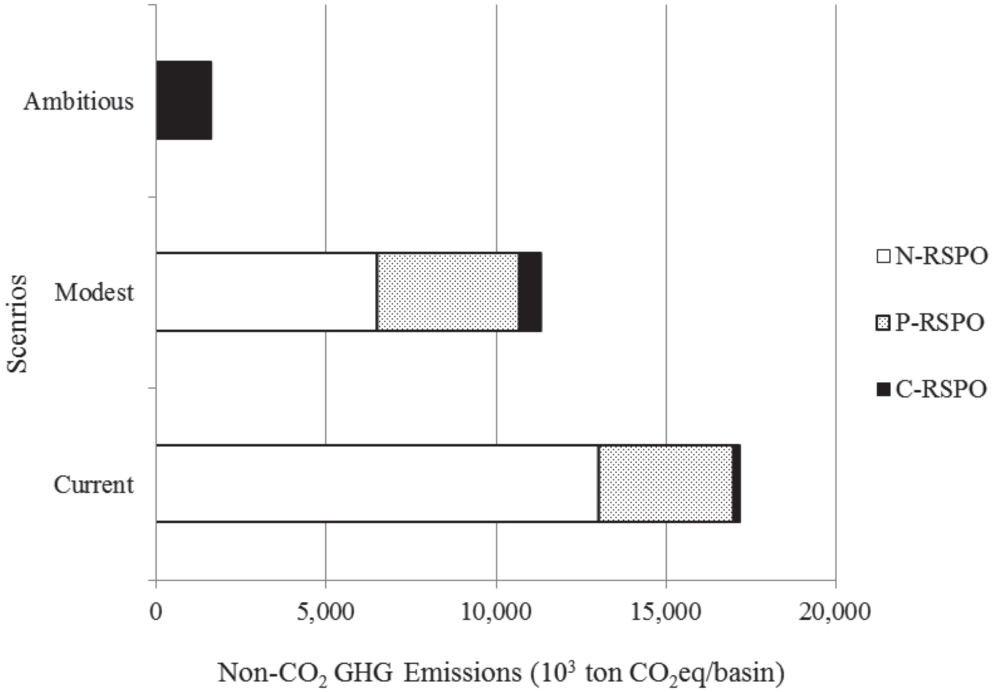

Figure 5.3 Non-CO_2greenhouse gas emissions from palm oil production in N-RSPO, P-RSPO and C-RSPO mills under different scenarios for the Tapi River Basin.

5.9. Discussion and conclusions

We quantified present and future emissions of CH_4 and N_2O from palm oil production in the Tapi river basin in Thailand. Our analysis distinguishes between emissions from oil palm plantations and palm oil processing mills. Our analysis indicates that there is a large potential for emission reduction. Current emissions are typically close to 2.5 ton CO_2-eq per ton of CPO produced. If, however, all producers would implement pollution reduction options that are currently applied by the few RSPO certified producers, emissions could be reduced to less than 0.2 ton CO_2-eq per ton of CPO produced. We found that it is technically possible to reduce emissions by more than 90%, compared to current practice. The total emissions of non-CO_2 greenhouse gasses from palm oil production in the Tapi river basin can be reduced from about 17 to about 2 million ton CO_2-eq per year. Many of the technical options (e.g. biogas, mulching) are widely applied in modern plantations and mills in Asia (Chavalparit, 2006; Hansen et al., 2012; Heriansyah, 2011; Kaewmai et al., 2013c; Poh and Chong, 2009; Yoshizaki et al., 2013)and have also been proven to be cost-effective, for instance because they lead to increased electricity production (biogas) or reduced need for fertilisers (e.g. mulching).

These reductions can be achieved by improved management of waste and wastewater. Empty-fruit-bunch (EFB) and Palm-oil-mill-effluent (POME) are the largest sources of non-CO_2 greenhouse gases, and technologies exist to reduce these emissions very effectively are anaerobic digestion or biogas capture for POME treatment and mulching, pellet production and burning for EFB. Nowadays, the biogas capture technology for POME treatment is a feasible and practical solution for palm oil mills. In contrast, reducing emissions from EFB may be more difficult to implement in practice. For instance, mulching EFB in the plantations is difficult. Most palm oil mills in Thailand do not own large-scale plantations. They are usually surrounded by small-scale and scattered plantations owned by smallholders who have no trucks to carry back the large volume of EFB. Burning of EFB is not yet widely implemented in Thailand due to capital investment barrier, maintenance of the boilers and insulation of tubes problems (Cuevas Remero, 2014). However, it seems to be feasible in the near future as the Thai government is currently promoting renewable energy from biomass. For pellet, there is currently no market in Thailand and pilot projects are required to evaluate if and how pellets can be used. In our study we only considered non-CO_2 greenhouse gasses, and we excluded the effects of land use change (which may lead to additional CO_2 and non-CO_2 greenhouse gas emissions) and we are not able to quantify the relative importance of CO_2 versus non-CO_2 greenhouse gasses in the sector. Nevertheless, our study shows that non-CO_2 greenhouse gasses comprise a significant emission, 17 million ton CO_2-eq per year, and that there are significant possibilities to reduce these emissions using proven and cost-effective technologies.

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Chapter 6

Improving environmental sustainability of Thai palm oil production in 2050

6. IMPROVING ENVIRONMENTAL SUSTAINABILITY OF THAI PALM OIL PRODUCTION IN 2050

Abstract

Palm oil production has increased in Thailand with considerable environmental impacts. The aim of this study is to analyse possibilities to examine how the environmental sustainability of Thai palm oil production can be improved in the coming decades. To this end, we integrated a sectoral and a landscape model in order to analyse scenarios for 2050. We do this with a focus on options to reduce (1) the effects of land use change on ecosystem services, and (2) the environmental impact of oil palm plantations and palm oil mills. Four future scenarios are developed; Business as Usual (BAU), Current Policy (CP), Strong Growth (GRT) and Green Development (GRN). The BAU scenario indicates that environmental impacts may double without additional improvement options. The CP scenario shows that current plans to increase palm oil production would considerably increase environmental impacts. Implementing only cost-effective options, as in the GRT scenario, is also not enough to avoid an increase in environmental impacts if the export of palm oil increases faster than currently envisaged. The GRN scenario assumes implementation of a combination of effective options, regardless of their costs. This would considerably reduce environmental impacts. Thus it is technically possible to improve environmental performance of palm oil production in Thailand.

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6.1. Introduction

During the past decades, oil palm cultivation in Thailand tripled (FAOSTAT, 2016b; OAE, 2016a). New oil palm plantations mainly replace existing crop or rubber plantations. However, since 2000, also natural forests have been cleared for plantations (Anonymous, 2010; Aratrakorn et al., 2006; Saswattecha et al., 2016a). Deforestation led to a loss in ecosystem services, resulting in the release carbon into the atmosphere. It also affects biodiversity conservation and water regulation (Babel et al., 2011; Saswattecha et al., 2016a).

The rapid expansion in Thai oil palm cultivation results from national policies that aim to promote the production of biodiesel, which is considered a clean fuel (Dallinger et al., 2013; Daniel and Gheewala, 2010; Kumar et al., 2013). However, the production of palm oil is also an important contributor of environmental pollutants, contributing to several problems such as global warming, eutrophication, acidification and air pollution. In addition, nutrients may be leaching from fertilized fields. The mills are sources of acidifying compounds and smog precursors from fibre combustion in boilers. And there are methane emission from disposal of palm oil-mill-effluent (POME) and empty-fruit-bunches (EFB) (Saswattecha et al., 2015b). This leads to the question whether or not Thai palm oil is produced sustainably (FAO and Nations, 2010; Kumar et al., 2013; Silalertruksa and Gheewala, 2012).

Comprehensive information on the overall environmental impact of palm oil production in Thailand is lacking. Likewise, it is not clear what possibilities exist to improve the environmental performance in the future. Such information is essential for policy makers as well as palm oil producers for future planning. Scenario analyses can be used to describe alternative images of the future reflecting the past, present and future development (Miser and Quade, 1988) and to provide information on the consequences of alternative decisions (Alcamo, 2008). Although it is widely applied in environmental systems analysis (Jawjit et al., 2008; Neto et al., 2009; Pluimers, 2001), no scenario analyses have been performed on the environmental sustainability of palm oil production in Thailand.

The aim of this study is to analyse possibilities to improve the environmental sustainability of palm oil production in Thailand in the coming decades. To this end, we integrated a sectoral and a landscape model that we recently developed in order to analyse future scenarios of palm oil production for the year 2050 with a special focus on options to reduce (1) the effects of land-use-change (LUC) caused by oil palm expansion on ecosystem services and (2) the environmental impacts of the plantations and mills. The results of this study could support policy makers and palm oil producers to develop plans to improve the environmental sustainability of palm oil production in Thailand.

6.2. Model description

Our analysis is based on two models that we recently developed; a sectoral and a landscape model for palm oil production in Thailand (we refer to crude-palm oil (CPO)) (Saswattecha et al., 2016a, 2016b). We linked these models and performed scenario analyses to evaluate the potential to reduce the overall environmental impact in 2050 (Figure 6.1). The landscape model is used to analyse potential LUC and its effects on ecosystem services; including carbon storage, biodiversity conservation and food and non-food provisioning services (Saswattecha et al., 2016a). The sectoral model is used to assess the effects of options for reducing environmental impacts of oil-palm plantations and palm oil mill operations (Saswattecha et al., 2016b). Six environmental impact categories are taken into account in the sectoral model; global warming, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater toxicity. These two models are described in more detail in Appendix E1.

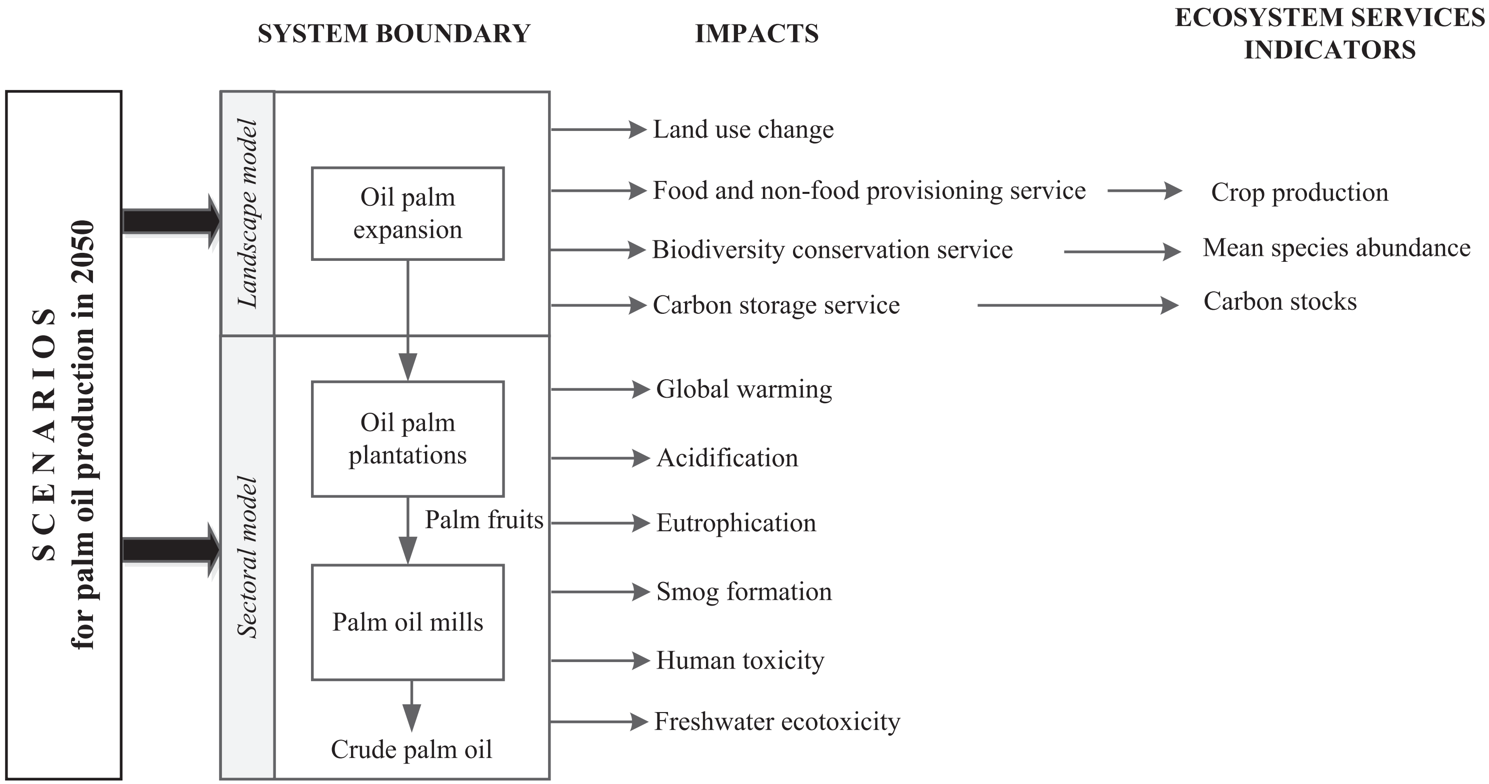

Figure 6.1 Overview of how the landscape and sectoral models are coupled in this study to analyse the environmental impacts of oil palm production

6.3. Scenario description

We developed four scenarios for the period 2012-2050: the business-as-usual (BAU), current-policy (CP), strong-growth (GRT) and green-development (GRN) scenarios. Tables 1-3 present scenario descriptions and assumptions (see Appendix E2 for details). For each scenario, we quantified LUC effects of oil palm expansion on three ecosystem services, and six environmental impacts of palm oil production (Figure 6.1). Three important factors are palm oil production capacity, land-use-management (LUM), and implementation of mitigation options (Figure 6.2).

The palm oil production capacity is mainly driven by the policy to promote biodiesel production (refer to Alternative Energy Development Plan: AEDP), launched by Ministry of Energy (MOE) (DEDE, 2012a). This policy sets the target for biodiesel production at almost 6 million litres per day, which requires approximately 3.9 million tons of palm oil. To meet this target, the Ministry of Agriculture and Cooperatives (MOAC) launched a strategic plan to increase oil palm plantations to 1.2 million ha, fresh-fruit-bunch (FFB) yields to 22 ton/ha and oil extraction rates to 20% by the end of 2026 (OAE, 2014). Some of the mitigation options in this study, such as cover crops, harvesting ripe fruits, mulching EFB and oil recovery from decanter cake, can increase FFB yields and oil extraction rates (Table 6.3). For our combination of options, we calculate the increase in FFB yields. These increases can contribute to meet the set targets for improving FFB yields and oil extraction rates in future scenarios.

LUM is the second important factor underlying our scenarios. It is influenced by national policies, as well as the international market. For instance, the Roundtable on Sustainable Palm Oil (RSPO) standard requires a new oil palm area to avoid using land that contains high carbon stocks (i.e. forests and peatland). Moreover, environmental mitigation options are important, as regulated by renewable energy policies and environmental regulations.

The base year for our study is 2012, which is the most recent year for which adequate data is available. Data on the environmental management of palm oil production, LUC effects of oil palm expansion, implementation of mitigation options in 2012 and for future years are taken from our previous studies (Saswattecha et al., 2016a, 2016b, 2015b).

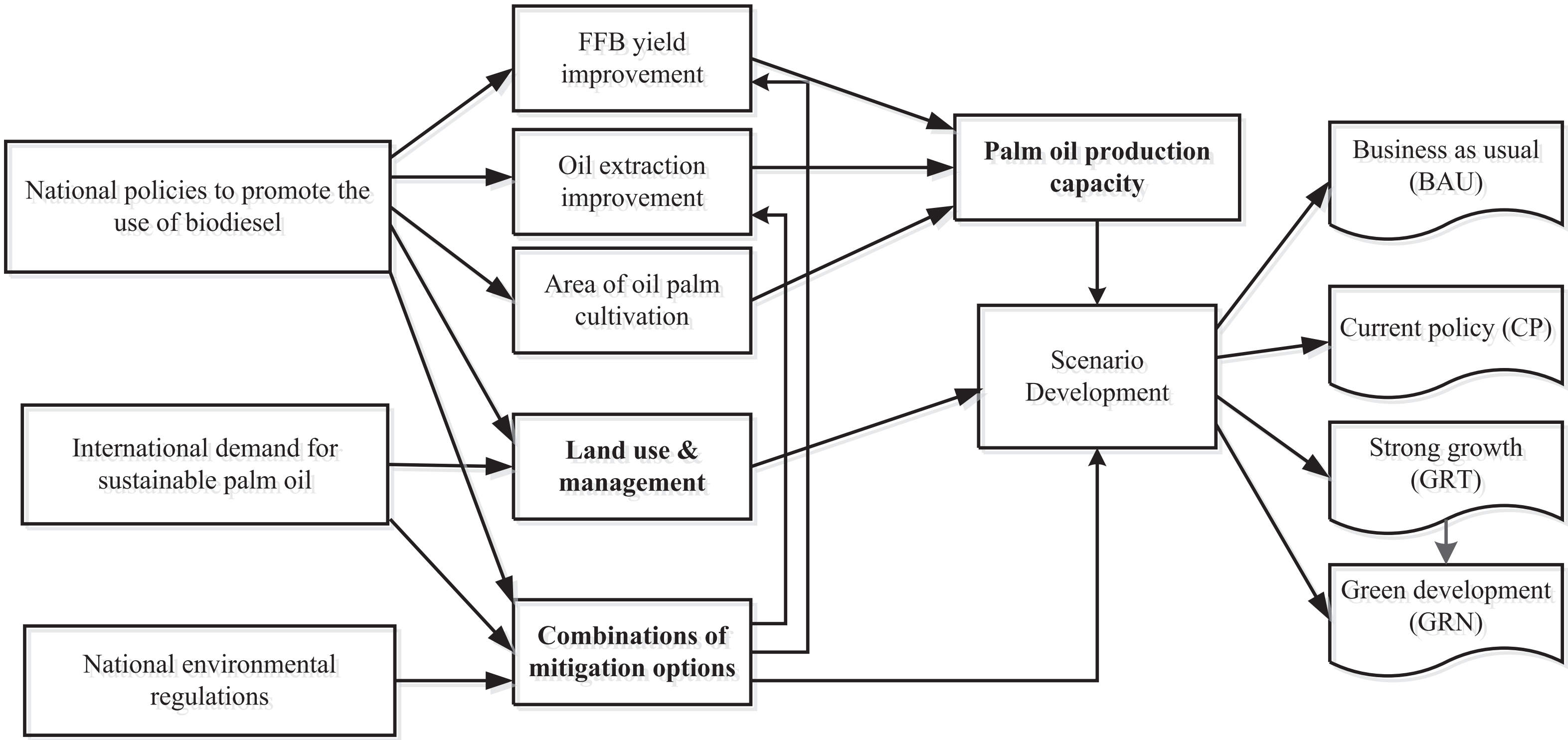

Figure 6.2 Overview of how four scenarios in this study were developed. The **bold text** indicates important drivers that were used to develop a series of scenarios. Dotted lines show that some of mitigation options may increase FFB yields in the plantations and improve oil extraction rate in the mills

Table 6.1 Description and assumptions of the base year and future scenarios for the Thai palm oil production in 2050 (see more details in Appendix E2). These scenarios are developed based on the current situation and Ministry of Agriculture and Cooperatives (MOAC)'s plan

Scenarios	Description	Assumptions			
		Land-use- management (LUM)[*]	Fresh Fruit Bunch (FFB) yields	Oil extraction rate (%OER)	Implementation of mitigation options[**]
Base year (2012)	The year 2012 is selected to show the current environmental management of palm oil production in Thailand.	0.7 million ha of oil palm area. Expanding oil palm area without land-use planning, and mainly replacing cropland.	19 ton/ha	17%	Biogas capture system, mulching EFB and EFB-combustion
Business-as-usual (BAU)	This scenario assumes that current environmental management of palm oil production in Thailand remains unchanged until 2050, and that no new environmental policies are implemented. There is a moderate growth in the oil palm production area	Expanding oil palm area up to 1.5[1] million ha in 2050 without implementation of land-use planning and mainly replacing cropland.	Yields remain 19 ton/ha until 2050.	%OER remain 17 until 2050.	Biogas capture system, mulching EFB and EFB-combustion
Current-policy (CP)	This scenario follows the MOAC plan to increase palm oil production for the domestic market, and assumes a continued increase until 2050. No additional environmental policies are implemented. This scenario can be seen as "the most likely future".	Expanding the area up to 2.1[2] million ha in 2050, mainly replacing cropland.	Yields increase up to 27[2] ton/ha in 2050.	%OER increase up to 25[2,5] in 2050.	Biogas capture system, mulching EFB and EFB-combustion
Strong-growth (GRT)	This scenario assumes a fast increase in the export of palm oil following international sustainability standards (RSPO).	Expanding the area up to 3.4[3] million ha in 2050, mainly replacing cropland.	Yields increase up to 35[3,4] ton/ha in 2050.	%OER increases up to 25[3,5] in 2050	The most paying and effective options are implemented.
Green-development (GRN)	This scenario assumes a shift towards environmentally friendly palm oil production, mainly for the domestic market.	Expanding the area up to 1.7[6] million ha in 2050, mainly replacing non-cropland.	Yields increase up to 35[3,4] ton/ha in 2050.	%OER increases up to 25[3,5] in 2050	The most effective options in each group of options are implemented.

[*] *See Table 6.2 for LUM practices.*
[**] *The proposed options are from our previous study* (Saswattecha et al., 2016b) *(Table 6.3)*
[1] *Expanding area by 2% per year* (Saswattecha et al., 2016a).
[2] *Based on the base year and the MOAC targets, we assume an annual growth rate of 0.04 million ha for oil palm planted area between 2012 and 2016, 0.21 ton/ha for FFB yields and 0.21% for oil extraction rate in the CP scenario.*
[3] *In the GRT and GRN scenarios, we assume that the annual growth rates of palm planted area, FFB yields and oil extraction rates are twice as high as in the CP scenario.*
[4] *Options that can improve FFB yields include: the right breeding program, irrigation management, planting density management, mulching EFB, and harvesting ripe fruits* (AgriSource, 2005; Heriansyah, 2011; Tiitinutchanon and Nakharin, 2012; Vengeta et al., 2008). *These can increase FFB yields in Thailand up to 40 ton/ha* (Tiitinutchanon and Nakharin, 2012; Vengeta et al., 2008). *We assume 35 ton FFB/ha feasible.*
[5] *assumed feasible for Thailand based on expert judgment.*
[6] *An increased oil palm area up to 1.67 million ha is assumed consistent with a sustainable scenario, following from our assumptions on suitable areas for oil palm development. See also Table 6.2 and Appendix E2.*

Table 6.2 Overview of land-use-management and specific assumptions for oil palm expansion in future scenarios

Land-use type converted to oil palm plantations	Base year (2012)	Business-as-usual (BAU)	Current-policy (CP)	Strong-growth (GRT)	Green-development (GRN)
Cropland (i.e. rubber, rice, and orchard)	65% of new oil palm plantations will be replacing cropland[a] without consideration of land suitability.	As the base year	Some cropland that is classified as highly or moderately suitable[b] for oil palm will be converted to oil palm plantations.	As the Current Policy scenario	Only cropland that is classified as highly suitable[b] for oil palm will be converted to oil palm plantations.
Natural ecosystems (i.e. forest, grassland and scrubland)	25% of new oil palm plantations will be replacing natural ecosystems[a] without a consideration of land suitability. Out of these, 5% are converted from natural forests and 20% are from grassland and scrubland.	As the base year	Natural forests are fully protected. Meanwhile, all available areas of grassland and scrubland in the suitable provinces[c] is converted to oil palm, but not more than in the BAU scenario.	As the cCurrent Policy scenario	All available areas of grassland and scrubland in the suitable provinces[c] will be converted to oil palm plantations.
Abandoned-land (i.e. abandoned rice fields, abandoned mining pits and bare land)	10% of new oil palm plantations will be established in abandoned rice fields[a].	As the base year	All available areas of abandoned-land in the suitable provinces will be converted, but should not exceed the area in the BAU scenario[c].	As the Current Policy scenario	All available areas of abandoned-land in the suitable provinces[c] will be converted to oil palm plantations.

[a] *Estimated from our previous study (Saswattecha et al., 2016). Detailed LUC patterns of oil palm expansion in the base year and BAU are presented in Appendix E2 (Table E2.1)*

[b] *Areas of cropland that are classified as highly and moderately suitable for oil palm cultivation are presented in Appendix E2 (Table E2.2), and derived from the LDD study on land suitable for oil palm (Anuraktiphan, 2010).*

[c] *The suitable provinces for planting oil palm are determined based on the LDD study on land suitability for oil palm (Anuraktiphan, 2010) and water stress index for fuel crop production (Gheewala et al., 2014). The available area of non-cropland (i.e. grassland, scrubland and abandoned-land) are from provincial LDD land-use data (Table E2.3 in Appendix E2).*

Table 6.3 Combinations of mitigation options in the base year and four scenarios (BAU, CP, GRT and GRN; options indicated with ✓are assumed to be combined in the scenarios). Information of mitigation options is taken from our previous study (Saswattecha et al., 2016b). A description of the scenarios is provided in Table 6.1.

Sub-system	Group of options	Options	2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Oil palm plantations	Optimising fertilisers use	Apply optimum dose of fertilisers	×	×	×	×	✓
		Apply slow-release fertilisers	×	×	×	×	✓
	Weed control	Cover crops	×	×	×	✓	✓
	Yield improvement	Harvesting ripe fruits	×	×	×	✓	✓
Palm oil mills	POME treatment	Biogas capture system	✓[1]	✓[1]	✓[1]	✓[3]	×
		Bioreactor plus upgrading biogas plant	×	×	×	×	✓
	EFB treatment	Mulching EFB	✓[2]	✓[2]	✓[2]	✓[4]	×
		EFB composting plant	×	×	×	✓[5]	×
		EFB-combustion	✓[2]	✓[2]	✓[2]	×	✓
		EFB ethanol production	×	×	×	×	×
		EFB pellets production	×	×	×	✓[5]	×
		EFB gasification	×	×	×	×	×
	NOx control for burning fibre	Non-thermal Plasma	×	×	×	×	✓
		Selective catalytic reduction	×	×	×	×	×
		Selective non-catalytic reduction	×	×	×	×	×
		Low-NOx burner	×	×	×	×	×
	SO_2 control for burning fibre	Wet scrubber	×	×	×	×	✓
	VOC control for burning fibre	Thermal incinerator	×	×	×	×	✓
	PM control for burning fibre	Cyclones	×	×	×	×	×
		Baghouse	×	×	×	×	✓[6]
		Electrostatic precipitator	×	×	×	×	×
	Boiler efficiency improvement	Pre-heating fibre	×	×	×	✓	✓
	Oil extraction improvement	Oil recovery from decanter cake	×	×	×	✓	✓[6]
		Oil recovery from fibre	×	×	×	×	✓[7]
		Oil recovery from POME	×	×	×	×	✓[7]
		Oil recovery from EFB	×	×	×	×	✓[7]
Total annual cost[8] ($/ton CPO/year)			**-44**	**-44**	**-44**	**-340**	**17**

1 - *We assume that 60% of palm oil mills in Thailand apply biogas capture system in this scenario.*

2 - *In this scenario, about 40% of EFB is left untreated whereas 30% of EFB is used for mulching in the plantations, 20% of EFB is used for combustion, and 10% of EFB is used for mushroom cultivation* (DEDE, 2012b; Papong et al., 2004; Saswattecha et al., 2016b). *We assume that using EFB for mushroom cultivation causes no environmental impacts.*

3 - *In this scenario, 80% of Thai palm oil mills applies biogas capture system in 2050.*

4 - *In our previous study (Saswattecha et al., 2016b), mulching EFB was found to be the most paying option with a positive net return. We therefore assume that 60% of untreated EFB is used for mulching.*

5 - *Currently, there is no market for EFB-compost and EFB-pellets in Thailand* (Cuevas Remero, 2014; Saswattecha et al., 2015a). *EFB composting is more environmental-friendly than EFB pellet production (Chiew and Shimada, 2013). We, therefore, assume that 30% of untreated EFB is used for composting and 10% for pellet production.*

6 - *Reduction potentials of baghouses and electrostatic precipitator are the same, but the total costs of baghouses are lower. We therefore assume that baghouses are used in this scenario.*

7 - *This scenario assumes that all options to recover oil loss are implemented.*

8 - *Total annual costs are from our previous study (Saswattecha et al., 2016b). A negative total annual cost means that the benefits of the options exceed the costs.*

6.4. Results

6.4.1. Palm oil production in 2050

Annual production of palm oil increases by a factor of two to ten between 2012 to 2050 in the different scenarios (Figure 6.3), and ranges from 5 million (BAU) to almost 30 million (GRT) tons per year. To meet the target of biodiesel production in the AEDP, at least 3.9 million tons of palm oil is required. Palm oil production in the BAU scenario will reach this amount by 2036. In the CP, GRT and GRN scenarios this production is reached before 2036, approximately 15 years earlier.

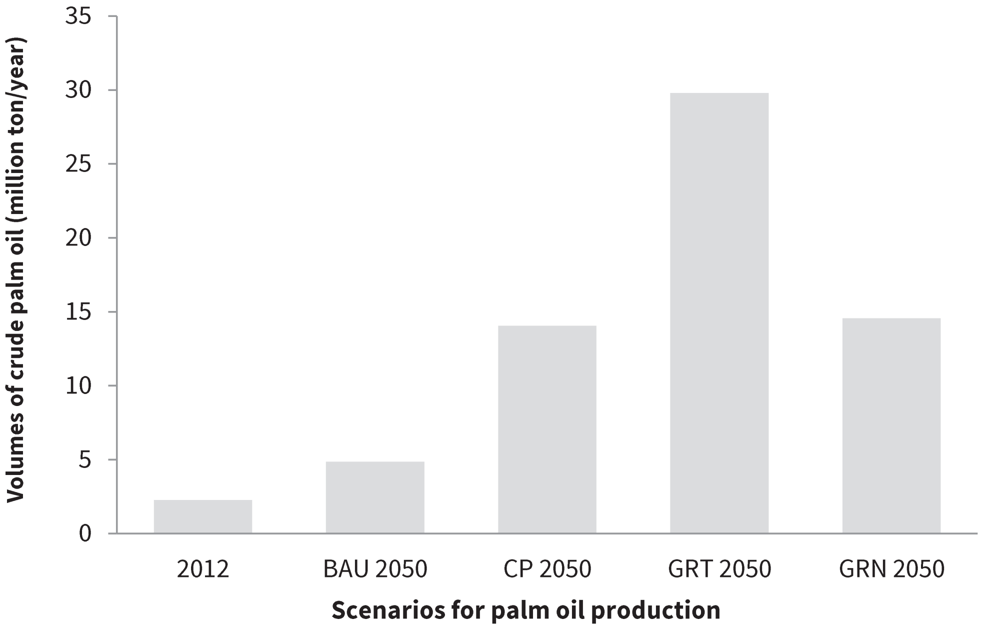

Figure 6.3 Crude palm oil production in 2012 and 2050. See section 3 for scenario descriptions.

The scenarios assume that FFB yields increase from 19 ton/ha in 2012 to 27-35 ton/ha in 2050 (Table 6.1). Some of the mitigation options help to realize this because they increase FFB yields as a side-effect. This holds, for instance, for harvesting ripe fruits and mulching EFB. Implementing such options helps to realize assumed FFB yields in the future. However, even if all options are realized, they increase FFB yields to not more than 25 ton/ha. To achieve 27-35 ton/ha, additional measures are needed, such as improved land management, breeding programs, irrigation management and planting density management (Tiitinutchanon and Nakharin, 2012; Vengeta et al., 2008).

6.4.2. Potential land-use-change (LUC) in 2050

An overview of LUC caused by oil palm expansion in 2050 is presented in Figure 6.5a while the detailed results are summarised in Appendix E3 (Table E3.1).

In the BAU scenario, the oil palm area doubles between 2012 and 2050. In this scenario MOAC's oil palm zoning policy is not implemented. As a result, natural forests are converted to oil palm plantations (up to approximately 40,000 ha deforestation in 2050). Forests are considered free land that farmers can easily grab, while cropland needs capital investment. Nevertheless, rubber plantations will be the most frequently converted to oil palm plantations, followed by orchard plantations, grassland and scrubland.

In the CP scenario, we assume that land-use is managed. Expanding oil palm plantations occur on arable land, replacing existing crops. This is done while taking into account land suitability (high and moderate suitability classes). Moreover, natural forests are well protected in 2050. As a result, about 112,000 ha or 80% of the new oil palm area in 2050 will result in the conversion of cropland, especially rubber plantations. Therefore, almost 20% of the plantation area will be in non-cropland (i.e. grassland, scrubland and abandoned-land).

In the GRT scenario, the assumptions on LUM are the same as in the CP scenario. This results in a similar LUC pattern, but in larger areas: approximately 2,470,000 ha or 90% of the new oil palm area will be from cropland. Rubber conversion contributes to almost 60%.

In the GRN scenario, oil palm areas mainly expand in what was non-cropland. The total plantation area is about 800,000 ha (or 80% of the new oil palm area in 2050). Only cropland that is highly suitable for oil palm plantations is used; this area is almost 180,000 ha (Table C1). We realise that some of non-cropland may be unsuitable or have a relatively low suitability for oil palm. Additional measures to maximise FFB yields are needed to meet the assumed FFB yields and oil extraction rates.

6.4.3. Impact on ecosystem services in 2050

The impact of expanding oil palm production on selected ecosystem services is illustrated in Figure 6.5b – 6.5d. Detailed results are summarised in Appendix E3.

6.4.3.1. Carbon storage service

Carbon (C) stocks are declining by expanding oil palm plantations in the BAU, CP and GRT scenarios, releasing 13-100 million tons of C into the atmosphere (Figure 6.5b and Table E3.2, Appendix E3). This is because natural forests and rubber plantations have larger carbon stocks than oil palm plantations. On the other hand, oil palm expansion in the GRN scenario increases the carbon storage. Almost 20 million tons of C from the atmosphere is sequestered in this scenario. This results from conversions of non-cropland, with lower carbon stocks, to oil palm plantations.

6.4.3.2. Biodiversity conservation service

We expressed the biodiversity as mean species abundance that corresponding to land-use (MSA_{LU}) (see also Table E3.3 and Table E3.4, Appendix E3 for details). Conversion of cropland to oil palm plantations has almost no effect on biodiversity. This follows from our assumption that all cropland have the same MSA_{LU}. This is also a case for conversion of grassland and scrubland to oil palm plantations. On the other hand, the conversion of forests to oil palm plantations lead to larger biodiversity losses. However, in some cases, oil palm plantations increase biodiversity (Figure 6.5c). This is the case after conversion of abandoned-land (i.e. abandoned rice fields, abandoned mining pits and bare land).

6.4.3.3. Food and non-food provisioning service

Oil palm expansion in all scenarios increases the production of FFB but decreases production of other crops (i.e. rice, fruits, maize, cassava and latex) (Figure 6.5d and Table E3.5, Appendix E3). In the BAU scenario, we assume that there is no LUM. This results in a broad range of crop losses, in particular in fruit production. Similarly, we assume that the LUM for oil palm expansion in the CP and GRT scenarios focuses on cropland conversion. As a result, there is a large loss in latex and rice production. In the GRN scenario, crop losses are small because the new oil palm area will mainly expand in non-cropland (i.e. grassland, scrubland and abandoned-land).

Our results indicate that expanding oil palm areas without LUM results in reduced fruit and rice production. This is a “food security” issue. This illustrates the importance of policies to ensure an appropriate balance between energy crops and food production.

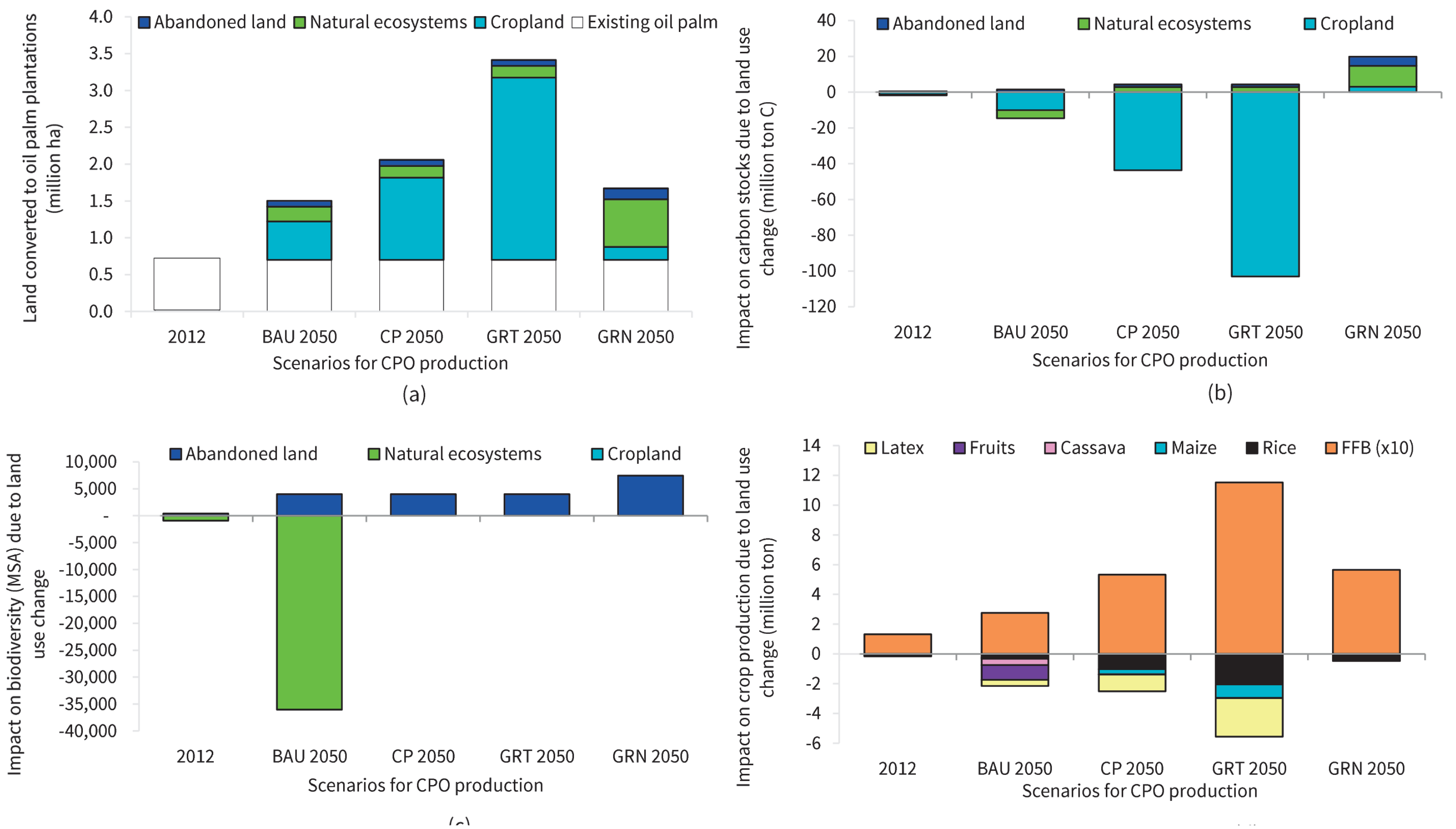

Figure 6.4 Overview of land-use-change caused by oil palm expansion in 2050 and its effects on selected ecosystem services; (a) Land-use-change, (b) Carbon storage service, (c) Biodiversity conservation service and (d) Food and non-food provisioning service. Negative values imply negative impacts (or loss of ecosystem services).

6.4.4. Environmental pollution by palm oil production in 2050

Figure 6.4 shows the environmental pollution from plantations and mills for 2012 and 2050. The environmental pollution is determined by the mitigation options (Table 6.3) and volumes of palm oil production in the four scenarios (Figure 6.3).

The BAU scenario assumes that the environmental management remains as in 2012, while palm oil production increases. As a result, environmental pollution for this scenario is twice as high as in 2012.

In the CP scenario, implementation of the current policy and plans will lead to a faster increase in palm oil production than in BAU, without implementation of additional mitigation options. As a result, the pollution is three times as high as in BAU.

The GRT scenario results in the largest environmental impacts for all categories, except for photochemical ozone formation. GRT pollution levels are 7-790% higher than in BAU. This indicates that implementing only the most cost effective option is not enough to avoid an increase in the environmental impacts of palm oil production in the coming decades. Note that mulching EFB increases emissions of N_2O and NOx and nitrate leaching as a side-effect in this scenario. In Figure 6.4, EFB disposal is therefore the largest contributor to environmental impacts.

In contrast, the GRN scenario results in the lowest environmental pollution levels in all impact categories, except for photochemical ozone formation. GRN pollution levels are 11-840% lower than that in the BAU scenario. The most effective reduction options are implemented in this scenario, reducing in particular emissions from EFB disposal. For instance, EFB-combustion not only avoids CH_4 emissions from untreated EFB but also large amounts of CO_2, SO_2 and NOx as a side-effect of connecting generated electricity to the grid. However, CO and VOC emissions are increased as a result of incomplete combustion, leading to photochemical ozone formation. Our results for the GRN scenario indicate that environmental impacts can be avoided to a large extent by the most effective mitigation options. However, the costs are relative high (approximately 250 million USD), in particular for EFB-combustion. Managing EFB can play an important role in the reduction or increase in environmental impacts.

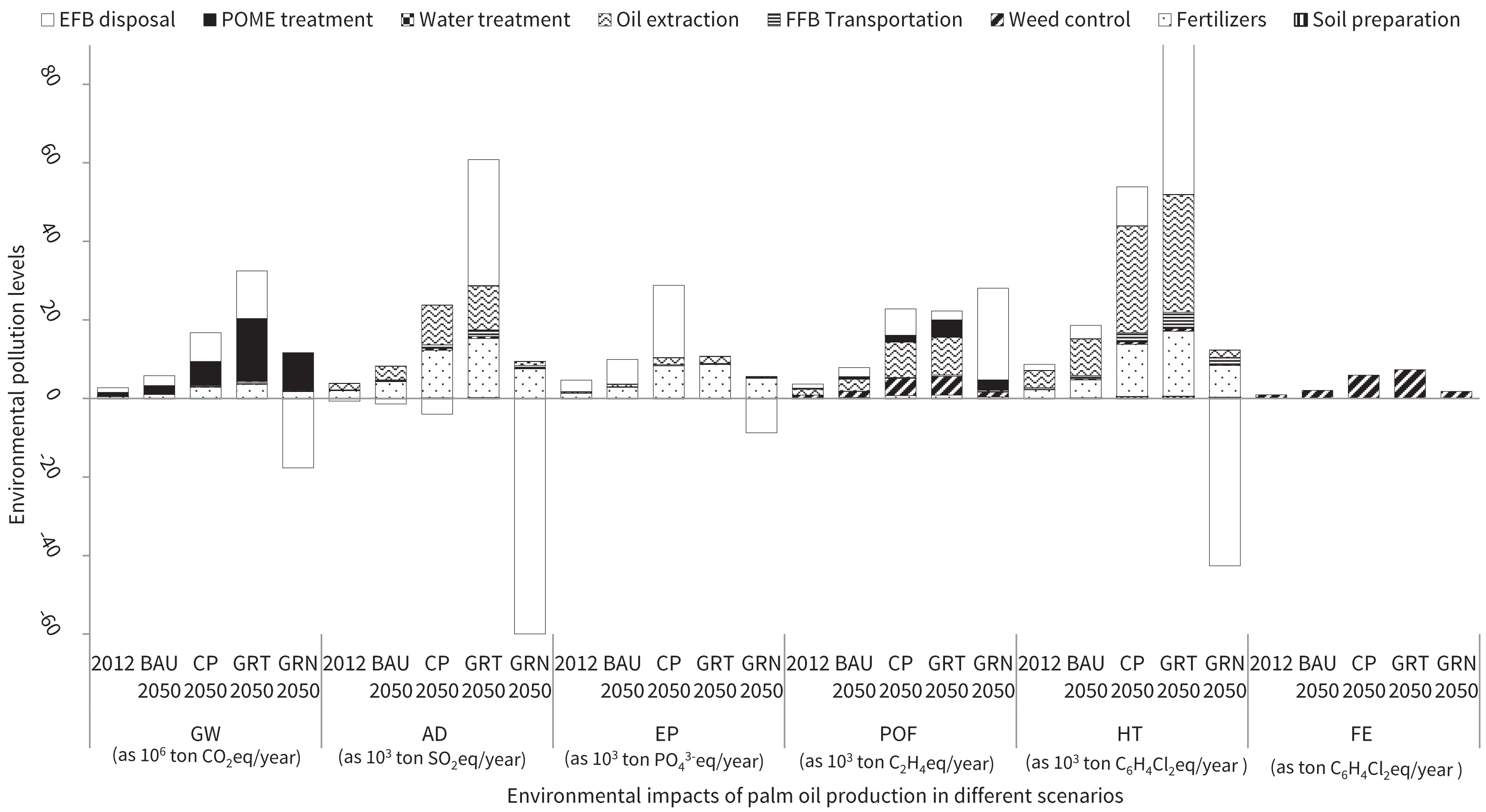

Figure 6.5 Environmental impacts of palm oil production in different scenarios; Business as Usual (BAU), Current Policy (CP), Strong Growth (GRT) and Green Development (GRN). Aggregated emissions (per ton CPO) specific for each activity are provided in Appendix E4 (Table D4). GW = Global Warming, AD = Acidification, EP = Eutrophication, POF = Photochemical Ozone Formation, HT = Human Toxicity and FE = Freshwater Ecotoxicity. Negative values imply net negative emissions (or avoided emissions elsewhere).

6.4.5. Net effect of greenhouse gas emissions

We quantified the total greenhouse gas emissions from plantations and mills, taking into account carbon sequestration and losses (section 4.3.1) and emissions of non-CO_2 greenhouse gases (section 4.4). Apart from the GRN, the environmental management in all scenarios result in high carbon emissions. The emissions associated with the palm oil operations in the plantations and mills are significantly higher than emissions from LUC (Figure 6.5). These emissions are mainly from untreated EFB, treating POME with (anaerobic) open ponds, and use of nitrogen fertiliser. Moreover, emissions from LUC are also prevalent in the CP and GRT scenarios, whereas emissions are mainly from the replacement of rubber plantations.

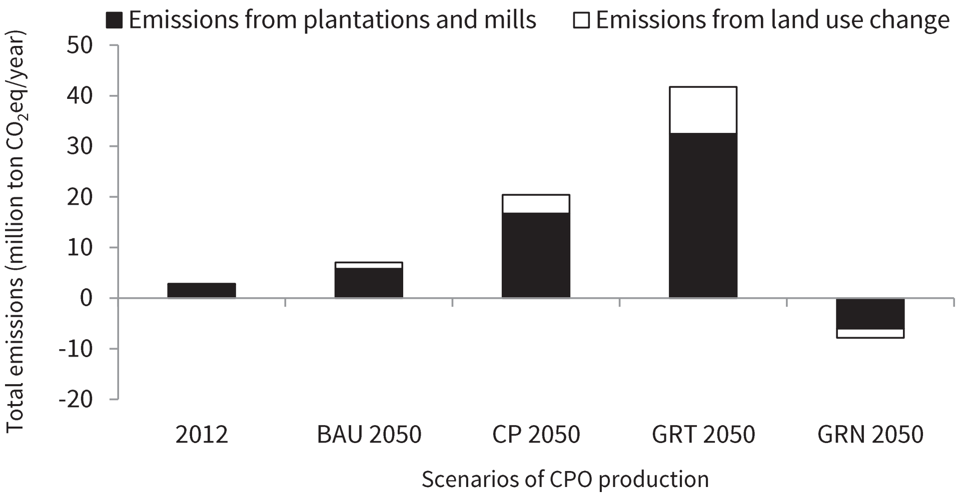

Figure 6 Net greenhouse gas emissions from land-use-change and operations in plantations and mills.

6.5. Discussion

6.5.1. Strengths and weaknesses of this study

We consider the comprehensiveness of our study as a strength. We account for the impacts of LUC on ecosystem services, as well as on pollution. And we account for the impacts of plantations as well as mills. Moreover, we analyse past and future trends. To our knowledge no such study exists for Thailand at the moment.

Accounting for total greenhouse gas emissions from LUC and the operations in plantations and mills (section 4.5) is an example of how comprehensive information may better inform policy makers as well as researchers. This may help to develop strategic plans to mitigate emissions and to deal with possible trade-offs. This finding is also in line with Ajani et al. (2013) and Teuscher et al. (2015).

A limitation of our analysis is that it does not account for spatially explicit analysis of environmental pollution. This could be a subject for further study. It does, however, affect the most important conclusions of our analysis.

Another issue is the fact that leftover biomass residues are openly burned among farmers after land conversion (Saswattecha et al., 2016a), which is a source of greenhouse gas emissions (Kanabkaew and Kim Oanh, 2011; Permadi and Kim Oanh, 2012). We ignore these emissions in our analysis because of lack of data, which could be considered as a weakness.

We also do not account for the full life cycle of biodiesel. We took only a partial life cycle of palm oil production, because we want to focus on the environmental performance of the palm oil sector in a specific region rather than on the environmental impact of the final product.

In this study, we only account for the so-called direct LUC: conversion of land-use to oil palm plantations. However, there can also be indirect effects of expanding oil palm plantations. For instance, when palm is grown instead of rubber, rubber may be grown in other regions. In worst case, this may also replace natural forests. In our earlier study (Saswattecha et al., 2016a) we show that such indirect deforestation happened after 2009. In our analysis, we calculated a large increase in planting oil palm for the CP, GRT and GRN scenarios assuming no deforestation. This may be too optimistic. Thus, the future impact on ecosystem services may be underestimated in this study.

6.5.2. Selection of mitigation options

In our previous study, 26 options were studied (Saswattecha et al., 2016b) and we individually assessed the mitigation options and its cost-effectiveness. In this study, some mitigation options were combined corresponding to the scenario description and assumptions. For instance, combinations of the mitigation options to reduce environmental impacts that are currently implemented in the mills are included in the BAU scenario. On top of the BAU scenario, the most cost-effective options (or the paying options that are effective) are included in the GRT scenario. This shows the implications if the Thai government would leave the market (price) to determine the environmental management of the Thai palm oil industry without any interventions. The BAU, CP and GRT scenarios may be considered feasible, since they assume either options that are already being used, or options that are cost effective.

However, the GRN scenario may not be considered easy to implement. In this scenario the most effective options in each group are selected to demonstrate what would happen if the Thai government would stimulate implementation of costly options. We realise that this scenario may not be realistic or feasible, because we do not indicate who would cover the costs of implementing mitigation options. It would require considerable subsidies or regulations to make implementation of this scenario possible.

While there are many combinations of options possible, we have selected only a few in our scenarios. One may prefer other combinations of mitigation options, depending on the purpose of the study. For instance, if global warming mitigation is a priority, one may select only biogas capture technology and EFB-combustion plant. If human toxicity mitigation is a priority, one may select EFB-combustion plant, pre-heating fibre, wet scrubbers and baghouse instead. In future studies, it would be interesting to analyse more combinations of various options.

6.5.3. Pathways to improve environmental sustainability of the Thai palm oil industry

Our analysis indicates that maximising FFB yield per hectare can reduce environmental impacts of the Thai palm oil production. As shown in the CP and GRN scenarios, a larger environmental impacts can be reduced in the GRN scenario than in the CP scenario where the area of oil palm expands faster with lower FFB yields. Moreover, options for improving oil extraction rates in the mills (i.e. oil recovery from decanter cake) can reduce environmental impacts to a larger extent than that options improving FFB yields (i.e. harvesting ripe fruits). For example, oil recovery from decanter cake can reduce acidification and human toxicity approximately three times greater than harvesting ripe fruits (Saswattecha et al., 2016b). Based on these findings improving FFB yields in existing and future plantations and increasing oil extraction rates in existing and future mills can be seen as a pathway to improve the environmental sustainability of palm oil production in Thailand. This is in line with Woittiez et al. (Woittiez et al., 2016).

Maximising the use of abandoned-land (i.e. abandon rice fields, abandon mining pits and bare land) could greatly avoid impact on ecosystem services. It is shown by the GRN scenario where the LUM focuses on abandoned-land with forest protection. The lowest impact on ecosystem services is calculated for this scenario. Another benefit of abandoned-land conversion is that we can avoid indirect LUC effects on deforestation. As discussed in section 5.2, expanding oil palm areas on rubber plantations can result in indirect LUC effect on deforestation. Thus expanding oil palm areas on abandoned-land without deforestation can be seen as a strategy to improve environmental sustainability. However, abandoned-land may be unsuitable for planting oil palm, leading to low FFB yields at high costs.

Applying cleaner technologies in palm oil mills can considerably reduce pollution of palm oil production in Thailand, as shown by the GRN scenario. This scenario implements a combination of the most effective options; including options to better manage EFB and fibre. A great amount of NOx and SO_2 can be avoided from EFB-combustion when electricity is connected to the grid. Also emissions (i.e. CH_4, NOx, SO_2, CO, VOC and PM) from fibre combustion can be removed when applying pollution control measures. Nonetheless, the options will probably not be implemented without incentives from the government; making implementation mandatory would imply additional large costs for the palm oil producers. Instead, strategic supportive plans (i.e. research and development, technology transfer, subsidies and incentives) could be considered and developed to promote these effective options.

Palm oil mills are recognised as a good source for energy (i.e. steam, heat and electricity), since there are excessive steam and heat from palm oil mills. POME, shell and EFB generated from palm oil mills have high potential to generate electricity (DEDE, 2007). This excessive energy is beneficial for other industries (i.e. oil palm refineries) if they are located nearby. However, palm oil mills are isolated from other factories, and therefore excessive energy is wasted. A zoning plan for palm oil mills can be seen as a way to improve environmental sustainability of palm oil production in Thailand. This zoning not only enhances the use of excessive steam and heat but also expands implementation of some mitigation options (i.e. biogas capture system and EFB-combustion) to a larger extent. This way, palm oil mills do not need to rely on exporting electricity to the grid alone.

6.6. Conclusion

In this study, we identified possibilities to improve environmental sustainability of palm oil production in Thailand. Four future scenarios for the period of 2012 – 2050 are developed; including business-as-usual (BAU), current-policy (CP), strong-growth (GRT) and green-development (GRN) scenario. These scenarios differ in LUM of oil palm expansion and environmental management of oil palm plantations and palm oil mills. We integrated landscape and sectoral models recently developed in our previous studies to analyse these scenarios with a special focus on options to reduce (1) LUC effects of oil palm expansion on selected ecosystem services and (2) environmental impacts of oil-palm plantations and palm oil mills. Three ecosystem services are selected and analysed in the landscape model: crop provisioning services, biodiversity conservation and carbon storage. Meanwhile, six environmental impacts are quantified in the sectoral model including global warming, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater ecotoxicity. The total costs of mitigation options employed in the scenarios are also included in our analysis.

Our analysis shows that in the BAU scenario, some areas of natural forests will be cleared for oil palms due to the lack of implementation of land-use planning, which adversely affects the biodiversity conservation, causing carbon emissions and reducing production from other crops. This indicates that the implantation of land-use planning and forest protection is necessary to avoid negative consequences on ecosystem services. Moreover, the environmental pollution associated with the plantations and mills is double the base year (2012). This indicates that without yield improvement and additional mitigation options the environmental impacts would be twice as high as the base year.

We also analysed the CP scenario, reflecting the implications of existing MOAC plans promoting biodiesel production in Thailand. This scenario also reduces other crop productions and seriously damages carbon storage services due to the conversion of rubber plantations which stores higher carbon stocks than oil palm plantations. This scenario emits almost 40 million tons C to the atmosphere. This indicates that promoting oil palm at the expense of rubber negatively affects the carbon storage service. However, our assumption of no deforestation is likely to be optimistic. This is because there is very limited arable land available for expanding any agricultural land, including oil palm in Thailand at the moment. In addition, environmental pollution is three times higher for the CP scenario when compared to BAU. This is due to the effects of increasing palm oil production without implementing additional mitigation options.

To identify possibilities for improving environmental sustainability of palm oil production in Thailand, the GRT and GRN scenarios were developed and analysed to reflect different strategies to manage environmental impacts of palm oil production. Of these, the GRN scenario is the most effective. This scenario positively impacts biodiversity conservation and carbon storage services and provides a minimum loss to other crop production. This is due to the land-use strategy to convert non-cropland (i.e. grassland, scrubland and abandoned-land) to oil palm plantations. Moreover, a large reduction in environmental pollution relative to the BAU scenario is calculated for 2050, except for the photochemical ozone formation, but at a higher cost. This reduction mainly results from the EFB-combustion, avoiding large amounts of CO_2, SO_2 and NOx emissions, while increasing VOC, CO (ozone precursors) and PM emissions. To reduce VOC, CO and PM emissions additional measures should be considered at the EFB-combustion plant. We realise that the GRN may be difficult to realise because this scenario ignores the costs of implementing mitigation options. The GRT scenario may be more feasible in this respect. This scenario assumes only the most paying options that are effective (or cost-effective options) are implemented in the growing palm oil industry. This scenario can be seen as the most cost-effective scenario. However, it also has the largest environmental impact: even higher than the BAU 2050 levels in all categories, except for photochemical ozone formation. This indicates that implementing only the most cost-effective options is insufficient to avoid an increase in the environmental impact of palm oil production.

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Chapter 7

Genneral discussion and conclusions

7. GENERAL DISCUSSION AND CONCLUSIONS

7.1. Introduction

The overall objective of this thesis was to analyse the environmental impacts of the palm oil industry in Thailand, and to examine options to enhance the environmental performance of the sector. Four research questions were formulated to achieve the overall objective of this thesis (see Chapter 1):

Research question 1: What are the effects of past oil palm expansion through land use change on ecosystem services?

Research question 2: What are environmental impacts associated with past palm oil production in Thailand?

Research question 3: What are the available options to reduce environmental impacts of palm oil production in Thailand and its cost-effectiveness?

Research question 4: What are the possible future scenarios for the palm oil industry in Thailand, and what are the associated environmental impacts?

In this chapter, I discuss the results, and draw conclusions. In section 7.2 I reflect on the modelling approach and analytical tools used in this thesis, discuss their advantages and disadvantages. Next, I discuss to what extent the key findings from this thesis can be generalized for other palm oil producing countries and I discuss the uncertainties in the results. The discussion is followed by the conclusions (section 7.3). This chapter is closed with recommendations for future research and for policy (section 7.4).

7.2. Discussion

7.2.1. Modelling approach and analytical tools

The four research questions are addressed using an integrated model that links a landscape approach to a sectoral approach (Figure 7.1). Several analytical tools, such as spatial modelling, partial life cycle assessment and scenario analysis, are used in the model. In the following, these tools are described and discussed in more detail.

In the landscape approach, I coupled spatial modelling and ecosystem services indicators to answer research question 1. Spatial modelling is commonly used in conjunction with a geographic information system (GIS) to analyse and visualise data in a spatially explicit manner (i.e. land use). Spatially explicit analyses help to better understand spatial processes and conclusions that are more difficult to formulate with numerical and textual data (Techopedia, 2016). Although it is a powerful tool, it requires high quality input data, time, and expert knowledge. In this kind of modelling, it is important to consider uncertainties associated with input data and modelling processes (Dendoncker et al., 2008; Wicke et al., 2012), which is discussed in section 7.3.3.

Combining spatial modelling and ecosystem services indicators makes it possible to analyse and project changes in land use management, and assess the consequent effects on ecosystem services. This combination has been regularly applied in the literature (Araya et al., 2015; Leh et al., 2013; Petz and Oudenhoven, 2012; Remme et al., 2014; Sumarga and Hein, 2014). I coupled spatial modelling and ecosystem services indicators to analyse land use change effects of oil palm expansion on ecosystem services in the Tapi river basin over the past decade. I used spatial modelling to analyse direct and indirect land use change caused by oil palm expansion and to better understand the land use change patterns: what types of land use are replaced by oil palms and to what extent? Next, I investigated three selected ecosystem services: carbon storage, biodiversity conservation and food and non-food provisioning services. These services are selected because they give a good indication of the overall environmental performance. Crop production is used as an indicator for the food and non-food provisioning service, carbon stocks for the carbon storage service and habitat loss for the biodiversity conservation service. Next, the results from this spatial analysis are used to develop assumptions on the land use management for future scenarios.

In the sectoral approach, I developed a model by combining environmental performance indicators (EPIs) and a partial life cycle assessment (LCA) to answer research question 2. EPIs are a practical measure to evaluate the environmental performance of a company over time (DANTES, 2006; Jasch, 2009). Meanwhile, LCA is a well-established method to assess the potential environmental impacts and resource use of a product or service throughout its life cycle (from raw material acquisition to production, use and disposal) (ISO, 2006). An advantage of the EPIs is that data are usually easily available at the company level. However, ad disadvantage of EPIs is that they typically focus only on the environmental performance of a company and ignore environmental impacts outside of the company. Coupling EPIs and LCA may solve some of these issues. Hermann et al. (2007) suggested that EPIs can be used as starting point to collect data that are available at a company, and then expand the scope towards an LCA approach to include other processes that are not take place at a company (i.e. raw material production and waste disposal). This combination helps a company to better understand environmental impacts of their product, and to identify what production steps are important sources of emissions. In this way, the relative contributions of emissions from different sub-processes to the total environmental impact can be studied. Another advantage is that the resulting data can be used for benchmarking and to further identify options for improvement (B. G. G. Hermann et al., 2007; Jasch, 2009). A disadvantage of LCA is that it requires a large amount of detailed data, time and expert knowledge to perform a full LCA (from cradle to grave). For example, conversion factors (i.e. emission factors, classification factors) are mostly well developed and available for the European continent, but data that are specific for Thailand is lacking. This introduces uncertainties when using such data for Thailand. This aspect is also discussed under section 7.2.3.

The combination of EPIs and LCA has been applied in several studies for various types of industries and products (Jawjit, 2006; Neto, 2007; Pluimers, 2001). In this thesis, a combination of EPIs and a partial LCA, is used for a gate-to-gate and cradle-to-gate assessment for the life cycle of palm oil production in the Tapi river basin. The results are used to assess the emissions and their sources that have to be considered for environmental improvement. Six environmental impacts (i.e. global warming, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater ecotoxicity) are selected and analysed in this thesis. At the end, environmental impacts are quantified and sources of emissions are examined.

There are some other tools for the assessment of environmental impact, such as a substance flow analysis (SFA) and environmental impact assessment (EIA). SFA is a tool to quantify the flows of substances in a defined system and identify where any hazardous accumulation or emissions occur (Brunner and Rechberger, 2004; Chevre et al., 2013, 2011). SFA is applied to analyse the contribution of different units in a system to the emissions, but it cannot easily be used to calculate the contribution to different environmental problems (Jawjit, 2006). The environmental impacts of the palm oil production are caused by several pollutants and some pollutants contribute to more than one problem (i.e. nitrogen oxides). This makes it complicated to perform SFA in this thesis. Thus, the choice was made to apply LCA in this thesis. Meanwhile, EIA is a site-specific tool used to assess the environmental impacts of a new localised project (as a source of pollution) on its surroundings (Payraudeau and Werf, 2005). However, this thesis does not aim to investigate the environmental impacts of a site-specific palm oil mill project making this tool unsuitable for this specific research.

Subsequently, I identified possible options to reduce these environmental impacts and evaluated their cost-effectiveness to answer research question 3. The sectoral model that I developed to quantify emissions was extended so that it can be used for cost-effectiveness analysis (CEA). CEA is a technique used to support decision makers with information on a relation between the costs of reduction options and the environmental improvement. The costs of options are expressed in monetary terms whereas the effects of environmental improvement are expressed in physical terms (Balana et al., 2011). A disadvantage of CEA is that it considers only costs of implementing and maintaining the options and ignores other monetary costs in the analysis, such as costs of environmental damage and costs of human health (Jawjit, 2006). To include these other costs, a cost-benefit analysis (CBA) could be applied. CBA is an applied economic tool to guide decision makers about economic efficiency of large investments from social point of view on resource allocation (Balana et al., 2011). Quantifying the monetary benefits (avoided damage or emissions) is, however, often associated with large uncertainties when compared to the monetary costs. To avoid such uncertainties, I made the choice for CEA in this thesis. As a result, this thesis only informs a decision maker about the most cost-effective options in achieving environmental improvement in the palm oil industry, rather than informs which option is economically worthwhile (Balana et al., 2011).

Lastly, to address research question 4, I explored possibilities to improve environmental sustainability of the palm oil industry in Thailand in coming decades. To this end, my landscape model and my sectoral model are integrated through a scenario analysis. The scenario analysis was performed to investigate future environmental impacts of the palm oil industry in Thailand as well as to explore possible strategies to improve environmental performance towards sustainable production. A set of future scenarios was developed and analysed reflecting a number of reduction strategies. Existing policies and plans that are currently driving the environmental performance of palm oil industry in Thailand were used as basis to formulate the scenario assumptions and targets of the Thai palm oil industry in 2050. The scenario period (time horizon) is almost 40 years (2012-2050). This period is chosen because (1) the life time of many reduction options is typically about 15-25 years (Table C6 in Appendix C), and (2) several reduction options need a change in human behaviour (Table C5 and Table C6 in Appendix C) which would need some years to be analysed.

Scenario analysis can be performed with and without a stakeholder participation. In this thesis, the choice was made to perform a scenario analysis without stakeholder participation because it is relatively time consuming and costly due to multiple cycles of storylines writing, quantification and scenario review from several participants, which is considered out of scope of this thesis. In future research, it is important that scenarios are discussed with and developed with the different stakeholders (i.e. famers and millers, policymakers).

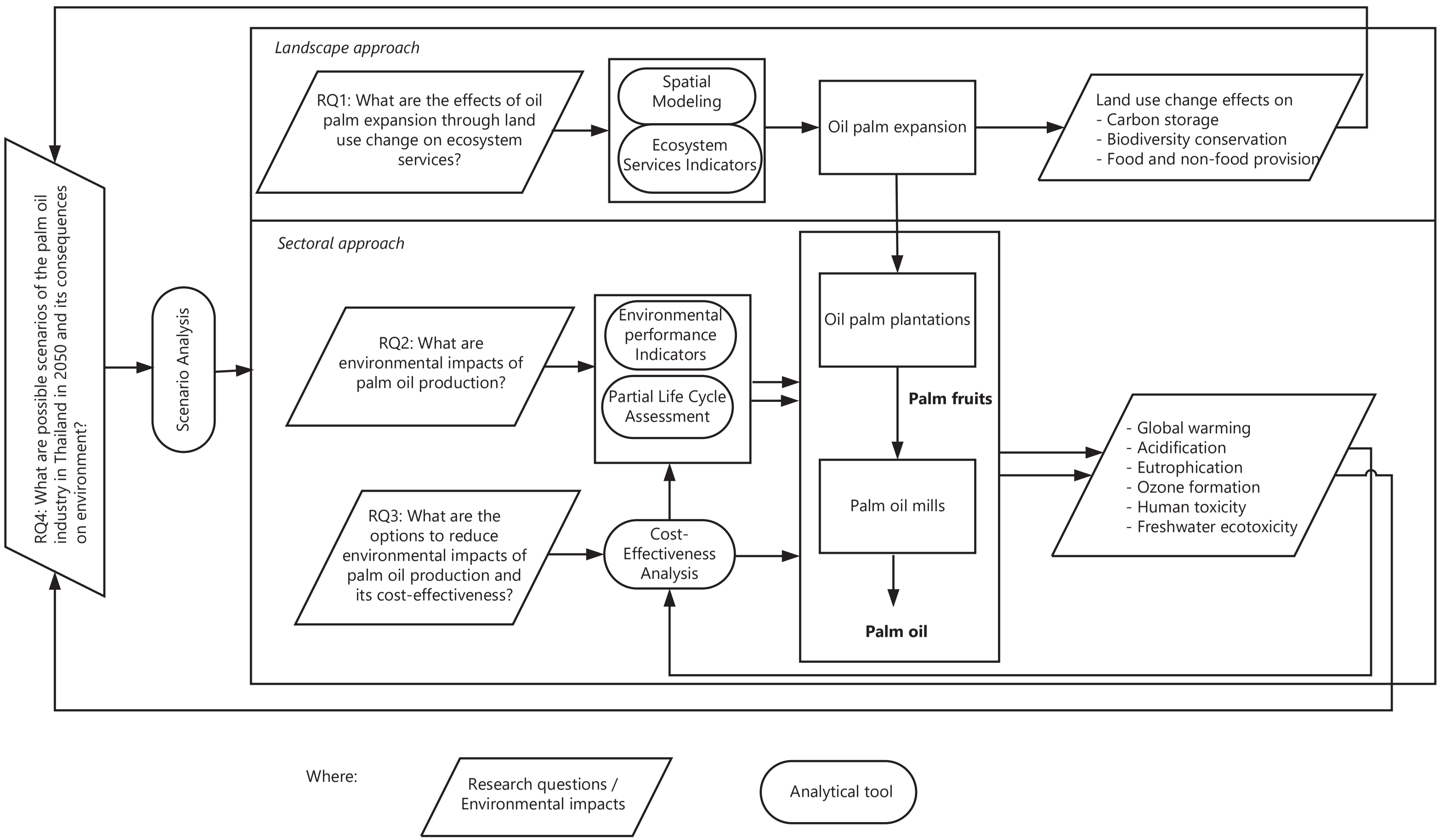

Figure 7.1 An overview of step-wise approach, environmental models and analytical tools used to address the four research questions in the thesis.

7.2.2. Can the results from this thesis be generalized?

Most palm oil is produced in Indonesia and Malaysia, so the question may rise to what extent the results of this thesis also apply to these two countries. However, the characteristics of palm oil production in Thailand differ considerably from Indonesia and Malaysia. As a result, the associated environmental impacts of palm oil produced differ as well. Thus, recommendations drawn in this thesis are very specific for Thailand and may not hold for Malaysia and Indonesia. In the following, I describe characteristic differences among the three countries in more detail.

First, the plantations in Malaysia and Indonesia are often associated with large-scale natural forests and peatlands clearing, in particular in Indonesia (Carlson et al., 2012; Gandois et al., 2013; Moore et al., 2013; Padfield et al., 2016; Ramdani and Hino, 2013; Varkkey, 2015; Wicke et al., 2011). Between 1975 and 2005, about 40 million ha of forests were lost in Indonesia and 5 million ha of forests were lost in Malaysia. These expansions have a large impact on ecosystems and services provided by natural forests and peatlands, such as reducing the carbon sequestration and biodiversity (Carlson et al., 2012; Gandois et al., 2013; Moore et al., 2013; Ramdani and Hino, 2013; Teuscher et al., 2015; Varkkey, 2015; Wicke et al., 2011). In Thailand, most new oil palm plantations are being started in agricultural land. Conversions of natural forests and peatland to oil palm is taking place (Anonymous, 2010; Saswattecha et al., 2016a) but not to a large extent in Thailand. About 15,000 ha of forest was lost in the past decade (Saswattecha et al., 2016a). This is because Thailand has a comparatively small area of forests and peatland compared to Malaysia and Indonesia (SEApeat, 2016). The oil palm cultivation in Thailand mainly replaced cropland (i.e. rubber plantations, rice fields and orchard plantations) and unused land (i.e. grassland and scrubland) in the past decade (Saswattecha et al., 2016a; Siangjaeo et al., 2011; Thongrak and Kiatpathomchai, 2011). Consequently, some areas of forests were cleared to replace the cropland that converted to oil palm which can be seen as an indirect effect of expanding oil palm cultivation (Saswattecha et al., 2016a). Thus, in Thailand deforestation is a more indirect effect of oil palm cultivation than in Malaysia and Indonesia.

Second, in Malaysia and Indonesia oil palm is cultivated to a large extent in large-scale plantations, while in Thailand smallholders dominate. In particular in Malaysia, the plantations are strongly influenced by the state (Varkkey, 2015). The plantations in Thailand are mainly small-scale plantations that belong to the smallholder farmers without a lot of state interference. Over 70% of oil palm areas in Thailand are smallholder areas (Dallinger, 2011; Termmahawong, 2014). These differences in scale of plantations can lead to different management practices in the plantations, affecting environmental pollution levels. For instance, the plantations in Malaysia are managed and controlled under the state-led companies, and relatively large amount of fertilisers are used per ton fresh fruit bunch (FFB) to maximise the FFB yields (Nor et al., 2011). It is two times higher than it is in Thailand (Nor et al., 2011; Saswattecha et al., 2015b). As a result, greenhouse gas emissions per ton FFB in Malaysia would be considerably higher than in Thailand. In Indonesia, about 60% of plantations are owned by companies and almost 40% of plantations belong to smallholder farmers (Harsono et al., 2012). The rate of fertilisers used per ton FFB is in the same as in Thailand. However, a key difference that an estimated 20 to 30% of oil palm plantations in Indonesia are located on peat lands. Because oil palm can only grow under drianed conditions (typically aorund 1 meter of drainage is required) this results in large CO_2 emissions, in the order of 90 ton CO_2 per ha per year. Consequently, on average, carbon emissions in Indonesia are considerably higher than in Thailand.

Third, the waste management in mills in Thailand differs from that in Malaysia and Thailand. In general, the operations in the palm oil mills are comparable in Thailand, Malaysia and Indonesia. Fibre and shell is commonly used as fuel in the boilers to produce stream (Abdullah and Sulaim, 2013; Faisal, 2013; Paltseva et al., 2016; Saswattecha et al., 2016b, 2015b). The differences are in the palm oil mill effluent (POME) and empty fruit bunch (EFB) management practices. POME treatment in Thailand is more advanced. Currently, about 60% of palm oil mills in Thailand apply biogas capture technologies to generate electricity and connect to the grid (Saswattecha et al., 2016b). In Malaysia and Indonesia, POME is typically treated by a series of open lagoons, and a relatively large source of methane emissions. Only 15% of the biogas produced in these countries is captured. In case biogas is captured, it is commonly flared (Nor et al., 2011; Rahayu et al., 2015). EFB is commonly returned to the plantations in Indonesia and Malaysia; some is incinerated as waste in the mills causing air pollution (Abdullah and Sulaim, 2013; Bakar et al., 2011; Faisal, 2013; Paltseva et al., 2016). Incineration of EFB in mills leads to lower methane emissions than landfilling, but it is a source of pollutants contributing to acidification, eutrophication, photochemical ozone formation and human toxicity problems (Abdullah and Sulaim, 2013; Bakar et al., 2011; Saswattecha et al., 2016b). In Thailand, 30% of the EFB is returned to the plantations while 20% is burned in the biomass power plants to generate electricity for the grid. Only 40% is left abandoned (Saswattecha et al., 2016b). Overall, palm oil mills in Thailand seem to be less polluting than mills in Indonesia and Malaysia.

Fourth, in Thailand, the middlemen system, which provides fruits harvesting, collecting and delivery services, is unique and common for Thailand. This is because the smallholder farmers usually do not have their own vehicles (i.e. trucks) to carry and deliver FFB to the mills. The quality of FFB mainly depends on (1) fruits harvesting practice and (2) management of middlemen. The fruits are commonly harvested unripe. A factor contributing to the harvesting unripe fruits is the pricing system for FFB. FFB price is commonly determined by weight rather than oil content (Dallinger, 2011; Dallinger et al., 2013; Termmahawong, 2014). This demotivates farmers or middlemen to harvest ripe fruits. Moreover, a higher price is given to loose fruits, (Termmahawong, 2014). This promotes middlemen attempting to increase the FFBs' weight by mixing sand and to generate more loosen (rotten) fruits by spraying water. Both harvesting unripe fruits and poor management of middlemen lead to the poor quality of FFB. In other countries such middlemen systems do usually not exist.

Fifth, in Thailand, the oil extraction rate is comparatively low (17%) when compared to Indonesia (21%) and Malaysia (20%) (Harsono et al., 2012; MPOB, 2016; OAE, 2016b). This indicates that mills are more efficient in Indonesia and Malaysia. This low oil extraction rate is mainly caused by the quality of the fresh fruits in the mills. More than 100 palm oil mills are registered in Thailand and most are located in the South, creating an overcapacity (DIT, 2016). This results in insufficient FFB supply. Mills regularly operate not at full capacity. To keep up minimum operations, these mills accept FFB of poor quality (i.e. unripe fruits and rotten fruits) from farmers or middlemen mentioned above.

Based on these differences, I believe that my results cannot be generalized easily to Indonesia and Malaysia. The land use change associated with expansion of the oil palm sector differs among the countries. And even though the sources (i.e. use of nitrogen fertilisers and disposal of POME and EFB) of emissions and environmental impacts in Thailand, Malaysia or Indonesia are the same, the recommendations to overcome the problems are country-specific because of the national context and local management practices. The model approach that I developed and information on individual mitigation option (effectiveness and costs) that I identified in this thesis, however, could be applied to other countries.

7.2.3. Uncertainties

Uncertainties exist in all environmental models. These uncertainties affect the quality and reliability of a model's results (Hou et al., 2013). These uncertainties need to be assessed and managed in order to improve the model's results. There can be uncertainties in the model inputs, model parameters and model structure. Many uncertainties are associated with a poor understanding of the system and poor availability of data (Dumedah and Walker, 2014; Hou et al., 2013; Walker et al., 2010).

An example of uncertainty about model inputs is the land use data used in the landscape model. The land use data in this thesis are from satellite images that are processed into digital land use maps with polygons representing different land use units. Uncertainties are introduced during this land use data processing (i.e. simplification and classification).

Another example relates to input data, such as activity data and costs of reduction options, in the sectoral model. Activity data were collected from only a small number of farmers and millers due to time and budget limitations. One may question to what extent these farmers and millers are representative for the whole study area. Farmers and millers in other locations may perform differently. Similarly, information on costs of some advanced options that do not exist in Thailand (i.e. EFB ethanol production technologies, non-thermal plasma technologies) was based on information from other countries. Assuming these data to be representative for the all farmers or for Thailand as a whole introduces uncertainties.

I assessed the uncertainties in this thesis to some extent. For instance, activity data were compared to other relevant studies and found to be in the same range (see Chapter 3). I did not assess the uncertainties in cost estimates. These sources of uncertainties are also discussed and reported in chapters 2,3 and 5.

An example of uncertainty about model parameter is related to the constant values that are used in the model for parameters that in fact vary spatially or temporally. For instance, carbon stocks and mean species abundance as used in the landscape model are assumed not to change over time or space. Also emission factors and classification factors as used in the sectoral model are fixed parameters and in the model not country-specific (Thailand) or site-specific (Tapi river basin). More specific values are lacking in Thailand or for the study area (Tapi river basin). My assumption that such constant parameters represent the study area in Thailand introduces uncertainties. These sources of uncertainties are also discussed and reported in chapters 2 and 3.

An example of uncertainty associated with the model structure relates to how I linked the landscape model and the sectoral model. These models are inconsistent in term of system, data input, and unit. The landscape model calculates the effects of oil palm expansion on the environment per specific area (e.g. ton carbon per hectare). Meanwhile, the sectoral model calculates environmental pressure per unit of palm oil (e.g. ton CO_2 per ton of crude palm oil) without consideration of location of oil palm plantations and palm oil mills. Integrating these two approaches may increase uncertainties in the model. Moreover, I did not consider how these models interact. This may also lead to uncertainties.

Hence, the uncertainties in this thesis are largely associated with model inputs and model parameters. The underlying cause of these uncertainties is the lack of country-specific data for Thailand. Therefore, further studies of national or local parameters used in the model (i.e. mean species abundance, carbon stocks, emission factors, and classification factors) are strongly recommended.

In this thesis I did not perform a systematic uncertainty analysis. Rather, I discussed the uncertainty on the basis of expert judgement, results comparison and qualitative discussions. There are methods for dealing with uncertainty assessment, including qualitative and quantitative approaches. Among these are data quality rating (alphabetical or numerical scores are assigned to inputs and parameters to express the uncertainties in a qualitative way (high-low)) and error propagation (calculation of the relative importance of uncertainty in input values to the overall uncertainties) (see Walker et al. 2010 for the details). Therefore, it would be interesting for future studies to further assess uncertainties by other methods.

7.3. Conclusions

7.3.1. The effects of oil palm expansion on ecosystem services

In chapter 2, the direct land use change (dLUC) and indirect land use change (iLUC) caused by oil palm expansion in the past are analysed using the spatially explicit landscape model. The Tapi river basin is selected as a case study area because it is the main oil palm producing basin of Thailand. I found that in the period of 2000-2012, dLUC was more important than iLUC. dLUC engaged with new oil palm plantations replacing cropland rather than natural ecosystems. Rubber was most commonly replaced by oil palm but there was also conversion of natural ecosystems. Later, during 2009 to 2012, iLUC strongly increased. Forests were cleared for rubber production as an indirect effect of oil palm expansion. This may be because available arable land has become limited for the oil palm expansion in the basin.

Although conversion of cropland for expanding oil palm areas was the main trend over the past decade, biodiversity conservation and carbon storage services were adversely affected. This is because a presence of clearing natural ecosystems (i.e. forests, wetlands/peatland, unused land, and mangrove forests) for oil palm. The oil palm expansion increased the production of fresh fruit bunch service in the basin, whereas, it actually decreased the production of other crops (i.e. latex, rice and fruits) in the basin.

7.3.2. Environmental impacts per ton of crude palm oil

Palm oil production contributes to several environmental impacts, such as global warming, acidification, ozone formation and human toxicity problems. In Chapter 3, these environmental impacts were quantified per ton of crude palm oil (CPO) produced in the Tapi river basin in the past.

I found that the main activities contributing to the environmental impacts include 1) burning fibre in boilers in mills 2) using fertilisers in plantations, 3) wastewater treatment and empty-fruit-bunch disposal in mills 4) gasoline use in weed cutters and 5) glyphosate use for weed control.

RSPO certification, an international sustainability standard, is known as a tool for environmental management. The implications of Roundtable on Sustainable Palm Oil (RSPO) certification on the environmental impacts were also analysed in Chapter 3. The environmental impacts of CPO produced by non-RSPO, potential RSPO, and RSPO certified mills were compared. The RSPO certified mills have a lower environmental impact, as a result of cleaner production methods. For instance, these mills implement modern waste management, such as biogas production from palm oil mill effluent. The implementation of biogas production was strongly influenced by the national renewable energy policy and plans. This indicates that RSPO certification alone is not enough to ensure sustainable palm oil production. Policy support leading to for example training of farmers and mill operators for enhancing environmental practices in both mills and plantations is also needed.

7.3.3. Options to reduce environmental impacts of palm oil production

There are several options to reduce the environmental impacts associated with palm oil production. In Chapter 4, 26 options in 11 groups were identified and investigated (see a description of each options in Appendix C1). There are three groups of options related to oil palm plantations (optimising fertiliser use, weed control and FFB yield improvement) whereas there are eight groups of options related to the palm oil mills (POME treatment, EFB treatment, NOx control, SO_2 control, VOC control, PM control boiler efficiency and oil extraction improvement). The reduction potentials of these options are analysed with respect to the reference case (this was defined as none of the options being applied) and their associated costs (i.e. investment, operation and maintainance, variable costs) were investigated.

I found that EFB combustion for power generation, wet scrubbers and heating fibre prior use in the boilers are the most effective in reducing a range of environmental impacts. These options are associated with reducing or avoiding acidifying, eutrophying, human toxic compounds and photochemical ozone precursors. Among these options, EFB combustion results in the most reduction, but at relative high costs. Some other options are found to be economical as they generate positive net return (paying options). Mulching EFB, maintaining specific species of cover crops in the oil palm plantations and harvesting ripe fruits were found to be the most paying options. Moreover, some options are found to be both economical and effective (or cost-effective) to reduce the environmental impacts. These include maintaining some species of cover crops, harvesting rip fruits, mulching EFB, EFB composting, EFB pellets production, heating fibre prior use in the boilers and oil recovery from decanter cake. Apparently, implementation of these options is currently limited due to a lack of knowledge and market need – however this aspect merits further research in order to specify specific information gaps with farmers and plantation operators.

In reality, implementation of these options is very much depending on one's scope of interests and preference. For instance, in Chapter 5, if one would focus only on non-CO_2 greenhouse gas emissions, the most cost-effective technologies to reduce these emissions are (1) mulching EFB to reduce the nitrogen fertiliser need and its associated N_2O emissions, (2) biogas capture systems to avoid CH_4 emissions from POME treatment, and (3) combustion and pellets production for avoiding CH_4 emissions from EFB disposal.

7.3.4. Future trends: environmental impacts of palm oil production in 2050

The possibilities to improve the environmental sustainability of palm oil production in Thailand in the coming decades were examined in Chapter 6. To do this, the landscape model and sectoral model previously developed were integrated to analyse the scenarios in 2050. Four scenarios reflecting different environmental management of palm oil production in Thailand were developed; including Business as Usual, Current Policy, Strong Growth and Green Development (see a description of four scenarios in Appendix D1). Next, their potential impacts on the environment were analysed as if the Thai government would change their current practices.

From the Business as Usual scenario, I learned that the environmental impacts may double compared to the present impacts without additional improvement options. Moreover, the current plans to increase palm oil production in the Current Policy scenario would increase environmental impacts considerably (three times higher than Business as Usual scenario). Only implementing the most cost-effective options as in the Strong Growth scenario would not be enough to avoid increased environmental impacts if the export of palm oil increases faster than currently envisaged. Technically, it is possible to sustainably produce palm oil when a combination of effective options is implemented (the green development scenario), but this is regardless of the costs.

All in all, integrating a landscape model and a sectoral model proved to be a powerful approach to perform an integrated environmental assessment. This approach can be easily applied in of a broad range of industries and can be used to monitor the changes in practices over time (present to future) at local and national levels. In this thesis, I found that using such integrated assessment to assess overall potential environmental impacts of palm oil production is rewarding since it provides a comprehensive information to support the decision making. Decision makers (i.e. palm oil producer and policy maker) would better understand (1) how the oil palm expansion affects ecosystem services, (2) what are key sources of environmental impacts arising from palm oil production and where the environmental management could be urgently improve, and (3) what are the most cost effective options to deal with these impacts, depending on a purpose of the users. To date, the palm oil industry in Thailand has been successful in avoiding environmental impacts by implementing a number of reduction options. However, the option that are currently applied are not the most effective choices. This clearly indicates that there is a room to improve environment sustainability of the palm oil industry. Correspondingly, this integrated assessment provides new information on possibilities to improve environmental sustainability of the palm oil industry that are beneficial for decision makers (i.e. palm oil producer and policy maker) in designing future strategies in environmental management and improvement in the industry as well as the country.

7.4. Recommendations

7.4.1. Recommendations for future research

There are three novel aspects that have been addressed in this thesis. These are (1) the development of an integrated model for environmental impact assessment of palm oil production in Thailand, taking account of the landscape and sectoral aspects, (2) the analysis of interactions between environmental impact reduction options for palm oil production in Thailand and their cost-effectiveness, and (3) a scenario analysis of the palm oil industry in Thailand. With a combination of these aspects, the overall objective of this thesis has been achieved and the knowledge gaps identified in chapter 1 addressed. However, there are some other interesting points that are recommended for future research, as discussed below.

First, the integrated model developed in this thesis aims to be used to support decision making in the palm oil production. However, this model is flexible in choices of expanding the scope of work as well as system boundaries. This is a technical advantage of the model. In the landscape model I show that the natural forests were cleared for oil palm plantations in the past decade, taking both direct and indirect land use change effects of expanding oil palm plantations into account. Deforestation strongly increased in recent years due to a limitation in the arable land available for oil palm expansion. This resulted in a destruction of ecosystem function and services provided by the forests. However, this thesis accounted only for the land use change effects on carbon storage and biodiversity conservation services, but it did not include the effects on hydrology services (i.e. water provisioning and regulating services that can determine a flood risk) which are essential services provided by the forests. Thus, expanding the scope of work to include hydrology services is highly recommended for future research. The sectoral model was designed to quantify potential environmental impacts, and evaluate the effectiveness and cost-effectiveness of reduction options only for palm oil production purpose. Therefore, expanding the system boundary to cover a downstream production, such as production of biodiesel and cooking oil, is recommended. To do so, a new reference case needs to be developed when the system boundaries are changed.

Second, this thesis performed a cost-effective analysis only for the options to reduce the environmental impacts to inform decision makers on the most cost-effective options for achieving environmental improvement in the palm oil industry, but did not account for the values of selected ecosystem services. It would be interesting for future research to perform ecosystem valuation and include this in a social cost-benefit analysis. This will better inform decision makers on the trade-offs in allocating resources and then justify and prioritize which policies or actions are the most effective ways to protect ecosystems and their services. Moreover, applying the cost-benefit analysis instead of the cost-effective analysis is recommended for future research on costs and environmental impacts of a certain large-scale palm oil project. This is rewarding since it will better inform decision makers on which reduction option is the most economically worthwhile.

Lastly, palm oil production not only deteriorates the environment but also affects the society. This thesis did not extensively perform social impact assessment. Only some social aspects, such as an increase in farmer' income and food security risk, are qualitatively discussed in chapters 2. This thesis shows that planting oil palm is more profitable than planting rice, orchard and rubber (increase farmer' income), and farmers turn to growing oil palm instead. This is putting a pressure on price increase in other food crops (i.e. rice and fruit) as well. If this trend will continue to increase in coming future, it will put a pressure on food security. Balancing between increasing fresh fruit bunch and reducing other crops is therefore an important issue in future policies on food security. These findings are in line with other studies (Daniel and Gheewala, 2010; Escobar et al., 2009; Naylor et al., 2007; Wilcove and Koh, 2010). The abovementioned social impacts are only examples of what is reported in Thailand. There may be some other aspects that are overlooked and unreported. Thus, further research on social impact assessment is recommended.

7.4.2. Policy recommendations

Based on the findings in this thesis, the environmental impacts of palm oil production in Thailand are likely to double in the coming decades. This because of a growing produciton and because a majority of Thai palm oil producers, in particular smallholder farmers, are still lacking knowledge on how to apply best management practices. A key concern is also scarcity of good crop land and encroachment on protected areas and forests driven by government pressure to expand plantation areas. The current policies aim to increase palm oil production alone without a consideration of promoting or implementing additional mitigation options. This clearly indicates that implementation of additional mitigation options is necessary to improve environmental sustainability of palm oil production in Thailand. In this thesis, I found that improving environmental sustainability of palm oil production in Thailand is technically possible. This is because several cost-effective options to reduce environmental impacts are currently available, but they are not yet implemented in a large scale. Although paying options are more preferable choices they are not sufficient to mitigate the increased environmental impacts in the future. The analysis in this thesis indicates that implementation of a combination of the most effective options results in a considerable environmental improvement, but at relatively high costs. This clearly indicates that government interventions are urgently needed to change current practices of the palm oil producers, and subsequently improve environmental sustainability of palm oil production in Thailand.

Based on these findings in each research question, I formulated several policy recommendations that are relevant for the government and palm oil industry.

Policy recommendations for land use planning and management.

From land use change analysis, I found that new oil palm plantations are mainly developed on cropland, in particular rubber plantations, in the Tapi river basin between 2000-2012. Consequently, replacing rubber by oil palm emits large amount of stored carbon into the air. Therefore, I would recommend the government to consider accounting for the effect on ecosystem services, such as carbon storage, in developing the future land use planning and management. Moreover, conversion of forests to oil palm plantations happened in the Tapi Basin in spite of the protected status of some of these forests in the last decade. This illegal and inappropriate land conversion strongly increased after 2009 because of an increasing scarcity of arable land for new oil palm plantations. Therefore, law enforcement on forest protection is very important for the future land use management development. To avoid a clearance of forests and its negative effects on ecosystem services, I would recommend the government to consider to promote oil palm cultivation on abandoned land (i.e. abandoned rice fields, bare land) in combination with not setting overambitious targets for oil palm plantations that can only be met by clearing forests.

Policy recommendations for pollution management

In this thesis, I found that the key activities contributing to multiple environmental impacts are 1) the use of fertilisers, 2) weed control, 3) fibre combustion, 4) POME treatment and 5) EFB treatment. These activities urgently need to be addressed to improve pollution management in the future. In this thesis, seven out of 26 options are found to be the most cost-effective in reducing multiple environmental impacts. They include maintaining specific species of cover crops, harvesting ripe fruits, mulching EFB, EFB composting, EFB pellets production, heating fibre prior use in the boilers and oil recovery from decanter cake. Out of these, maintaining specific species of cover crops, harvesting ripe fruits, mulching EFB are found to be the most economical or paying options as their benefits exceed costs. However, these options are not currently implemented to a large extent due to a lack of knowledge. This limitation can be overcome if the government consider to introduce and promote these cost-effective options to the palm oil producers in the future policies and plans. However, implementation only the cost-effective options may not be sufficient to avoid increases in the environmental impacts if the export of palm oil increases palm oil production faster than current production. In this regards, the government could consider to invest in implementation of a combination of effective options in the future policies and plans. This combination of effective options may include but not be limited to options as listed below:

- Applying optimum dose of fertilisers and using slow-release fertilisers to optimize the fertiliser use.
- Maintaining specific species of cover crops in the oil palm plantations to avoid herbicide use for weed control.
- Harvesting ripe fruits to increase FFB yields.
- Installing upgraded biogas capture systems to reduce methane emissions from POME as well as to produce clean methane gas that is comparable to quality of natural gas.
- EFB combustion for power generation to avoid methane emissions from EFB as well as to connect electricity to the grid.

- Heating fibre prior use in the boilers to improve boiler efficiency and reduce fibre consumption.
- Installing non-thermal plasma unit to reduce NOx emissions from burning fibre.
- Installing wet scrubber unit to reduce SO_2 emissions from burning fibre.
- Installing thermal incinerator unit to reduce VOC emissions from burning fibre.
- Installing baghouse unit to reduce PM emissions from burning fibre.
- Recovering oil loss in decanter cake to improve oil extraction in the palm oil mills.

Out of these effective options, EFB combustion, wet scrubbers and pre-heating fibre are proven to be the most effective in reducing multiple environmental impacts in a larger extent. Nowadays, most of these effective options are available in the market but still expensive. Therefore, policy subsidies and incentives to motivate the palm oil producers in implementing these effective options are strongly recommended to consider in the future policies and plans. To this end, I strongly believe that producing environmentally sustainable palm oil in Thailand is technically possible if a combination of the effective choices is implemented in the future.

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Appendices

Appendix A

Additional information for Chapter 2

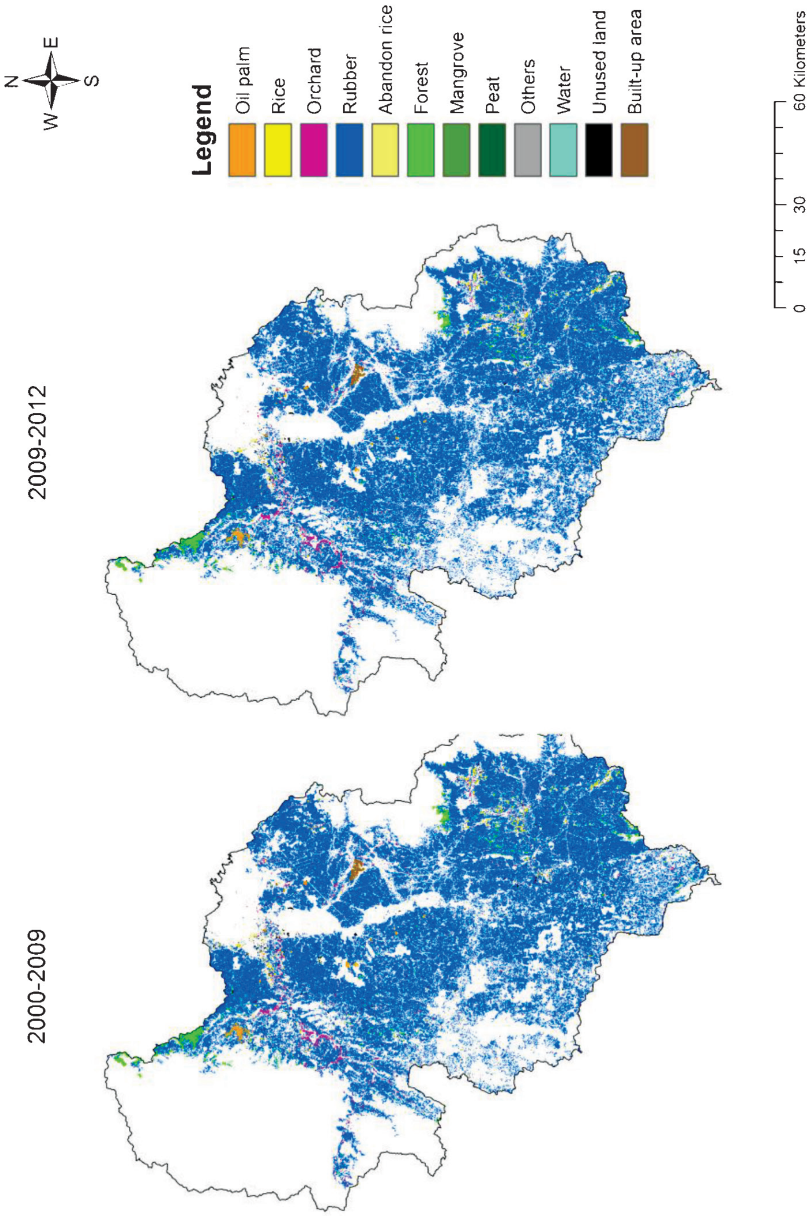

Figure A1 Area of land (ha) converted to rubber plantations for the periods 2000-2009 and 2009-2012.

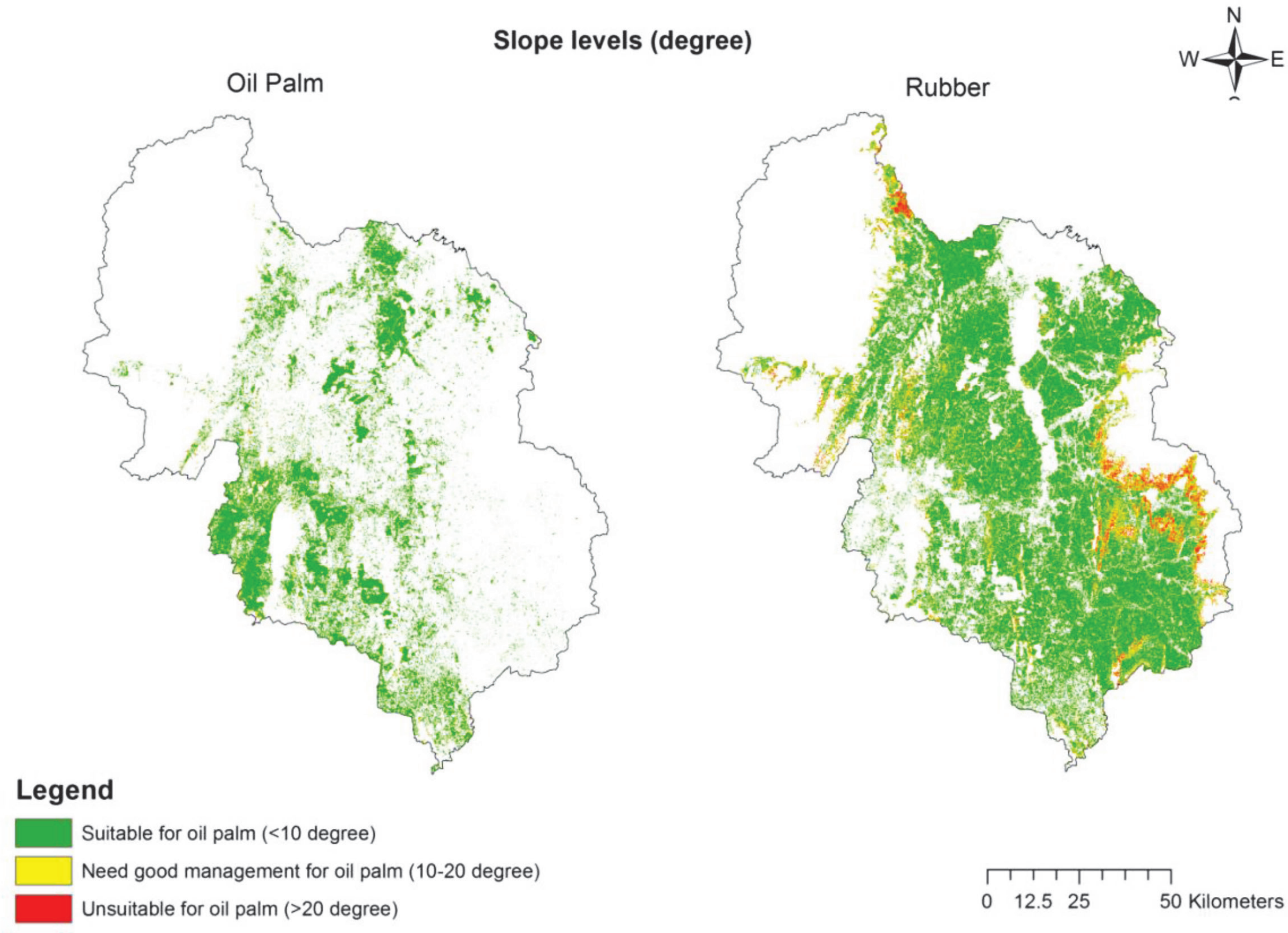

Figure A2 Slope levels of rubber and oil palm plantations from 2009 to 2012 in the Tapi River Basin.

Table A1 Carbon stock pools taken from literature for modelling carbon storage service.

Land use	Carbon stock pool (ton C/ha)			Location	Age (year)	Soil Depth (cm)	Source
		IPCC[a]	This study				
Oil palm	Above-ground biomass	63.92	43	Johor, Malaysia	23	-	Lab analysis by Khalid et al. (1999a)
	Below-ground biomass	n.a.	7.95	Johor, Malaysia	23	0-100	Lab analysis by Khalid et al. (1999b)
	Litter/ Dead organic matter	-*	-*				IPCC guideline (2006a).
	Soil organic carbon	63.65	63.65	Krabi, Thailand	13	0-30	IPCC guideline (2006a).
Rubber	Above-ground biomass	83.66	137.15	Songkhla, Thailand	26	-	Allometric equation by Chiarawipa et al. (2012)
	Below-ground biomass	n.a.	10.20			-	
	Litter/Dead organic matter	-*	2.65			-	
	Soil organic carbon	63.65	55.81			0-50	
Rice	Above-ground biomass	n.a.	2.49	Nan, Thailand	n.a.	-	Lab analysis by Pibumrung (2007)
	Below-ground biomass	n.a.	0.47			-	
	Litter/Dead organic matter	-*	-			-	
	Soil organic carbon	51.70	51.70				IPCC guideline (2006a).
Orchards	Above-ground biomass	n.a.	8.15	Nan, Thailand	n.a.	-	Lab analysis by Pibumrung (2007)
	Below-ground biomass	n.a.	1.04			-	
	Litter/Dead organic matter	-*	0.02			-	
	Soil organic carbon	63.65	63.65				IPCC guideline (2006a).
Abandon rice	Assumption: Carbon stock pools are as same as rice field						
Forest	Above-ground biomass	131.60	150.07	National reserves forest, Nan, Thailand	n.a.	-	Lab analysis by Pibumrung (2007)
	Below-ground biomass	n.a.	19.56			-	
	Litter/Dead organic matter	5.20	6.86			-	
	Soil organic carbon	47.00	124.21			0-40	
Mangrove	Above-ground biomass	n.a.	117.81	Nakhon-Si-Thammarat, Thailand	20	-	Lab analysis by Sriladda and Puangjit (2007)
	Below-ground biomass	n.a.	2.69			-	
	Litter/Dead organic matter	n.a.	n.a.				
	Soil organic carbon	47.00	70	Samut Songkram, Thailand	12	0-100	Lab analysis by Kridiborworn (2010)

Land use	Carbon stock pool (ton C/ha)			Location	Age (year)	Soil Depth (cm)	Source
		IPCC[a]	This study				
Wetlands and peatland	Above-ground biomass	n.a.	44.91	Nakhon-Si-Thammarat, Thailand	n.a.	-	Lab analysis by Wanthongchai et al. (2013)
	Below-ground biomass	n.a.	28.59	Sarawak, Malaysia	n.a.	-	Allometric equations by Verwer and Meer (2010)
	Litter/Dead organic matter	n.a.	27.65	Narathiwat, Thailand	n.a.	-	Lab analysis by Bunyavejchewin and Nuyim (1996)
	Soil organic carbon	82.00	504	Thailand	n.a.	0-100	Review by Verwer and Meer (2010)
Unused land	Above-ground biomass	8.00	5.91	Nan, Thailand	6	-	Lab analysis by Pibumrung (2007)
	Below-ground biomass	n.a.	1.01			-	
	Litter/Dead organic matter	n.a.	0.15			-	
	Soil organic carbon	n.a.	89.20			0-40	

[*] In IPCC Guidelines for National Greenhouse Gas Inventories - Tier 1, the dead wood and litter stocks are not present in the cropland.
n.a. – Data is not available

Table A2 The iLUC effects of (a) rice and (b) orchard expansion during the periods 2000-2009 and 2009-2012

(a) Rice

LUC (as a consequence of rice expansion)	2000-2009			2009-2012		
	Converted to rice (gross), in ha	Converted to rice (net), in ha	iLUC effect from oil palm expansion (ha)	Converted to rice (gross), in ha	Converted to rice (net), in ha	iLUC effect from oil palm expansion (ha)
Cropland						
- oil palm	51	-3,186	-	102	-2,131	-
- rubber	2,380	-11,535	-	150	-3,387	-
- orchards	396	-1,535	-	0	-9	-
- abandon rice	2,043	287	287	78	-189	-
Sub-total	4,871		287	330		-
Natural and unused land						
- forest	29	-43	-	1	1	1
- mangrove	-	-	-	-	-	-
- Wetlands and peat land	13	13	13	0	0	0
- unused land	177	-782	-	-	-65	-
Sub-total	218		13	1		1
Other						
- Water	15	-220	-	-	-6	-
- Built-up area	428	-1,202	-	-	-22	-
- Other agriculture land	701	591	591	-	-36	-
Sub-total	1,144		591	-		-
TOTAL	6,233		890	331		1

[1] ***gross*** *= area converted to rice. The gross values are taken from the spatial analysis by ArcGIS 10.0.*
[2] ***net*** *= area converted to rice (**gross**) minus area of rice converted to other types of land use. Positive values of this net change are considered "the indirect land use change (iLUC)". A negative net change indicates that area of rice replaced by other land use types exceeds the area converted to rice.*

(b) Orchards

LUC (as a consequence of orchard expansion)	2000-2009			2009-2012		
	Converted to orchards (gross), in ha	**Converted to orchards (net), in ha**	**iLUC effect from oil palm expansion (ha)**	**Converted to orchards (gross), in ha**	**Converted to orchards (net), in ha**	**iLUC effect from oil palm expansion (ha)**
Cropland						
- oil palm	943	-3,111	-	107	-3,433	-
- rice	1,931	1,535	1,535	9	9	9
- rubber	22,187	5,211	5,211	758	-4,961	-
- abandon rice	1,025	519	519	13	13	13
Sub-total	26,086		7,265	887		22
Natural and unused land						
- forest	1,710	-419	-	16	14	14
- mangrove	-	-133	-	-	-1	-
- Wetlands and peat land	52	22	22	-	-	-
- unused land	787	-1,386	-	149	-111	-
Sub-total	2,549		22	165		14
Other						
- Water	1,311	-224	-	9	-10	-
- Built-up area	1,356	-2,646	-	1,198	899	899
- Other agriculture land	680	-132	-	129	-24	-
Sub-total	3,346		-	1,337		899
TOTAL	31,981		7,287	2,390		934

[1] ***gross*** *= area converted to orchards. The gross values are taken from the spatial analysis by ArcGIS 10.0.*
[2] ***net*** *= area converted to orchards (**gross**) minus the area of orchards converted to other types of land use. Positive values of this net change are considered "the indirect land use change (iLUC)". A negative net indicates that the area of orchards replaced by other land use types exceeds the area converted to orchards.*

Table A3 Interview results for farmers who recently started oil palm cultivation.

Description	Number of farmers (N=14)	Relative share (%)
Area (ha)		
< 8 ha (smallholder)	12	86
≥ 8 ha (large-scale)	2	14
Oil palm age (year)		
0-2 years	1	7
3-15 years	12	86
> 15 years	1	7
Oil palm variety		
Complex	1	7
Tenera	2	15
Do not know	11	79
Source of seedlings		
Government	2	14
Private sector	11	79
Self-breeding	1	7
In case of planting other crops besides oil palm, how do the farmers manage other crops after planting oil palm?		
No change	14	100
Reasons for planting oil palm – can answer more than one choice		
Expect higher income than a previous crop	2	14
Regular income	2	14
Easy to manage / less labour work	1	7
Neighbour's suggestion	5	36
Government campaign *A grant from the Office of the rubber replanting aid fund (ORRAF) with 100,000 THB/ha for 5 years*	2	14
Suitable land for oil palm	10	71
Other	2	14
- *Trial*	*2*	*100*
Reasons for planting oil palm – can answer more than one choice (1 = most important, 6 = least important)		
1) Suitable land for oil palm		
2) Neighbour's suggestion		
3) Regular income		
4) Expected higher income than a previous crop		
5) Government campaign		
6) Easy to manage / less labour work		
Satisfaction after planting oil palm		
Satisfied because	**8**	**57**
Easy to manage	6	75
Gaining a higher income	2	25
Unsatisfied	**6**	**43**
Unstable (decreasing) price	2	33
Difficult farm management	1	17
Low productivity	3	50
Land ownership		
Heritage	6	43
Buy a new land	6	43
Land reforms by government	2	14

Description	Number of farmers (N=14)	Relative share (%)
Other	-	-
Previous land use before planting oil palm		
Rubber	4	29
Betel nut	1	7
Rice	3	21
Abandon rice	1	7
Unused land	3	21
Degraded forest (land reform)	2	14
Land clearing method		
Burning and tillage	8	57
Tillage	3	21
Manual cutting	3	21
Other	1	7
Main problems when planting oil palm (can answer more than one choice)		
Flood / Drought	7	50
Decreasing price	3	21
Low productivity	3	21
Rodent problem	1	7
Expanding oil palm in the future		
Expanding oil palm because	**8**	**57**
Expectation of increasing price in the future	1	12.5
Available land for planting oil palm	1	12.5
Easy to manage	2	25
Increase investment in oil palm to earn more income	4	50
No expansion of oil palm because	**6**	**43**
No land available	5	83
Difficult farm management	1	17
Willingness to replant oil palm		
Willing to replant because	**10**	**71**
Easy to manage	3	30
Suitable land for oil palm	5	50
Higher income than previous crop	2	20
Prefer to change to other crops	**2**	**14**
Rubber	2	100
Other	**2**	**14**
Heritage for daughter/son	1	50
Changing to residential/commercial building	1	50
Motives for changing the investment decision if prices of FFB decrease		
In case of investment change	**2**	**14**
Planting rubber	2	14
In case of no investment change	**12**	**86**
Trial plot	1	8
No available land	1	8
Have to wait until end of lifetime	10	83
Motives for changing the investment decision if prices of FFB increase		
In case of investment change	**5**	**36**
Expanding oil palm area because farmers want to gain more income	4	80

Description	Number of farmers (N=14)	Relative share (%)
Change to rubber	1	20
In case of no investment change	**9**	**64**
Trial plot	1	11
Lack of budget	1	11
Have to wait until end of lifetime	7	78
Impact of rapid and large expansion of oil palm		
No impact	4	29
Decreasing prices of FFB	8	57
Drought/Flood	2	14

Table A 4 Interview result for farmers who recently started rubber cultivation.

Description	Number of farmers (N=13)	Relative share (%)
Area (ha)		
< 8 ha (smallholder)	9	69
≥ 8 ha (large-scale)	4	31
Rubber age (year) (can answer more than one choice if have many rubber plots)		
0-7 years	1	8
8-20 years	9	69
> 20 years	5	38
Rubber variety		
PRIM 600	12	92
Do not know	1	8
Source of seedlings		
Government	4	31
Private sector	8	62
Do not know	1	8
In case of planting other crops besides rubber, how do the farmers manage other crops after planting rubber?		
No change	13	100
Reasons for planting rubber – can answer more than one choice		
Expect higher income than a previous crop	4	31
Regular income	3	23
Easy to manage / less labour work	1	8
Neighbour's suggestion	2	15
Government campaign *A grant from the Office of the rubber replanting aid fund (ORRAF) with 100,000 THB/ha for 5 years*	3	23
Suitable land for rubber	8	62
Reasons for planting rubber – can answer more than one choice (1 = most important, 6 = least important)		
1) Suitable land for rubber		
2) Expected higher income than a previous crop		
3) Regular income		
4) Government campaign		
5) Neighbour's suggestion		
6) Easy to manage / less labour work		
Satisfaction after planting rubber		
Satisfied because	**10**	**77**
Gain a higher income than previous crop	4	40
High productivity	3	30
Easy to manage	1	10
Skillful at planting rubber	1	10
Unsatisfied	**3**	**23**
Unstable (decreasing) prices of latex	3	100
Land ownership		
Heritage	6	46
Buy a new land	5	38
Land reforms by government	2	15
Other	-	-
Previous land use before planting rubber		

Description	Number of farmers (N=13)	Relative share (%)
Rice	5	38
Abandon rice	1	8
Unused land	4	31
Land reforms	2	15
Orchards	1	8
Land clearing method		
Burning and tillage	10	77
Tillage	3	23
Main problems when planting rubber (can answer more than one choice)		
Fungi disease	10	77
Flood	2	15
Decreasing price	1	8
Low soil quality	1	8
Expanding rubber in the future		
Expanding rubber because	**5**	**38**
Increase investment in rubber to earn more income	4	80
Easy to manage	1	20
No expansion of rubber because	**8**	**62**
Lack of budget and labour	4	50
Change to other crops	1	12.5
Change to commercial/residential buildings	1	12.5
Planted area is big enough	1	12.5
Drought	1	12.5
Willingness to replant rubber		
Willing to replant because	**9**	**69**
Skillful at planting rubber	4	44
Suitable land for rubber	3	33
Easy to manage	1	11
Higher income than previous crop	1	11
Prefer to change to other crops	**4**	**31**
Oil palm	3	75
Vegetables	1	25
Motives for changing the investment decision if prices of latex decrease		
In case of investment change	**4**	**31**
Change to oil palm	3	75
Change to vegetables	1	25
In case of no investment change	**9**	**69**
Skillful at planting rubber	6	67
Lack of (family) labour	3	33
Motives for changing the investment decision if prices of latex increase		
In case of investment change	**5**	**38**
Expanding rubber area because farmers want to gain more income	3	60
Change to oil palm	1	20
Change to vegetables	1	20
In case of no investment change	**8**	**62**
Lack of land	5	62.5
Lack of budget and labour	3	37.5

Table A 5.1 Interview result for farmers who recently started both oil palm and rubber cultivation, and switched in some plots of rubber to oil palm.

Description	Number of farmers (N=10)	Relative share (%)
Area (ha)		
< 8 ha (smallholder)	-	-
≥ 8 ha (large-scale)	10	100
Oil palm age (year) (can answer more than one choice if have many oil palm plots)		
0-2 years	-	-
3-15 years	11	73
> 15 years	4	27
Oil palm variety		
Surat 2	4	40
Surat 7	1	10
Complex ratera	2	20
DxP	2	20
Do not know	1	10
Source of seedlings		
Government	4	33
Private sector	8	67
Rubber age (year) (can answer more than one choice if have many oil palm plots)		
0-7 years	2	17
8-20 years	8	67
> 20 years	2	17
Rubber variety		
PRIM 600	6	60
PRIM 235	1	10
Do not know	3	30
Source of seedlings		
Government	2	20
Private sector	8	80
After switching in some plots of rubber to oil palm, how do the farmers manage remaining area?		
No change	9	90
Continue change 2 ha of rubber plots to oil palm after planting oil palm for 7 years because of fungi disease	1	10
Reasons for planting oil palm – can answer more than one choice		
Expected higher income than a previous crop	4	19
Regular income	3	14
Easy to manage / less labour work	3	14
Neighbour's suggestion	1	5
Government campaign *A grant from the Office of the rubber replanting aid fund (ORRAF) with 100,000 THB/ha for 5 years*	4	19
Suitable land for oil palm	6	29
Reasons for planting oil palm – can answer more than one choice **(1 = most important, 6 = least important)**		

Description	Number of farmers (N=10)	Relative share (%)
1) Suitable land for oil palm		
2) Expected higher income than a previous crop		
3) Government campaign		
4) Regular income		
5) Easy to manage / less labour work		
6) Neighbor's suggestion		
Satisfaction after planting oil palm		
Satisfied because	**9**	**57**
Easy to manage	5	56
Gaining a higher income	3	33
Regular income	2	22
Can plant in seasonal flood area	1	11
Unsatisfied	**1**	**10**
Rubber price is higher than oil palm price	1	100
Land ownership for oil palm – can answer more than one choice		
Heritage	8	73
Buy a new land	2	18
Land reforms by government	1	9
Land ownership for rubber – can answer more than one choice		
Heritage	7	64
Buy a new land	3	27
Land reforms by government	1	9
Previous land use before planting oil palm – can answer more than one choice in case of having many oil palm plots		
Rubber	9	60
Rice	2	13
Unused land	1	7
Degraded forest (land reforms)	3	20
Previous land use before planting rubber – can answer more than one choice in case of having many rubber plots		
Rubber	5	45
Coffee	1	9
Rice	1	9
Unused land	1	9
Degraded forest (land reforms)	3	27
Land clearing method		
Burning and tillage	7	70
Tillage	2	20
Natural decompose	1	10
Main problems when planting oil palm (can answer more than one choice)		
No problem	5	50
Flood / Drought	2	20
Rodent problem	2	20
Low productivity	1	10
Main problems when planting rubber (can answer more than one choice)		
No problem	1	10
Fungi disease	8	80
Flood / Drought	1	10
Expanding oil palm in the future		

Description	Number of farmers (N=10)	Relative share (%)
Expanding oil palm because	**7**	**70**
Easy to manage	3	43
Increase investment in oil palm to earn more income by acquiring land from unused land or land reforms	4	57
No expansion of oil palm because	**3**	**30**
Lack of (family) labour	2	67
Prefer to expand rubber area	1	33
Expanding rubber in the future		
Expanding rubber because	**7**	**70**
Rubber tree can be sold after the end of lifetime	4	57
Increase in rubber investment to earn more income by acquiring land from unused land or land reforms	3	43
No expansion of rubber because	**3**	**30**
Lack of (family) labour	3	100
Willingness to replant oil palm		
Willing to replant because	**9**	**90**
Easy to manage	2	22
Suitable land for oil palm	1	11
Regular income	2	22
Skillful at planting oil palm	4	44
Prefer to change to other crops	**1**	**10**
Rubber	1	100
Willingness to replant rubber		
Willing to replant because	**7**	**70**
Rubber tree can be sold after the end of lifetime	3	43
Skillful at planting oil palm	4	57
Prefer to change to other crops	**3**	**30**
Oil palm because easy to manage and regular income	3	100
Motives for changing the investment decision in oil palm if prices of FFB decrease		
In case of investment change	**3**	**30**
Multi-crops plantations	1	33
Change to rubber	2	67
In case of no investment change	**7**	**70**
Waiting until the oil palm reach end of lifetime	2	29
Expectation of increasing price in the future	3	43
Difficult to find a suitable land	1	14
Lack of labour	1	14
Motives for changing the investment decision in oil palm if prices of FFB increase		
In case of investment change	**3**	**30**
Expanding oil palm area by buying a new land	3	100
In case of no investment change	**7**	**70**
Lack of labour	1	14
Difficult to find a suitable land	2	29
Waiting until the oil palm reach end of lifetime	3	43
Heritage for next generation	1	14
Motives for changing the investment decision in rubber if prices of latex decrease		
In case of investment change	**4**	**40**
Planting oil palm because easy to manage	2	50

Description	Number of farmers (N=10)	Relative share (%)
Changing rubber variety	1	25
Multi-crops plantations	1	25
In case of no investment change	**6**	**60**
Waiting until rubber reach end of lifetime	2	33
Expectation of increasing price in the future	2	33
Difficult to find a suitable land	1	17
Lack of labour	1	17
Motives for changing the investment decision in rubber if prices of latex increase		
In case of investment chaneg	**5**	**50**
Expanding rubber area to earn more income by buying a new land	5	100
In case of no investment change	**5**	**50**
Suitable land for oil palm	1	20
Lack of labour	3	60
Keep the area for next generation (Heritage)	1	20
Impact of rapid and widely expansion of oil palm		
No impact	4	40
Decreasing prices of FFB	4	40
Drought/Flood	2	20

Table A 5.2 Result of farmer interviews concerning annual cost-income comparison between oil palm and rubber (unit: THB/rai).

Description	Rubber Mean±SD	Sample (N=10)	Oil palm Mean±SD	Sample (N=10)
Fertilisers cost	1,003±446	10	1,451±930	10
Labour cost for Fertilizing	183±76	3	280±311	2
Herbicides cost	132±84	4	455±531	3
Labour cost for cutting weeds/spraying herbicides	182±115	5	167±58	3
Labour cost for harvesting	8,450±1,626	2	1,901±1,190	6
Land cost	43,485±638	3	10,000±0	2
Seedling cost	1,483±638	8	3,073±2,055	10
Fuel cost	142±69	4	104±77	4
Income	22,858±8,151	8	20,246±14,013	7
Net profit*	11,284		12,816	

** Land cost is not included in the net profit calculation*

Appendix B

Additional information for Chapter 3

Table B1 Emission factor (EF)

Activity (α)	Compound (ε)	Emission Factor (EFε,α)	Unit	Reference
Fertiliser production				
N Fertiliser	CO_2	3089	g/kg N	Ecoinvent (2010)
	CH_4	7.922	g/kg N	
	N_2O	0.040	g/kg N	
	SO_2	3.999	g/kg N	
	NOx	3.939	g/kg N	
	NMVOC	1.588	g/kg N	
	CO	4.497	g/kg N	
	PM	3.412	g/kg N	
P Fertiliser (P_2O_5)	CO_2	1504	g/kg P	Ecoinvent (2010)
	CH_4	2.258	g/kg P	
	N_2O	0.025	g/kg P	
	SO_2	34.79	g/kg P	
	NOx	4.675	g/kg P	
	NMVOC	0.720	g/kg P	
	CO	2.037	g/kg P	
	PM	5.240	g/kg P	
K Fertiliser (K_2O)	CO_2	441.8	g/kg K	Ecoinvent (2010)
	CH_4	1.705	g/kg K	
	N_2O	0.036	g/kg K	
	SO_2	0.747	g/kg K	
	NOx	1.531	g/kg K	
	NMVOC	0.362	g/kg K	
	CO	1.011	g/kg K	
	PM	0.374	g/kg K	
Fertiliser use				
N Fertiliser				
Direct emissions	N_2O	10.00	g/kg N	IPCC (2006b)
	NOx	25.00	g/kg N	Pluimers, J (2001)
	NO_3^-	300.0	g/kg N	Pluimers, J (2001)
Indirect emissions of N-fertilisers as NOx and NH_3	N_2O	1.000	g/kg N	IPCC (2006)
Indirect emissions after N-leaching and runoff	N_2O	2.250	g/kg N	IPCC (2006b)
Boron production				
	CO_2	78.58	g/kg	Ecoinvent (2010)
	CH_4	0.072	g/kg	
	N_2O	0.003	g/kg	
	SO_2	0.154	g/kg	
	NOx	0.765	g/kg	
	NMVOC	0.121	g/kg	
	CO	0.221	g/kg	
	PM	3.001	g/kg	

Activity (α)	Compound (ε)	Emission Factor (EFε,α)	Unit	Reference
Glyphosate production	CO_2	9704	g/kg	Ecoinvent (2010)
	CH_4	25.62	g/kg	
	N_2O	0.227	g/kg	
	SO_2	26.61	g/kg	
	NOx	18.19	g/kg	
	NMVOC	15.25	g/kg	
	CO	67.02	g/kg	
	PM	14.09	g/kg	
Electricity generation	CO_2	560.0	g/kWh	EGAT (2011)
	CH_4	4.126	g/kWh	Ecoinvent (2010)
	N_2O	0.014	g/kWh	
	NOx	1.280	g/kWh	Krittayakasem (2011)
	PM	0.020	g/kWh	
	SO_2	0.430	g/kWh	
	NMVOC	0.223	g/kWh	Ecoinvent (2010)
	COD	0.345	g/kWh	
	CO	0.141	g/kWh	
Biomass combustion	CO_2	100.0	t/TJ	IPCC (2006c)
	CH_4	0.030	g/MJ	
	N_2O	0.004	g/MJ	
	SO_2	0.038	g/MJ	EEA (2009a)
	NOx	0.150	g/MJ	
	NMVOC	0.146	g/MJ	
	CO	1.596	g/MJ	
	PM	0.156	g/MJ	
Gasoline production	CO_2	433.6	g/kg	Lewis (1997)
	CH_4	0.810	g/kg	
	SO_2	3.595	g/kg	
	NOx	2.083	g/kg	
	NMVOC	9.801	g/kg	
	CO	0.248	g/kg	
	PM	0.107	g/kg	
Diesel production	CO_2	316.8	g/kg	Lewis (1997)
	CH_4	0.055	g/kg	
	SO_2	0.218	g/kg	
	NOx	1.751	g/kg	
	NMVOC	3.966	g/kg	
	CO	0.710	g/kg	
	PM	2.669	g/kg	

Activity (α)	Compound (ε)	Emission Factor (EFε,α)	Unit	Reference
Heavy oil production	CO_2	231,707	g/kg	Lewis (1997)
	CH_4	0.631	g/kg	
	SO_2	1.297	g/kg	
	NOx	1.427	g/kg	
	NMVOC	3.349	g/kg	
	CO	0.178	g/kg	
	PM	0.049	g/kg	
Diesel used in Tractor	CO_2	3.160	g/kg fuel	EEA (2010)
	CH_4	0.055	g/kg fuel	
	N_2O	0.136	g/kg fuel	
	SO_2	0.700	g/kg fuel	
	NOx	35.04	g/kg fuel	
	NMVOC	3.366	g/kg fuel	
	CO	10.94	g/kg fuel	
	PM	1.738	g/kg fuel	
Gasoline used in weed cutter	CO_2	3197	g/kg fuel	EEA (2010)
	CH_4	2.200	g/kg fuel	
	N_2O	0.017	g/kg fuel	
	SO_2	0.700	g/kg fuel	
	NOx	2.765	g/kg fuel	
	NMVOC	242.2	g/kg fuel	
	CO	620.8	g/kg fuel	
	PM	3.726	g/kg fuel	
Diesel used in pick-up truck (<3.5 t)	CO_2	251.2	g/km	EEA (2012)
	CH_4	0.012	g/km	IPCC (2006d)
	N_2O	0.004	g/km	
	SO_2	0.056	g/km	EEA (2012)
	NOx	1.660	g/km	
	NMVOC	0.133	g/km	
	CO	1.340	g/km	
	PM	0.356	g/km	
Diesel used in 10-wheel truck (20-26 ton)	CO_2	753.6	g/km	EEA (2012)
	CH_4	0.080	g/km	IPCC (2006d)
	N_2O	0.029	g/km	
	SO_2	0.168	g/km	EEA (2012)
	NOx	10.70	g/km	
	NMVOC	0.486	g/km	
	CO	1.930	g/km	
	PM	0.418	g/km	

Activity (α)	Compound (ε)	Emission Factor (EFε,α)	Unit	Reference
Heavy oil used in vessel	CO_2	3111	g/kg	IPCC (2006d)
	CH_4	0.281	g/kg	
	N_2O	0.080	g/kg	
	SO_2	0.540	g/kg	EEA (2011)
	NOx	79.30	g/kg	
	NMVOC	2.700	g/kg	
	CO	7.400	g/kg	
	PM	6.200	g/kg	
Kaolin production	CO_2	197.8	g/kg	Ecoinvent (2010)
	CH_4	0.391	g/kg	
	N_2O	0.004	g/kg	
	SO_2	0.528	g/kg	
	NOx	0.256	g/kg	
	NMVOC	0.057	g/kg	
	CO	0.064	g/kg	
	PM	0.114	g/kg	
Alum production	CO_2	469.9	g/kg	Ecoinvent (2010)
	CH_4	0.720	g/kg	
	N_2O	0.012	g/kg	
	SO_2	7.804	g/kg	
	NOx	1.399	g/kg	
	NMVOC	0.191	g/kg	
	CO	0.335	g/kg	
	PM	1.522	g/kg	
Sodium sulphite production	CO_2	1316	g/kg	Ecoinvent (2010)
	CH_4	2.303	g/kg	
	N_2O	0.034	g/kg	
	SO_2	36.70	g/kg	
	NOx	2.499	g/kg	
	NMVOC	0.424	g/kg	
	CO	0.988	g/kg	
	PM	1.271	g/kg	
Sodium carbonate production	CO_2	942.6	g/kg	Ecoinvent (2010)
	CH_4	4.018	g/kg	
	N_2O	0.019	g/kg	
	SO_2	2.258	g/kg	
	NOx	1.479	g/kg	
	NMVOC	3.268	g/kg	
	CO	0.0007	g/kg	
	PM	0.707	g/kg	
Anaerobic process	CH_4	200.0	g /kg COD	IPCC (2006e)
	NMVOC	15.00	g /m^3	EEA (2009b)
EFB- open dumping	CH_4	57.33	g /kg waste	IPCC (2006f)

Table B2 Classification factor

Environmental impacts (μ)	Pollutant (ε)	Classification factor (CFμ,ε)			Reference
Global warming	CO_2	1g =	1	CO_2 eq	IPCC (2007)
	CH_4	1g =	25	CO_2 eq	
	N_20	1g =	298	CO_2 eq	
Acidification	SO_2	1g =	1	SO_2 eq	CML (2012)
	NOx	1g =	0.5	SO_2 eq	
Eutrophication	NOx	1g =	0.13	PO_4^{3-} eq	CML (2012)
	NO_3^-	1g =	0.1	PO_4^{3-} eq	
	N	1g =	0.42	PO_4^{3-} eq	
	PO_4^{3-}	1g =	1	PO_4^{3-} eq	
	P	1g =	3.06	PO_4^{3-} eq	
	COD	1g =	0.022	PO_4^{3-} eq	
Photochemical ozone formation	NMVOC	1g =	0.416	C_2H_4 eq	CML (2012)
	CO	1g =	0.027	C_2H_4 eq	
	CH_4	1g =	<0.016	C_2H_4 eq	
	NOx	1g =	0.028	C_2H_4 eq	
Human toxicity	SO_2	1g =	0.096	$C_6H_4Cl_2$ eq	CML (2012)
	NOx	1g =	1.2	$C_6H_4Cl_2$ eq	
	PM	1g =	0.82	$C_6H_4Cl_2$ eq	
	Glyphosate	1g =	0.015	$C_6H_4Cl_2$ eq	
Freshwater ecotoxicity	Glyphosate	1g =	0.922	$C_6H_4Cl_2$ eq	CML (2012)

Table B3 Emissions from oil palm plantation
Unit: g pollutant/t FFB

Activity			CO_2			CH_4			N_2O		
			N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO
Soil preparation	Diesel	Production	54	54	54	0.01	0.01	0.01	-	-	-
		Transportation	5.96	5.96	5.96	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
		Use	0.53	0.53	0.53	0.01	0.01	0.01	0.02	0.02	0.02
Fertiliser management	Mineral - N	Production	12,046	13,331	10,893	30.90	34.19	27.94	0.16	0.17	0.14
		Transportation	134	149	121	0.01	0.02	0.01	<0.01	0.01	<0.01
		Use (direct emission)	-	-	-	-	-	-	61	68	55
		Use (indirect emission)	-	-	-	-	-	-	20	22	18
	Mineral - P	Production	4,361	3,234	1,970	6.55	4.86	2.96	0.07	0.05	0.03
		Transportation	100	74	45	0.01	0.01	<0.01	<0.01	<0.01	<0.01
		Use	-	-	-	-	-	-	-	-	-
	Mineral - K	Production	4,595	3,735	6,070	17.73	14	23	0.38	0.31	0.50
		Transportation	358	291	473	0.04	0.03	0.05	0.01	0.01	0.02
	Boron	Production	-	30	13	-	0.03	0.01	-	<0.01	<0.01
		Transportation	-	13	5.80	-	<0.01	<0.01	-	<0.01	<0.01
Weed control	Glyphosate	Production	1,029	181	12	2.72	0.48	0.03	0.02	<0.01	<0.01
		Transportation	3.60	0.64	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
		Use	-	-	-	-	-	-	-	-	-
	Gasoline	Production	224	104	23	0.42	0.19	0.04	-	-	-
		Transportation	18	8.43	1.87	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
		Use	1,654	765	170	1.14	0.53	0.12	0.01	<0.01	<0.01
FFB Transportation	Diesel	Production	2,720	123	79	0.47	0.02	0.01	-	-	-
		Transportation	303	14	8.82	0.03	<0.01	<0.01	0.01	<0.01	<0.01
		Use	2,303	1,215	786	0.20	0.06	0.04	0.07	0.02	0.01

Table B3 Emissions from oil palm plantation (cont.)
Unit: g pollutant/t FFB

Activity			SO_2			NOx			NO_3^-		
			N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO
Soil preparation	Diesel	Production	0.04	0.04	0.04	0.30	0.30	0.30	-	-	-
		Transportation	<0.01	<0.01	<0.01	0.08	0.08	0.08	-	-	-
		Use	0.12	0.12	0.12	5.92	5.92	5.92	-	-	-
Fertiliser management	Mineral - N	Production	16	17	14	15	17	14	-	-	-
		Transportation	0.03	0.04	0.03	1.74	1.92	1.57	-	-	-
		Use (direct emission)	-	-	-	98	108	88	1,170	1,295	1,058
		Use (indirect emission)	-	-	-	-	-	-	-	-	-
	Mineral - P	Production	101	75	46	14	10	6.12	-	-	-
		Transportation	0.03	0.02	0.01	1.29	0.96	0.58	-	-	-
		Use	-	-	-	-	-	-	-	-	-
	Mineral - K	Production	7.77	6.32	10	16	13	21	-	-	-
		Transportation	0.09	0.07	0.12	4.63	3.76	6.12	-	-	-
	Boron	Production	-	<0.01	<0.01	-	0.29	0.13	-	-	-
		Transportation	-	<0.01	<0.01	-	0.17	0.08	-	-	-
Weed control	Glyphosate	Production	2.82	0.50	0.03	1.93	0.34	0.02	-	-	-
		Transportation	<0.01	<0.01	<0.01	0.05	0.01	<0.01	-	-	-
		Use	-	-	-	-	-	-	-	-	-
	Gasoline	Production	1.86	0.86	0.19	1.08	0.50	0.11	-	-	-
		Transportation	<0.01	<0.01	<0.01	0.24	0.11	0.03	-	-	-
		Use	0.36	0.17	0.04	1.43	0.66	0.15	-	-	-
FFB Transportation	Diesel	Production	1.87	0.08	0.05	15	0.68	0.44	-	-	-
		Transportation	0.08	<0.01	<0.01	4.06	0.18	0.12	-	-	-
		Use	0.51	0.27	0.18	27	8.03	5.19	-	-	-

Table B3 Emissions from oil palm plantation (cont.)

Unit: g pollutant/t FFB

Activity			NMVOC			CO			PM		
			N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO
Soil preparation	Diesel	Production	0.67	0.67	0.67	0.12	0.12	0.12	0.45	0.45	0.45
		Transportation	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01
		Use	0.57	0.57	0.57	1.85	1.85	1.85	0.29	0.29	0.29
Fertiliser management	Mineral - N	Production	6.19	6.85	5.60	18	19	16	13	15	12
		Transportation	0.22	0.25	0.20	0.33	0.36	0.30	0.17	0.18	0.15
		Use (direct emission)	-	-	-	-	-	-	-	-	-
		Use (indirect emission)	-	-	-	-	-	-	-	-	-
	Mineral - P	Production	2.81	1.55	0.94	7.94	4.38	2.67	20	11	6.86
		Transportation	0.17	0.12	0.08	0.24	0.18	0.11	0.12	0.09	0.06
		Use	-	-	-	-	-	-	-	-	-
	Mineral - K	Production	3.77	3.06	4.98	11	8.55	14	3.89	3.16	5.13
		Transportation	0.60	0.49	0.79	0.87	0.71	1.15	0.44	0.36	0.58
	Boron	Production	-	0.05	0.02	-	0.08	0.04	-	1.15	0.51
		Transportation	-	0.02	0.01	-	0.03	0.01	-	0.02	0.01
Weed control	Glyphosate	Production	1.62	0.29	0.02	7.10	1.25	0.09	1.49	0.26	0.02
		Transportation	0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
		Use	-	-	-	-	-	-	-	-	-
	Gasoline	Production	5.07	2.34	0.52	0.13	0.06	0.01	0.06	0.03	0.01
		Transportation	0.03	0.01	<0.01	0.05	0.02	<0.01	0.02	0.01	<0.01
		Use	125	58	13	321	148	33	1.93	0.89	0.20
FFB Transportation	Diesel	Production	34	1.53	0.99	6.10	0.27	0.18	23	1.03	0.67
		Transportation	0.52	0.02	0.02	0.77	0.03	0.02	0.39	0.02	0.01
		Use	1.39	0.64	0.42	8.11	6.48	4.19	1.96	1.72	1.11

Table B3 Emissions from oil palm plantation (cont.)
Unit: g pollutant/t FFB

Activity			Glyphosate		
			N-RSPO	P-RSPO	C-RSPO
Soil preparation	Diesel	Production	-	-	-
		Transportation	-	-	-
		Use	-	-	-
Fertiliser management	Mineral - N	Production	-	-	-
		Transportation	-	-	-
		Use (direct emission)	-	-	-
		Use (indirect emission)	-	-	-
	Mineral - P	Production	-	-	-
		Transportation	-	-	-
		Use	-	-	-
	Mineral - K	Production	-	-	-
		Transportation	-	-	-
	Boron	Production	-	-	-
		Transportation	-	-	-
Weed control	Glyphosate	Production	-	-	-
		Transportation	-	-	-
		Use	0.11	0.02	<0.01
	Gasoline	Production	-	-	-
		Transportation	-	-	-
		Use	-	-	-
FFB Transportation	Diesel	Production	-	-	-
		Transportation	-	-	-
		Use	-	-	-

Table B4 Emissions from palm oil mill
Unit: g pollutant/t CPO

Activity			CO_2			CH_4			N_2O		
			N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO
Oil extraction	Diesel	Production	647	795	494	0.11	0.14	0.09	-	-	-
		Transportation	72	89	55	0.01	0.01	0.01	0.00	0.00	0.00
		Use	6.46	7.93	4.93	0.11	0.14	0.09	0.28	0.34	0.21
	Electricity	Production	1,668	1,265	1,280	12	9.32	9.43	0.04	0.03	0.03
	Fibre	Combustion	-	-	-	175	255.36	133.03	23.32	34.05	17.74
	Kaolin	Production	1,775	2,308	1,683	3.50	4.56	3.32	0.04	0.05	0.04
		Transportation	305	396	289	0.03	0.04	0.03	0.01	0.01	0.01
Water treatment	Alum	Production	31	91	268	0.05	0.14	0.41	0.00	0.00	0.01
		Transportation	2.28	6.56	19	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Sodium sulphite	Production	79	44	114	0.14	0.08	0.20	<0.01	<0.01	<0.01
		Transportation	2.04	1.14	2.94	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Sodium carbonate	Production	62	63	25	0.26	0.27	0.11	<0.01	<0.01	<0.01
		Transportation	2.97	2.26	0.91	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Wastewater treatment	POME	Anaerobic process	-	-	-	56,474	7,672	2,342	-	-	-
Waste Generation	Empty fruit bunch	Open dumping	-	-	-	53,794	60,742	-	-	-	-

Table B4 Emissions from palm oil mill (cont.)
Unit: g pollutant/t CPO

Activity			SO_2			NOx			COD		
			N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO
Oil extraction	Diesel	Production	0.45	0.55	0.34	3.58	4.40	2.73	-	-	-
		Transportation	0.02	0.02	0.01	0.97	1.19	0.74	-	-	-
		Use	1.43	1.76	1.09	72	88	55	-	-	-
	Electricity	Production	1.28	0.97	0.98	3.81	2.89	2.93	1.03	0.78	0.79
	Fibre	Combustion	224	327	170	875	1,277	665	-	-	-
	Kaolin	Production	4.74	6.16	4.49	2.30	2.99	2.18	-	-	-
		Transportation	0.08	0.10	0.08	5.32	5.19	3.79	-	-	-
Water treatment	Alum	Production	0.52	1.51	4.45	<0.01	<0.01	0.01	-	-	-
		Transportation	<0.01	<0.01	0.01	0.04	0.09	0.25	-	-	-
	Sodium sulphite	Production	2.20	1.23	3.18	0.15	0.08	0.22	-	-	-
		Transportation	<0.01	<0.01	<0.01	0.04	0.01	0.04	-	-	-
	Sodium carbonate	Production	0.15	0.15	0.06	0.10	0.10	0.04	-	-	-
		Transportation	<0.01	<0.01	<0.01	0.04	0.03	0.01	-	-	-
Wastewater treatment	POME	Anaerobic process	-	-	-	-	-	-	7.26	7.03	4.93
Waste Generation	Empty fruit bunch	Open dumping	-	-	-	-	-	-	-	-	-

Table B4 Emissions from palm oil mill (cont.)
Unit: g pollutant/t CPO

Activity			N			P			NMVOC		
			N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO
Oil extraction	Diesel	Production	-	-	-	-	-	-	8.10	9.95	6.18
		Transportation	-	-	-	-	-	-	0.12	0.15	0.10
		Use	-	-	-	-	-	-	6.88	8.45	5.25
	Electricity	Production	-	-	-	-	-	-	0.66	0.50	0.51
	Fibre	Combustion	-	-	-	-	-	-	854	1,246	649
	Kaolin	Production	-	-	-	-	-	-	0.51	0.67	0.49
		Transportation	-	-	-	-	-	-	0.52	0.67	0.49
Water treatment	Alum	Production	-	-	-	-	-	-	0.01	0.04	0.11
		Transportation	-	-	-	-	-	-	<0.01	0.01	0.03
	Sodium sulphite	Production	-	-	-	-	-	-	0.03	0.01	0.04
		Transportation	-	-	-	-	-	-	<0.01	<0.01	<0.01
	Sodium carbonate	Production	-	-	-	-	-	-	0.22	0.22	0.09
		Transportation	-	-	-	-	-	-	0.01	<0.01	<0.01
Wastewater treatment	POME	Anaerobic process	0.40	1.09	0.62	0.12	1.09	0.62	51	-	-
Waste Generation	Empty fruit bunch	Open dumping	-	-	-	-	-	-	-	-	-

Table B4 Emissions from palm oil mill (cont.)
Unit: g pollutant/t CPO

Activity			CO			PM		
			N-RSPO	P-RSPO	C-RSPO	N-RSPO	P-RSPO	C-RSPO
Oil extraction	Diesel	Production	1.45	1.78	1.11	5.45	6.70	4.16
		Transportation	0.18	0.22	0.14	0.09	0.11	0.07
		Use	22	27	17	3.55	4.36	2.71
	Electricity	Production	0.42	0.32	0.32	0.06	0.05	0.05
	Fibre	Combustion	9,307	13,585	7,077	912	1,331	694
	Kaolin	Production	0.57	0.75	0.54	1.02	1.33	0.97
		Transportation	0.75	0.98	0.71	0.38	0.49	0.36
Water treatment	Alum	Production	0.02	0.06	0.19	0.10	0.29	0.87
		Transportation	0.01	0.02	0.05	<0.01	0.01	0.02
	Sodium sulphite	Production	0.06	0.03	0.09	0.08	0.04	0.11
		Transportation	0.01	<0.01	0.01	<0.01	<0.01	<0.01
	Sodium carbonate	Production	<0.01	<0.01	<0.01	0.05	0.05	0.02
		Transportation	0.01	0.01	<0.01	<0.01	<0.01	<0.01
Wastewater treatment	POME	Anaerobic process	-	-	-	-	-	-
Waste Generation	Empty fruit bunch	Open dumping	-	-	-	-	-	-

Table B 5.1 Environmental impacts of 1 ton palm kernel

Study case	Global Warming (GW) as g CO_2eq	Acidification (AD) as g SO_2eq	Eutrophication (EP) as g PO_4^{3-}eq	Photochemical Ozone Formation (POF) as g C_2H_4 eq	Human Toxicity (HT) as g $C_6H_4Cl_2$eq
N-RSPO	895,964	575	259	577	1,032
P-RSPO	552,478	615	255	499	1,189
C-RSPO	76,814	374	189	198	660

Table B 5.2 Environmental impacts of the palm kernel production in the Tapi River basin (unit per basin)

Study case	Global Warming (GW) as t CO_2eq	Acidification (AD) as t SO_2eq	Eutrophication (EP) as t PO_4^{3-}eq	Photochemical Ozone Formation (POF) as t C_2H_4 eq	Human Toxicity (HT) as t $C_6H_4Cl_2$eq
N-RSPO	4,752,191	3,051	1,376	3,061	5,475
P-RSPO	1,392,244	1,551	642	1,259	2,997
C-RSPO	71,898	350	177	186	618

Appendix C

Additional information for Chapter 4

APPENDIX C - Additional information for Chapter 4

Appendix C1 Description of options to reduce emissions

Oil palm plantations

Group of options to minimise fertiliser use

Fertilisers are used to maximize FFB yields. We account for nitrogen (N) fertiliser in the model as a source of N_2O, NOx and NO_3^- (Table 4.1). N_2O emissions include direct emissions from fertilised fields and indirect emissions after losses of N-fertiliser to, for instance, aquatic systems.

An effective way to reduce N_2O emissions is through reduction of the N-inputs to soils. Several studies report that increasing the efficiency of fertilisers can reduce N-inputs as well as increase yields (Benbi, 2013; Smith and Siciliano, 2015; Ussiri and Lal, 2013; Vries, 2012). According to Kroeze and Mosier (2000), *Apply optimum dose of fertilisers and Apply slow-release fertilisers* could save about 10-20% of fertiliser inputs in temperate climates. Such estimates do not exist for the tropical climate. We assumed that similar reductions are possible in oil palm plantations in Thailand. We assumed that investment and operating costs are negligible and thus only variable costs are considered in the cost estimation.

In Thailand, most of farmers are smallholders with limited knowledge on fertiliser use. Implementation of the option *Applying optimum doses of fertilisers,* therefore, requires training of farmers. Recently, a joint project (with a budget of 6.65 million THB) by Shell Thailand and Patum Vegetable Oil Co., Ltd was carried out to support Thai smallholder farmers to produce palm oil more sustainably (Shell, 2015, personal communication). In total, 797 farmers were participating and trained on best management practices. The training addressed fertiliser management and pest control. We used this information to calculate the costs of training per person and allocated these training costs equally to *Apply optimum dose of fertilisers* and *Cover crops*.

Group of options on FFB yield improvement

Yield improvement leads to reductions in emissions and environmental impacts. Dallinger (2011) shows that harvesting only ripe fruits can increase palm oil production in Thailand. Current practice is that often unripe fruits are harvested as well. These have a low oil content. This has been a problem in Thailand for decades. It is a consequence of the FFB pricing system that usually depends on the weight of FFBs rather than on oil content. Smallholder famers harvest unripe fruits whenever they need income. Farmers usually harvest FFB in week 18, but the fruits are ripe in week 21. The option *Harvesting ripe fruits,* improves FFB yields by 12% ($if_{y,i}$ = 0.12) as a result of which the oil content of fruits increases by 15% (AgriSource, 2005). This option can be achieved by changing harvesting practice. There are no investment costs. The benefits from yield increase are accounted for in the model as variable costs.

Group of options on weed control

Farmers typically remove weeds using herbicides. To avoid using herbicides, Samedani et al. (2014) suggested that the weed control can be managed through planting *Cover crops* between sods. We assumed that this could reduce the use of herbicides and gasoline in a weed cutter by 50% ($rf_{\alpha,i}$ = 0.5). Moreover, it could increase FFB yields by 8% ($if_{y,i}$ = 0.08) when compared to the plot using herbicides. Cover crops are natural vegetation and often removed because farmers perceive them as weeds (DOA, 2011). To change farmers' perceptions and weed control practice, farmers need to be trained. We estimated the costs of training to be similar to the trainings costs for the option *Apply optimum dose of fertilisers.*

Palm oil mills

Group of options on POME treatment

Kaewmai et al. (2013b) reported that a change from open lagoons to *biogas capture systems* could reduce CH4 emissions by 50% ($rf_{\varepsilon,\alpha,i}$ = 0.5) relative to anaerobic open lagoons. Nowadays, various types of biogas technology are available, such as covered lagoons, upflow anaerobic sludge blanket reactors, and hybrid channel digesters. Covered lagoons are the most promising technology with the shortest payback period (DEDE, 2010; Trangkwachirakul, 2015). This option is, therefore, taken into accounted in our model. *Biogas capture systems* not only provides a better POME treatment but also electricity generation from captured biogas. The Thai government promotes renewable energy production by providing 0.03 THB/kWh when producers sell electricity from biogas to the grid (DEDE, 2012a). This is included in the cost estimations.

We also included the option *Upgrading biogas* to make it comparable to natural gas. It may be possible to use upgraded biogas for transportation in the future. Pre-treatment of biogas is needed before it can be transported through natural gas networks. In principle, upgrading implies to an increase of the CH_4 concentration from 50% to more than 96%, as well as to remove CO_2 and H_2S from the biogas. The CH_4 reduction by *Upgrading biogas* is the same as for *Biogas capture systems* ($rf_{\varepsilon,\alpha,i}$ = 0.5). An advantage of *Upgrading biogas* is that it could increase electricity generation from 31% to 40% when compared to electricity generated from the *Biogas capture systems* (Pattanapongchai and Limmeechokchai, 2011).

Group of options on EFB treatment

Several options to use EFBs are reported in literature. For instance, *Mulching EFB* in the oil palm plantations is recommended by Heriansyah (2011). We assume that this can be done in all oil palm planted areas, so that all untreated EFB can be avoided ($rf_{\alpha,i}$ = 1).

A co-benefit of *Mulching EFB* is that it could substantially reduce the use of chemical fertilisers. Mulching 40 tons of EFB per ha may release enough nutrients for oil palms when EFB decays (Heriansyah, 2011). We, therefore, considered fertiliser reduction ($rf_{\alpha,i}$ = 1) as a side-effect of mulching in the model. We calculated the cost saving for fertiliser reduction based on three formulas (N-P-K: 46-0-0, 18-46-0 and 0-0-60). Note that the nutrient content of EFB may differ among regions. For instance, higher K content is reported in Malaysia (N: P: K = 0.54 : 0.06 : 2.03) than in Thailand (Heriansyah, 2011).

For Thailand, Univan (2011) reported that one ton of EFB can provide 17.5 kg of N, 2.9 kg of P and 18.3 kg of K. Mulching 40 tons of EFB would thus provide 36 kg of N, 6 kg of P and 38 kg K. This is considerably higher than the amount of fertilisers that smallholder farmers usually apply (Table 6.2). The extra N-input from *Mulching EFB* amounts to 33 kg N/ton FFB and causes emissions of N_2O *(*$EFS_{\varepsilon,i,\alpha}$ *= 6.50)*, NOx *(*$EFS_{\varepsilon,i,\alpha}$ *= 2.64)* and NO_3^- *(*$EFS_{\varepsilon,i,\alpha}$ *= 10.98)*. We considered these emissions as negative side effect in our analysis. Emission factors of the side effect are derived from literature (IPCC, 2006b; Pluimers, 2001).

Moreover, *Mulching EFB* can promote growth and improve FFB yields through soil improvement, soil erosion reduction and nutrient loss prevention (Heriansyah, 2011; Moradi et al., 2015; Univan, 2011). In Malaysia, Heriansyah (2011) showed that applying 40 ton EFB/ha/year would increase FFB yields by 3-24% relative to a control plot fertilised by chemical fertilisers alone. An average yield increase of 13% ($if_{y,i}$ = 0.13) is used to calculate this side-effect on FFB yields.

Nevertheless, there are some drawbacks of *Mulching EFB.* EFB can be a breeding site for rhino beetles if stacking was not done properly. A single pile of EFB should be placed in the inter-rows and away from the palm fronds and harvester path. EFB is relatively heavy and voluminous. Therefore, costs of transportation of EFB from a mill to plantations and labour for spreading EFB are relatively high. Note that we ignored emissions of EFB transportation in this study because of the uncertainties in transportation distances and the types of vehicles used.

Alternatively, EFB can be processed to bio-compost. In an *EFB Composting plant*, EFB is usually chopped to increase the surface area contact with microorganisms. The chopped EFB is then placed in open windrows, which are turned regularly by a turning machine to avoid anaerobic conditions (Chiew and Shimada, 2013; Schuchardt et al., 2008, 2002; Singh et al., 2010; Stichnothe and Schuchardt, 2011). Approximately, 90% of the generated EFB can be consumed in the composting plant ($rf_{\alpha,i}$ = 0.9) (Schuchardt et al., 2002).

EFB combustion is also proposed as an environmental improvement option (ABO, 2010; Arrieta et al., 2007; Chiew and Shimada, 2013; Patthanaissaranukool et al., 2013). EFB can be used to generate electricity to be sold to the grid, using a direct-fired power generator. An EFB-power plant is able to handle all generated EFB (UNFCCC, 2007). Thus, we assumed that all untreated EFB can be avoided ($rf_{\alpha,i}$ = 1). This can avoid CH_4 emissions from untreated EFB, but it indirectly generates other pollutants during combustion. We considered emissions during combustion as a negative side-effect. Since electricity from *EFB combustion* replaces some electricity from the grid, the side-effect is then calculated and compared to the emissions from the grid. Note that electricity generation in Thailand is mainly based on natural gas (67%), followed by lignite and coal (20%) (EPPO, 2013).

We assumed that *EFB combustion* increases CH_4 ($EFS_{\varepsilon,i,\alpha}$ = *-0.005*), N_2O ($EFS_{\varepsilon,i,\alpha}$ = *-0.15)*, CO ($EFS_{\varepsilon,i,\alpha}$ = *-3.12)*, VOC ($EFS_{\varepsilon,i,\alpha}$ = *-1.14)* and PM emissions ($EFS_{\varepsilon,i,\alpha}$ = *-3.04)* but decreases CO_2 ($EFS_{\varepsilon,i,\alpha}$ = *9.74)*, SO_2 ($EFS_{\varepsilon,i,\alpha}$ = *2.22)* and NOx emissions ($EFS_{\varepsilon,i,\alpha}$ = *2.53)*. These emission factors are derived from literature (Ecoinvent, 2010; EGAT, 2011; Jawjit et al., 2010; Krittayakasem et al., 2011).

EFB pellets production is another option. Pellets can be used as biomass fuel (Chavalparit et al., 2006; Chiew and Shimada, 2013). Approximately 90% of EFB can be used to produce EFB pellets ($rf_{\alpha,i}$ = 0.9) (TÜV NORD CERT GmbH, 2012).

As EFB has a high content of cellulose and hemicelluloses, *EFB ethanol production* has been suggested. An EFB ethanol plant can handle all EFB generated by a mill ($rf_{\alpha,i}$ = 1) (Chiew and Shimada, 2013; Piarpuza¡n et al., 2011; Tan et al., 2010).

Finally, *EFB Gasification* - a conversion of biomass to gaseous fuels using fluidized bed biomass gasifier, has been recommended (Asadullah, 2014; Lahijani and Zainal, 2011a; Mohammed et al., 2011a, 2011b; Ogi et al., 2013). A commercial plant in Malaysia could use all untreated EFB to produce bio-oil and electricity ($rf_{\alpha,i}$ = 1) (Lahijani and Zainal, 2011b).

Group of options on NOx control for fibre combustion

Many NOx control technologies exist. In this study, four technologies are selected: Low-NOx burners, Selective non-catalytic reduction, Selective catalytic reduction and non-thermal plasma.

Low-NOx burner - To avoid NOx formation, a low availability of oxygen is introduced into in the primary combustion zone to limit the temperature. A wide range of NOx removal efficiencies (10-50%) has been reported (EPA, 1999; Trozzi et al., 2013; US-DOE, 1996). We used an average removal efficiency of 30% ($rf_{\varepsilon,\alpha,i}$ = 0.3) in the calculations.

Selective non-catalytic reduction - Without use of a catalyst, ammonia or urea is injected in the flue-gas to reduce NOx emission by forming harmless nitrogen and water vapour. This could remove NOx emissions by around 30-50% relative to an untreated case (EPA, 2003b; Trozzi et al., 2013). An average NOx removal efficiency of 40% ($rf_{\varepsilon,\alpha,i}$ = 0.4) is used in the model. Mendoza-Covarrubias et al. (2011) reported that *Selective non-catalytic reduction* increases N_2O emissions by 20% of NOx removed while working. We therefore included this negative side-effect on N_2O formation in the model analysis.

Selective catalytic reduction – NOx is removed from the flue gas by injected ammonia through a catalyst converting nitrogen oxides to nitrogen and water vapour. NOx removal efficiencies range between 70% and 90% (EPA, 2003a; Trozzi et al., 2013). An average NOx removal efficiency of 80% ($rf_{\varepsilon,\alpha,i}$ = 0.8) is used in the model. However, *Selective catalytic reduction* has a negative side-effect on N_2O formation by 10% of NOx removed (Kim, 2013). This increased N_2O is therefore included in the model.

Non-thermal plasma - Ozone is used to reduce NOx emissions by raising the valence of nitrogen in a reaction chamber. Here, NOx is converted to the higher-oxidized state. After that, NOx is hydrolyzed and removed with a scrubber as nitric acid. Reported removal efficiencies range from 80% to 95% (EPA, 2005a, 2005b, 1999). An average NOx removal efficiency of 90% ($rf_{\varepsilon,\alpha,i}$ = 0.9) is used in the model analysis.

Group of options on SO_2 control for fibre combustion

Wet scrubber technology is commercially and widely applied for SO_2 control in the food and agriculture industry (EPA, 2003c). It is, therefore, also considered in this study. This device is operated by letting the flue gas flows upward and contacted with liquid droplets of limestone in the chamber. Limestone reacts with sulphur to form calcium sulfate (gypsum). Note that income from selling gypsum is not included in our analysis. Removal efficiencies range from 80% to 99% relative to the untreated case (EPA, 2003c; Trozzi et al., 2013). We used an average removal efficiency of 90% ($rf_{\varepsilon,\alpha,i}$ = 0.9) in the model analysis. Besides SO_2 removal, this device can also remove other pollutants, such as particulate matter (PM) by 50-99% ($rf_{\varepsilon,\alpha,i}$ = 0.85), NOx by 55-75% ($rf_{\varepsilon,\alpha,i}$ = 0.65) and VOC by 50-95% ($rf_{\varepsilon,\alpha,i}$ = 0.74) (EPA, 2003c; Ruitang and Xiang, 2008). We included these positive side-effects in the model.

Group of options on VOC control for fibre combustion

A *Thermal incinerator* is used to control VOC emissions from a wide variety of industrial processes. However, its fuel consumption is high. VOC removal efficiency is in the range of 98-99.99% ($rf_{\varepsilon,\alpha,i}$ = 0.99) (EPA, 2003d). Besides VOC, also other pollutants are removed, such as PM by 79-96% ($rf_{\varepsilon,\alpha,i}$ = 0.88) and CO by 78-99% ($rf_{\varepsilon,\alpha,i}$ = 0.89) (EMIS, 2015; EPA, 2003d). On the other hand, CO_2 and NOx emissions increase when VOC and the supported fuel are combusted (EMIS, 2015). Note that we ignored the increase in CO_2 and NOx emissions in the model.

Group of options on PM control for fibre combustion

In our analysis, three types of PM control devices are considered.

Cyclones - PM is removed by centrifugal and inertial forces. Cyclones themselves are not adequate to meet a stringent air pollution regulations (Rashid et al., 1998), but serve an important purpose as pre-cleaners for more final control devices, such as, wet scrubber and electrostatic precipitators (EPA, 2003e). The PM removal efficiency is in the range of 70-90% ($rf_{\varepsilon,\alpha,i}$ = 0.8).

Baghouse - PM in flue gas is passed through a tightly woven or felted fabric and collected. PM removal efficiency ranges between 99 and 99.99% ($rf_{\varepsilon,\alpha,i}$ = 0.99) (EPA, 2003f).

Electrostatic precipitator – This device controls PM by using electrical forces to move particles in the flu gas onto collection surfaces. PM removal efficiencies of 99-99.99% are reported (EPA, 2003g).

Group of option on boiler efficiency improvement

Boiler efficiencies can be improved by *Pre-heating fibre* using heat from flue gas. As a result, the combustion temperature are optimized and biomass consumption will be decreased. DEDE (2007) reported that a reduction in fuel consumption by 50% ($rf_{\alpha,i}$ = 0.5) can be achieved. We assumed that the saved fibre is sold. Co-benefit from selling the saved fibre in included in the model.

Group of options on oil extraction improvement

DEDE (2006) and Chavalparit (2006) indicate that oil extraction efficiencies can be improved by changing machines and minimizing oil losses in the waste products (i.e. decanter cake, fibre, POME and EFB). Changing machines is costly and, sometimes, seems unnecessary. While, minimizing the oil losses in the waste-products is more practical. There is a room for oil recovery improvement through adjustment of equipment operation and control. No device is needed. Therefore, only co-benefits of yield improvement is included in the model.

Oil recovery from decanter cake – Oil in decanter cake can be recovered by adjustment of decanter inlet feed-rate and sludge density and temperature. An oil recovery rate of 5.5% ($if_{y,i}$ = 0.055) is reported (DEDE, 2006).

Oil recovery from fibre - Oil in fibre is mainly influenced by operation of the screw press system as well as the pre-treatment of palm fruits in the digester. Thus, adjustment of equipment operation and control could reduce oil losses in fibre. An oil recovery rate of 1% ($if_{y,i}$ = 0.01) is reported (DEDE, 2006).

Oil recovery from POME – Oil in POME can be recovered by improving operational efficiencies of sludge handling in the settling tank (i.e. feed-rate and temperature adjustment). An oil recovery rate of 0.5% ($if_{y,i}$ = 0.005) is reported (DEDE, 2006).

Oil recovery from EFB - EFB is first chopped and then pressed to extract the oil. An EFB shredder and EFB press are needed for this. An oil recovery rate of 0.5% ($if_{y,i}$ = 0.005) is reported (DEDE, 2006). The pressed EFB is ready to use or sell as fuel. Moreover, this option increases PK production by 1% ($if_{y,i}$ = 0.01) (Chavalparit, 2006). However, it is likely that this option may result in a higher BOD load in POME. In this study, we ignored this side effect because BOD is not listed as important emissions (Table 4.1).

Table C1 Increases in the production of fresh fruit bunches, crude palm oil or palm kernel.

Group of options	Options	Productivity increase *(if)*			Source
		Fresh fruit bunch	Crude palm oil	Palm kernel	
Weed control	Cover crops	0.08[a]			Estimated from Samedani et al.(2014)
FFB yield improvement	Harvesting ripe fruits[b]	0.12			AgriSource (2005)
EFB treatment	Mulching EFB	0.13[a]			Estimated from Heriansyah (2011)
Oil extraction improvement	Oil recovery from decanter		0.055		Chavalparit (2006) and DEDE (2006)
	Oil recovery from fibre		0.01		
	Oil recovery from EFB		0.005	0.01	
	Oil recovery from POME		0.005		

a - Increase in fresh fruit bunch is a side-effect of this option (see also Table A2, Appendix A)
b - We assumed that the farmers usually harvest fruits at week 18 but the fruits are ripe at week 21.

Table C2 Reduction factors for options aiming at decreasing the use of fertilisers, gasoline, herbicides and the waste of empty fruit bunches or fibre.

Group of options	Options	Activity inputs to be reduced	Reduction factor *(rf)*	Source
Optimising fertilisers use	Apply optimum dose of fertilisers	N-fertiliser	0.2	Kroeze and Mosier (2000)
	Apply slow-release fertilisers		0.1	
Weed control	Cover crops[a]	Gasoline	0.5	Samedani et al.(2014)
		glyphosate	0.5	
EFB treatment	Mulching EFB[a]	EFB	1	OAE (2016a)
		Fertilisers[b]	1	Heriansyah (2011)
	Combustion	EFB	1	Patthanaissaranukool et al. (2013) and UNFCCC (2007)
	Ethanol production		1	ExC (2004), Arrieta et al. (2007), ABO (2010), PiarpuzÃ¡n et al (2011) and Chiew and Shimada (2013)
	Gasification		1	Asadullah (2014) , Lahijani and Zainal (2011a), Mohammed et al (2011a, 2011b), and Ogi et al. (2013)
	Pellets production		0.9	Chavalparit et al (2006) and Chiew and Shimada (2013)
	Composting plant		0.9	Schuchardt et al. (2008, 2002), Singh et al. (2010), Stichnothe and Schuchardt (2011) and Chiew and Shimada (2013),
Boiler efficiency improvement	Pre-heating fibre	Fibre	0.5	DEDE (2007)

a - this option increases fresh fruit bunch yield as a side effect (see Table A1, Appendix A).
b - this option reduces fertilisers use as a side-effect; this option is primarily aiming at avoiding untreated EFB.

Table C3 Reduction factors for emissions of pollutants. **Bold** and underlined reduction factors are for pollutants for which the option is primarily implemented. Negative reduction factors mean that option cause an increase in emissions. Between brackets: reported ranges from literature (not available for all pollutants).

Group of options	Options	Reduction Factor (*rf*)								Source
		CH_4	N_2O	SO_2	NOx	VOC	NO_3^-	CO	PM	
POME treatment	Biogas capture system[a]	**0.5**								DEDE (2010) and Kaewmai et al.(2013b)
	Bioreactor plus upgrading biogas plant	**0.5**								Pattanapongchai and Limmeechokchai (2011)
EFB treatment	Mulching EFB[b]		-6.50		-2.64		-10.98			This study
	Combustion[c]	-0.005	-0.15	2.22	2.53	-1.14		-3.12	-3.04	This study
	Gasification[c]								-0.29	This study
NOx control for fibre combustion	Selective catalytic reduction		-0.08		**0.8 (0.70–0.90)**					EPA (2003a) Kim (2013) and Trozzi et al. (2013)
	Selective non-catalytic reduction		-0.08		**0.4 (0.30-0.50)**					EPA (2003b) , Mendoza-Covarrubias,(Mendoza-Covarrubias et al., 2011) and Trozzi et al. (2013)
	Low-NOx burner				**0.3 (0.10-0.50)**					EPA (1999) and Trozzi et al. (2013)
	Non-Thermal Plasma				**0.9 (0.80-0.95)**					EPA (EPA, 2005a, 2005b)
SO_2 control for fibre combustion	Wet scrubber			**0.9 (0.80-0.99)**	0.65 (0.55-0.75)	0.74 (0.52-0.95)			0.85 (0.70-0.99)	EPA (2003c) Ruitang and Xiang (2008) and Trozzi et al. (2013)
VOC control for fibre combustion	Thermal incinerator[d]					**0.99 (0.98-0.99)**		0.89 (0.78-0.99)	0.88 (0.79-0.96)	EPA (2003d) and EMIS (2015)

Group of options	Options	Reduction Factor (*rf*)								Source
		CH_4	N_2O	SO_2	NOx	VOC	NO_3^-	CO	PM	
PM control for fibre combustion	Cyclones								**0.8 (0.70-0.90)**	EPA (2003e)
	Baghouse								**0.99 (0.99->0.99)**	EPA (2003f)
	Electrostatic precipitator								**0.99 (0.99- >0.99)**	EPA (2003g)

[a] *Cover lagoon technology is considered in this study because of the short payback period (DEDE, 2010).*

[b] *This option primarily aims at avoiding untreated EFB (see Table A2, Appendix A). However, as a side-effect it increase emissions. Reduction factors in the table are emissions after implementation of this option* (IPCC, 2006b; Pluimers, 2001).

[c] *This option primarily aims at avoiding untreated EFB (see Table A2, Appendix A). However, it gives a side-effect on increase or decrease emissions. Reduction factors given in the table are emissions after implementation of this option* (EEA, 2009b; IPCC, 2006c) *in reference to emissions of electricity generation from the grid* (Ecoinvent, 2010; EGAT, 2011; Jawjit et al., 2010; Krittayakasem et al., 2011).

[d] *It should be note that, aThermal incinerator would increase CO_2 and NOx emissions(EMIS, 2015) but we ignored this in the calculation.*

Table C4 Aggregated emissions and environmental impacts after implementation of reduction options.

(a) Global warming potential (unit: kg CO_2eq/ton CPO)

Sub-system	Activity (Aα)		Reference	Harvesting ripe fruits	Oil recovery - decanter	Oil recovery - fibre	Oil recovery - EFB	Oil recovery - POME	Optimum fertilisers	Slow-release fertilisers	Cover crops	Mulching EFB	EFB-combustion	EFB-Ethanol	EFB-Gasification	EFB-pellets	EFB-compost	Pre-heating fibre
Cultivation	Soil preparation	Diesel	0.30	0.27	0.23	0.28	0.29	0.29	0.30	0.30	0.28	0.27	0.30	0.30	0.30	0.30	0.30	0.30
	Fertiliser management	N fertiliser	167	149	125	157	160	160	133	150	154	129	167	167	167	167	167	167
		P fertiliser	21	19	16	20	20	20	21	21	19	-	21	21	21	21	21	21
		K fertiliser	25	22	19	23	24	24	25	25	23	-	25	25	25	25	25	25
	Weed Control	Glyphosate	5	4	4	5	5	5	5	5	2	4	5	5	5	5	5	5
		Gasoline	10	8	10	9	9	9	9	9	4	8	10	10	10	10	10	10
	FFB transportation	Diesel	12	10	11	11	12	12	12	12	11	10	12	12	12	12	12	12
Palm oil production	Palm oil extraction	Diesel	0.82	0.82	0.77	0.81	0.80	0.80	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
		Electricity	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		Fibre	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	5
		Kaolin	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Water treatment	Alum	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
		Sodium sulphite	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
		Sodium carbonate	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	Wastewater treatment	POME	1,412	1,412	1,338	1,398	1,386	1,386	1,412	1,412	1,412	1,412	1,412	1,412	1,412	1,412	1,412	1,412
	Waste disposal	Empty fruit bunch	1,345	1,345	1,275	1,332	1,320	1,320	1,345	1,345	1,345	614	-1,213*	-	-	175	175	1,345
		SUM	**3,012**	**2,987**	**2,813**	**2,971**	**2,951**	**2,951**	**2,978**	**2,995**	**2,988**	**2,065**	**454**	**1,667**	**1,667**	**1,843**	**1,843**	**3,006**

(a) Global warming potential (unit: kg CO_2eq/ton CPO) (continued)

Sub-system	Activity (Aα)		Reference	Biogas capture	Upgrading biogas	Selective catalytic reduction	Selective non-catalytic reduction
Cultivation	Soil preparation	Diesel	0.30	0.30	0.30	0.30	0.30
	Fertiliser management	N fertiliser	167	167	167	167	167
		P fertiliser	21	21	21	21	21
		K fertiliser	25	25	25	25	25
	Weed Control	Glyphosate	5	5	5	5	5
		Gasoline	10	10	10	10	10
	FFB transportation	Diesel	12	12	12	12	12
Palm oil production	Palm oil extraction	Diesel	0.82	0.82	0.82	0.82	0.82
		Electricity	2	2	2	2	2
		Fibre	11	11	11	12	12
		Kaolin	2	2	2	2	2
	Water treatment	Alum	0.04	0.04	0.04	0.04	0.04
		Sodium sulphite	0.08	0.08	0.08	0.08	0.08
		Sodium carbonate	0.07	0.07	0.07	0.07	0.07
	Wastewater treatment	POME	1,412	706	706	1,412	1,412
	Waste disposal	Empty fruit bunch	1,345	1,345	1,345	1,345	1,345
		SUM	**3,012**	**2,306**	**2,306**	**3,013**	**3,013**

- No emissions of greenhouse gases are released after implementation of the option

** This option can both avoid CH_4 emissions from untreated EFB (direct-effect) as well as provide an extra CO_2 reduction when partly supplies electricity to the grid (side-effect). This results in a negative value showing a net sink for greenhouse gas emissions after implantation of the option.*

(b) Acidification (unit: kg SO_2eq/ton CPO)

Sub-system	Activity (Aα)		Reference	Harvesting ripe fruits	Oil recovery - decanter	Oil recovery - fibre	Oil recovery - EFB	Oil recovery - POME	Optimum fertilisers	Slow-release fertilisers	Cover crops	Mulching EFB	EFB-combustion	Pre-heating fibre	Selective catalytic reduction	Selective non-catalytic reduction	Low NOx burner	Non-Thermal Plasma	Wet Scrubber
Cultivation	Soil preparation	Diesel	15	13	11	14	14	14	15	15	14	13	15	15	15	15	15	15	15
	Fertiliser management	N fertiliser	326	291	246	308	313	313	261	294	301	407	326	326	326	326	326	326	326
		P fertiliser	485	433	365	458	465	465	485	485	447	-	485	485	485	485	485	485	485
		K fertiliser	81	72	61	77	78	78	81	81	75	-	81	81	81	81	81	81	81
	Weed Control	Glyphosate	17	15	13	16	16	16	17	17	8	15	17	17	17	17	17	17	17
		Gasoline	18	14	18	16	16	16	16	16	7	14	18	18	18	18	18	18	18
	FFB transportation	Diesel	69	59	63	66	66	66	69	69	61	59	69	69	69	69	69	69	69
Palm oil production	Palm oil extraction	Diesel	40	40	38	40	39	39	40	40	40	40	40	40	40	40	40	40	40
		Electricity	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
		Fibre	661	661	627	655	649	649	661	661	661	661	661	317	311	486	530	268	175
		Kaolin	9	9	8	9	9	9	9	9	9	9	9	9	9	9	9	9	9
	Water treatment	Alum	0.59	0.59	0.56	0.58	0.58	0.58	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
		Sodium sulphite	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		Sodium carbonate	0.22	0.22	0.21	0.22	0.21	0.21	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
	Wastewater treatment	POME	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Waste disposal	Empty fruit bunch	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1,798	-4,116*	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		SUM	**1,727**	**1,622**	**1,456**	**1,663**	**1,671**	**1,671**	**1,660**	**1,693**	**1,638**	**3,022**	**-2,389***	**1,383**	**1,377**	**1,552**	**1,596**	**1,334**	**1,242**

- No emissions of acidifying compounds are released after implementation of the option

n.a. - Not applicable.

* *This option can provide an extra SO_2 and NOx reduction when partly supplies electricity to the grid (side-effect). This results in a negative value show in negative emissions for acidifying emissions after implantation of the option.*

(c) Eutrophication (unit: kg PO_4^{3-}eq/ton CPO)

Sub-system	Activity (Aα)		Reference	Harvesting ripe fruits	Oil recovery - decanter	Oil recovery - fibre	Oil recovery - EFB	Oil recovery - POME	Optimum fertilisers	Slow-release fertilisers	Cover crops	Mulching EFB	EFB-combustion	Pre-heating fibre	Selective catalytic reduction	Selective non-catalytic reduction	Low NOx burner	Non-Thermal Plasma	Wet Scrubber
Cultivation	Soil preparation	Diesel	4	3	3	3	4	4	4	4	3	3	4	4	4	4	4	4	4
	Fertiliser management	N fertiliser	590	527	445	557	566	566	472	531	545	1,084	590	590	590	590	590	590	590
		P fertiliser	9	8	7	8	8	8	9	9	8	-	9	9	9	9	9	9	9
		K fertiliser	12	11	9	11	11	11	12	12	11	-	12	12	12	12	12	12	12
	Weed Control	Glyphosate	1.15	1.03	0.87	1.08	1.10	1.10	1.15	1.15	0.56	1.02	1.15	1.15	1.15	1.15	1.15	1.15	1.15
		Gasoline	2	1.43	2	2	2	2	2	2	1	1.42	2	2	2	2	2	2	2
	FFB transportation	Diesel	17	15	16	16	16	16	17	17	15	15	17	17	17	17	17	17	17
Palm oil production	Palm oil extraction	Diesel	10	10	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10
		Electricity	0.50	0.50	0.47	0.49	0.49	0.49	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
		Fibre	114	114	108	113	112	112	114	114	114	114	114	55	23	68	80	11	40
		Kaolin	0.99	0.99	0.94	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
	Water treatment	Alum	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		Sodium sulphite	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		Sodium carbonate	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Wastewater treatment	POME	0.69	0.69	0.65	0.68	0.68	0.68	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
	Waste disposal	Empty fruit bunch	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4,782	-598*	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		SUM	**761**	**694**	**600**	**724**	**732**	**732**	**642**	**701**	**711**	**6,012**	**162**	**701**	**670**	**715**	**726**	**658**	**687**

- No emissions of eutrophying compounds are released.
n.a. - Not applicable.
** This option can provide an extra NOx reduction when partly supplies electricity to the grid (side-effect). This results in a negative value for eutrophying emissions after implantation of the option.*

(d) Photochemical ozone formation (unit: kg C2H4eq/ton CPO)

Sub-system	Activity (Aα)		Reference	Harvesting ripe fruits	Oil recovery - decanter	Oil recovery - fibre	Oil recovery - EFB	Oil recovery - POME	Optimum fertilisers	Slow-release fertilisers	Cover crops	Mulching EFB	EFB-combustion	EFB-Ethanol	EFB-Gasification	EFB-pellets	EFB-compost
Cultivation	Soil preparation	Diesel	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Fertiliser management	N fertiliser	29	26	22	28	28	28	23	26	27	23	29	29	29	29	29
		P fertiliser	7	6	5	7	7	7	7	7	6	-	7	7	7	7	7
		K fertiliser	13	11	9	12	12	12	13	13	12	-	13	13	13	13	13
	Weed Control	Glyphosate	4	4	3	4	4	4	4	4	2	4	4	4	4	4	4
		Gasoline	311	252	311	279	277	277	282	282	130	250	311	311	311	311	311
	FFB transportation	Diesel	13	11	12	13	13	13	13	13	12	11	13	13	13	13	13
Palm oil production	Palm oil extraction	Diesel	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
		Electricity	0.18	0.18	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		Fibre	632	632	599	626	620	620	632	632	632	632	632	632	632	632	632
		Kaolin	0.70	0.70	0.66	0.69	0.69	0.69	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	Water treatment	Alum	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
		Sodium sulphite	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		Sodium carbonate	0.10	0.10	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Wastewater treatment	POME	360	360	341	357	354	354	360	360	360	360	360	360	360	360	360
	Waste disposal	Empty fruit bunch	323	323	306	320	317	317	323	323	323	101	1,603**	-	-	42	42
		SUM	**1,705**	**1,640**	**1,621**	**1,657**	**1,644**	**1,644**	**1,671**	**1,674**	**1,519**	**1,393**	**2,985****	**1,382**	**1,382**	**1,425**	**1,425**

(d) Photochemical ozone formation (unit: kg C_2H_4eq/ton CPO) (continued)

Sub-system	Activity (Aα)		Reference	Pre-heating fibre	Biogas capture	Upgrading biogas	Selective catalytic reduction	Selective non-catalytic reduction	Low NOx burner	Non-Thermal Plasma	Wet Scrubber	Thermal incinerator
Cultivation	Soil preparation	Diesel	3	3	3	3	3	3	3	3	3	3
	Fertiliser management	N fertiliser	29	29	29	29	29	29	29	29	29	29
		P fertiliser	7	7	7	7	7	7	7	7	7	7
		K fertiliser	13	13	13	13	13	13	13	13	13	13
	Weed Control	Glyphosate	4	4	4	4	4	4	4	4	4	4
		Gasoline	311	311	311	311	311	311	311	311	311	311
	FFB transportation	Diesel	13	13	13	13	13	13	13	13	13	13
Palm oil production	Palm oil extraction	Diesel	9	9	9	9	9	9	9	9	9	9
		Electricity	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		Fibre	632	303	632	632	612	622	625	610	353	58
		Kaolin	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	Water treatment	Alum	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
		Sodium sulphite	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		Sodium carbonate	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Wastewater treatment	POME	360	360	191	191	360	360	360	360	360	360
	Waste disposal	Empty fruit bunch	323	323	323	323	323	323	323	323	323	323
		SUM	**1,705**	**1,377**	**1,536**	**1,536**	**1,686**	**1,695**	**1,698**	**1,683**	**1,427**	**1,131**

- No emissions of photochemical ozone precursor compounds are released after implementation of the option

*** This option causes large emissions of VOC and CO when partly supplies electricity to the grid (side-effect). This results in an increase in photochemical ozone formation compounds after implantation of the option.*

(e) Human toxicity (unit: kg $C_6H_4Cl_2$eq/ton CPO)

Sub-system	Activity (Aα)		Reference	Harvesting ripe fruits	Oil recovery - decanter	Oil recovery - fibre	Oil recovery - EFB	Oil recovery - POME	Optimum fertilisers	Slow-release fertilisers	Cover crops	Mulching EFB	EFB-combustion	EFB-Gasification	Pre-heating fibre
Cultivation	Soil preparation	Diesel	37	33	28	35	35	35	37	37	34	32	37	37	37
	Fertiliser management	N fertiliser	672	600	506	634	644	644	537	605	620	978	672	672	672
		P fertiliser	179	160	135	169	172	172	179	179	165	-	179	179	179
		K fertiliser	130	116	98	122	125	125	130	130	120	-	130	130	130
	Weed Control	Glyphosate	17	15	13	16	17	17	17	17	8	15	17	17	17
		Gasoline	25	21	25	23	23	23	23	23	11	20	25	25	25
	FFB transportation	Diesel	173	149	158	165	166	166	173	173	154	148	173	173	173
Palm oil production	Palm oil extraction	Diesel	99	99	94	98	97	97	99	99	99	99	99	99	99
		Electricity	5	5	4	5	5	5	5	5	5	5	5	5	5
		Fibre	1,819	1,819	1,724	1,801	1,786	1,786	1,819	1,819	1,819	1,819	1,819	1,819	873
		Kaolin	11	11	10	11	11	11	11	11	11	11	11	11	11
	Water treatment	Alum	0.30	0.30	0.28	0.29	0.29	0.29	0.30	0.30	0.30	0.30	0.30	0.30	0.30
		Sodium sulphite	0.50	0.50	0.47	0.49	0.49	0.49	0.50	0.50	0.50	0.50	0.50	0.50	0.50
		Sodium carbonate	0.22	0.22	0.21	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
	Wastewater treatment	POME	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Waste disposal	Empty fruit bunch	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4,314	-2,928*	367	n.a.
		SUM	**3,168**	**3,046**	**2,796**	**3,080**	**3,080**	**3,080**	**3,032**	**3,099**	**3,066**	**7,442**	**240**	**3,536**	**2,222**

(e) Human toxicity (unit: kg $C_6H_4Cl_2$eq/ton CPO) (continued)

Sub-system	Activity (Aα)		Reference	Selective catalytic reduction	Selective non-catalytic reduction	Low NOx burner	Non-Thermal Plasma	Wet Scrubber	Thermal incinerator	Cyclones	Baghouse	Electrostatic precipitator
Cultivation	Soil preparation	Diesel	37	37	37	37	37	37	37	37	37	37
	Fertiliser management	N fertiliser	672	672	672	672	672	672	672	672	672	672
		P fertiliser	179	179	179	179	179	179	179	179	179	179
		K fertiliser	130	130	130	130	130	130	130	130	130	130
	Weed Control	Glyphosate	17	17	17	17	17	17	17	17	17	17
		Gasoline	25	25	25	25	25	25	25	25	25	25
	FFB transportation	Diesel	173	173	173	173	173	173	173	173	173	173
Palm oil production	Palm oil extraction	Diesel	99	99	99	99	99	99	99	99	99	99
		Electricity	5	5	5	5	5	5	5	5	5	5
		Fibre	1,819	979	1,399	1,504	874	482	1,161	1,221	1,079	1,079
		Kaolin	11	11	11	11	11	11	11	11	11	11
	Water treatment	Alum	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
		Sodium sulphite	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
		Sodium carbonate	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
	Wastewater treatment	POME	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Waste disposal	Empty fruit bunch	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		SUM	**3,168**	**2,329**	**3,168**	**2,853**	**2,224**	**1,831**	**2,510**	**2,570**	**2,428**	**2,428**

- No emissions of human toxifying compounds are released.

n.a. - Not applicable.

** This option can provide a reduction of SO_2 and NOx emissions when partly supplies electricity to the grid (side-effect). This results in a negative value showing a net sink for human toxifying emissions after implantation of the option.*

(f) Freshwater ecotoxicity (unit: kg $C_6H_4Cl_2$eq/ton CPO)

Sub-system	Activity (Aα)		Reference	Mulching EFB	Harvesting ripe fruits	Oil recovery - decanter	Oil recovery - fibre	Oil recovery - EFB	Oil recovery - POME	Cover crops
Cultivation	Soil preparation	Diesel	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Fertiliser management	N fertiliser	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		P fertiliser	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		K fertiliser	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Weed Control	Glyphosate	437	387	390	329	413	419	419	211
		Gasoline	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	FFB transportation	Diesel	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Palm oil production	Palm oil extraction	Diesel	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		Electricity	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		Fibre	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		Kaolin	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Water treatment	Alum	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		Sodium sulphite	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		Sodium carbonate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Wastewater treatment	POME	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Waste disposal	Empty fruit bunch	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		SUM	**437**	**387**	**390**	**329**	**413**	**419**	**419**	**211**

n.a. - Not applicable.

Table C5 Information on costs of options: oil palm plantations

Group of options	Options	Items	Cost	Unit	Source
Optimising fertilisers use	Apply optimum dose of fertilisers	Fertiliser 46-0-0	0.39	$/kg Fertiliser	DIT (2014a)
		Labour for fertilizing	0.02	$/kg Fertiliser	AgriSource (2005)
		Cost of training*	117	$/person	Shell (2015)
	Apply slow-release fertilisers	Slow-release fertiliser	5	$/kg Fertiliser	Germinal (2015)
		Labour for fertilizing	0.02	$/kg Fertiliser	AgriSource (2005)
Weed control	Cover crops	Glyphosate	3	$/L Glyphosate	AgriSource (2005)
		Labour for spraying	0.88	$/L Glyphosate	AgriSource (2005)
		Cost of training*	117	$/person	Shell (2015)
		FFB price	0.13	$/kg FFB	DIT (2014b)
FFB yield improvement	Harvesting ripe fruits	FFB price	0.13	$/kg FFB	DIT (2014b)

* Cost of training is equally share to options *Apply optimum dose of fertilisers* and *Cover crops*

Table C6 Information on costs of options: palm oil mills.

Group of options	Options	Items	Investment ($)	Lifetime (year)	O&M ($/year)	Variable	Reference
POME treatment	Biogas capture system	Covered lagoon	971,600	15	214,620	-	DEDE (2010)
		Power generation *(capacity 1.9 MW)*	982,800	7[a]	-	-	
		Adder for selling electricity ($/kWh)	-	-	-	0.0084	DEDE (2012a)
	Bioreactor plus upgrading biogas plant	Cost for upgrading biogas *(biogas reactor + upgrading plant)*	733,000	15	213,660	-	Pattanapongchai and Limmeechokchai (2011)
		Power generation *(capacity 1.2 MW)*	579,600	7[a]	-	-	DEDE (2010)
		Adder for selling electricity ($/kWh)	-	-	-	0.0084	DEDE (2012a)
EFB treatment	Mulching EFB	Transport FFB to plantation ($/kg EFB)	-	-	-	0.0034	DOAE (2011)
		Labour for stacking EFB ($/day)	-	-	-	8.40	MOL (2012)
		FFB price ($/kg FFB)	-	-	-	0.13	DIT (2014b)
		Fertiliser 46-0-0 ($/kg Fertiliser)	-	-	-	0.39	OAE (2015)
		Fertiliser 18-46-0 ($/kg Fertiliser)	-	-	-	0.50	OAE (2015)
		Fertiliser 0-0-60 ($/kg Fertiliser)	-	-	-	0.56	OAE (2015)
	Composting plant	Composting plant *(capacity 13,800 ton compost/year)*	485,053	10	68,943	-	Schuchardt et al. (2002)
		EFB-compost price ($/kg)	-	-	-	0.014	
	Combustion	Combustion plant *(capacity 8.9 MW)*	24,202,140	25	1,268,784	-	UNFCCC (2007)

Group of options	Options	Items	Investment ($)	Lifetime (year)	O&M ($/year)	Variable	Reference
		(capacity 8.9 MW)					
		Transportation of EFB; 200 km radius ($/year)	-	-	-	1,640,615	
		Adder for selling electricity ($/kWh)	-	-	-	0.0084	
	Ethanol production	Model plant ($/year)	9,500,000	-	-	-	ExC (2004)
		Bio-ethanol price ($/year)	-	-	-	8,500,000	
	Pellets production	Pellet production plant *(capacity 4.35 ton pellet/hr, annual operation time 7,116 hr)*	2,934,904	15	928,159	-	TÜV NORD CERT GmbH (2012)
		Pellets price ($/ton)	-	-	-	53	
	Gasification	Gasification plant *(capacity 500 kWh)*	272,733	15	19,578	-	Asadullah (2014) and Mukhopadhyay (2004)
		Adder for selling electricity ($/kWh)	-	-	-	0.0084	DEDE (2012a)
NOx control for fibre combustion	Non-Thermal Plasma	Model plant	1,312,500	20[b]	32,813	-	EPA (2005a)
	Selective catalytic reduction	Model plant	896,000	20	53,760[c]	-	Suwannahong (2015) and Jawjit (2006)
	Selective non-catalytic reduction	Model plant	672,000	20	40,320[c]	-	
	Low-Nox burner	Model plant	224,000	20	13,440[c]	-	
SO_2 control for fibre combustion	Wet scrubber	Model plant	156,800	15	14,112[c]	-	
VOC control for fibre combustion	Thermal incinerator	Model plant	95,771[d]	20[b]	2,640[e]	-	EPA (2003d) and EMIS (2015)

Group of options	Options	Items	Investment ($)	Lifetime (year)	O&M ($/year)	Variable	Reference
PM control for fibre combustion	Cyclones	Model plant	112,000	15	5,600[c]	-	Suwannahong (2015) and Jawjit (2006)
	Baghouse	Model plant	84,000	15	4,200[c]	-	
	Electrostatic precipitator	Model plant	280,000	10	22,400[c]	-	
Boiler efficiency improvement	Pre-heating fibre	Belt conveyor (including installation)	6,760	20	406	-	Schuchardt et al. (2002)
		Fibre price ($/kg)	-	-	-	0.015	Anonymous (2015)
Oil extraction improvement	Oil recovery from decanter	CPO price ($/kg CPO)	-	-	-	0.76	DIT (2014b)
	Oil recovery from fibre	CPO price ($/kg CPO)	-	-	-	0.76	
	Oil recovery from POME	CPO price ($/kg CPO)	-	-	-	0.76	
	Oil recovery from EFB	EFB shredder	56,000	15	1,680[f]	-	(Chavalparit, 2006; Jawjit, 2006)
		EFB press[g]	56,000	15	1,680	-	
		PK price ($/kg PK)	-	-	-	0.014	
		CPO price ($/kg CPO)	-	-	-	0.76	(DIT, 2014b)

- Not applicable

a - Expert judgement.

B - Lifetime of the device is assumed to be as for Selective Catalytic Reduction.

C – O&M costs are estimated from Jawjit (2006), with a range of 5 – 9% depending on pollution control technology.

D - Based on EMIS (2015); value is from a hydrogenating edible oil process (flow rate 200 Nm^3/h because the process is similar to palm oil production.

E - Based on EMIS (2015), the flow rate of 200 Nm^3/h is smaller than the range in EPA (2003d). O&M 231ost are therefore estimated based on the lowest value in the range. Note that when a palm oil mill is expanding, this device can often handle higher flue gas streams.

F - O&M costs are assumed to be the same as for EFB pellet production, accounting for 3% of investment cost.

G - Associated costs are assumed to be the same as for the EFB shredder.

Appendix D

Additional information
for Chapter 5

APPENDIX D - Additional information for Chapter 5

Table D1 Emission factors adopted from Saswattecha et al. (2015b)

Activity (A)	Pollutant	Emission factors (EF)	Unit	Reference
Fertiliser production				
N Fertiliser				
	CH_4	7.922	g /kg N	Eco-invent (2010)
	N_2O	0.040	g /kg N	
P Fertiliser				
	CH_4	2.258	g /kg P	Eco-invent (2010)
	N_2O	0.025	g /kg P	
K Fertiliser				
	CH_4	1.705	g/kg K	Eco-invent (2010)
	N_2O	0.036	g/kg K	
Fertiliser use:				
N Fertiliser				
- direct emissions	N_2O	10.00	g /kg N	IPCC (2006b)
- indirect emissions after N leaching and runoff	N_2O	2.250	g /kg N	IPCC (2006b)
- indirect emissions of N Fertiliser as NOx, NH_3	N_2O	1.000	g /kg N	IPCC (2006b)
Boron production				
	CH_4	0.072	g/kg	Eco-invent (2010)
	N_2O	0.003	g/kg	
Glyphosate production				
	CH_4	25.62	g/kg	Eco-invent (2010)
	N_2O	0.227	g/kg	
Electricity generation				
	CH_4	4.126	g/kWh	Eco-invent (2010)
	N_2O	0.014	g/kWh	
Biomass combustion				
	CH_4	0.030	g/MJ	IPCC (2006c)
	N_2O	0.004	g/MJ	
Gasoline production				
	CH_4	0.810	g/kg	Lewis (1997)
Diesel production				
	CH_4	0.055	g/kg	Lewis (1997)
Heavy oil production				
	CH4	0.631	g/kg	Lewis (1997)
Diesel use for:				
Soil preparation (Tractor)	CH_4	0.055	g/kg fuel	EMEP/EEA (2010)
	N_2O	0.136	g/kg fuel	
Weed cutting (Lawn mower)	CH_4	2.200	g/kg fuel	EMEP/EEA (2010)
(Gasoline : two-stroke)	N_2O	0.017	g/kg fuel	
Light-duty Truck	CH_4	0.012	g/km	IPCC (2006d)
<3.5 ton	N_2O	0.004	g/km	
Heavy-duty Truck	CH_4	0.080	g/km	IPCC (2006d)
20-26 ton	N_2O	0.029	g/km	

Activity (A)	Pollutant	Emission factors (EF)	Unit	Reference
Ship using bunker oil (international navigation)	CH_4 N_2O	0.281 0.080	g/kg fuel g/kg fuel	IPCC (2006d)
Stream production (boiler)	CH_4 N_2O	0.003 0.0006	g/MJ g/MJ	IPCC (2006c)
Chemical use: Kaolin production	CH_4 N_2O	0.391 0.004	g/kg g/kg	Eco-invent (2010)
Alum production	CH_4 N_2O	0.720 0.012	g/kg g/kg	Eco-invent (2010)
Sodium sulfite production	CH_4 N_2O	2.303 0.034	g/kg g/kg	Eco-invent (2010)
Phosphate compound production	CH_4 N_2O	4.018 0.019	g/kg g/kg	Eco-invent (2010)
Wastewater treatment: Anaerobic	CH_4	200.0	g /kg COD	IPCC (2006e)
EFB disposal: Open dump	CH_4	57.33	g /kg EFB	IPCC (2006f)

Table D2 Disaggregated emissions from oil palm plantation (unit: g pollutant/ton FFB)

Activity			N-RSPO		P-RSPO		C-RSPO	
			CH_4	N_20	CH_4	N_20	CH_4	N_20
Soil preparation	Diesel	- production	0.01	-	0.01	-	0.01	-
		- transportation	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
		- combustion	0.01	0.02	0.01	0.02	0.01	0.02
Fertiliser management	Mineral - N	- production	31	0.16	34	0.17	28	0.14
		- transportation	0.01	<0.01	0.02	0.01	0.01	<0.01
		- use (direct emission)	-	61	-	68	-	55
		- use (indirect emission)	-	19.92	-	22.04	-	18
	Mineral - P	- production	7	0.07	5	0.05	3	0.03
		- transportation	0.01	<0.01	0.01	0.00	0.00	0.00
		- use	-	-	-	-	-	-
	Mineral - K	- production	18	0.38	14	0.31	23	0.50
		- transportation	0.04	0.01	0.03	0.01	0.05	0.02
	Boron	- production	-	-	0.03	<0.01	0.01	<0.01
		- transportation	-	-	<0.01	<0.01	<0.01	<0.01
Weed control	Glyphosate	- production	3	0.02	0.48	<0.01	0.03	<0.01
		- transportation	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
		- use	-	-	-	-	-	-
Weed cutting	Gasoline	- production	0.42	-	0.19	-	0.04	-
		- transportation	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
		- use	1.14	0.01	0.53	<0.01	0.12	<0.01
FFB Transportation	Diesel	- production	0.47	-	0.02	-	0.01	-
		- transportation	0.03	0.01	<0.01	<0.01	<0.01	<0.01
		- combustion	0.20	0.07	0.06	0.02	0.04	0.01

- *not applicable*

Table D3 Disaggregated emissions from palm oil mill (unit: g pollutant/ton CPO)

Activity			N-RSPO		P-RSPO		C-RSPO	
			CH_4	N_20	CH_4	N_20	CH_4	N_20
Palm oil extraction	Diesel	- production	0.11	-	0.14	-	0.09	-
		- transportation	0.01	<0.01	0.01	<0.01	0.01	<0.01
		- combustion	0.11	0.28	0.14	0.34	0.09	0.21
	Electricity	- production	12	0.04	9.32	0.03	9	0.03
	Fibre	- combustion	175	23	255	34	133	18
	Kaolin	- production	4	0.04	4.56	0.05	3.32	0.04
		- transportation	0.03	0.01	0.04	0.01	0.03	0.01
Water treatment	Alum	- production	0.05	<0.01	0.14	<0.01	0.41	0.01
		- transportation	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Sodium sulphite	- production	0.14	<0.01	0.08	<0.01	0.20	<0.01
		- transportation	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Sodium carbonate	- production	0.26	<0.01	0.27	<0.01	0.11	<0.01
		- transportation	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Wastewater treatment	POME	- Anaerobic process	56,474	-	7,672	-	2,342	-
Waste Generation	Empty fruit bunch	- open dumping	53,794	-	60,742	-	-	-

- *not applicable*

Appendix E

Additional information
for Chapter 6

Appendix E1 - Description of our model

Landscape model

The landscape model was recently published (Saswattecha et al., 2016) and can be used to analyse potential land-use-change (LUC) caused by oil palm expansion in 2050 and its effects on selected ecosystem services. Three ecosystem services are considered in the model: food and non-food provisioning, biodiversity conservation and carbon storage (Figure 6.1).

The land-use-management (LUM) for expanding oil palm plantations in Thailand for 2050 in a series of scenarios determine the potential LUC and its effects on selected ecosystem services. Assumptions for LUM employed in different future scenarios were developed based on (1) our previous result on direct LUC caused by oil palm expansion (Table B1 in Appendix B) (Saswattecha et al., 2016), (2) a study on land suitability for oil palm by the Land Development Department (LDD) (Table B2 in Appendix B) (Anuraktiphan, 2010), (3) a water stress index for fuel crops production (Gheewala et al., 2014) and (4) provincial land-use data developed by LDD (LDD, 2016a, 2016b, 2016c, 2016d, 2016e). A detailed description and assumption for LUM made specifically for each scenario are summarized in Table 6.2.

In our earlier study, we analysed both direct and indirect LUC effects of oil palm expansion in the Tapi river basin in Thailand. Although our previous analysis was only for the basin we considered that our previous result can represent Thailand as a whole because of the following reasons:

(1) palm oil production from the Tapi river basin is accounts for 60% of total palm oil production in Thailand (DIT, 2012a, 2012b, 2011);
(2) Office of Agricultural Economics launched the oil palm zoning by focusing to expand the oil palm planted areas in the South of Thailand; including Suratthani, Krabi, Chumporn and Nakhon-si-thammarat (MOAC, 2013), and the Tapi river basin covers three of these provinces; and
(3) Land-use in these four provinces is similar, dominating by oil palm and rubber plantations (LDD, 2016c).

In this current study, we aim to analyse LUC effects for Thailand as a whole. Quantifying indirect LUC is associated with uncertainties (Wicke et al., 2012). Furthermore, upscaling from the Tapi basin to the national level may lead to even more uncertainties. Therefore, we focus mainly on direct LUC effects of oil palm expansion and consider the indirect LUC effects only in the discussion (section 5.2).

We used three indicators for ecosystem services. First, crop production (in tons) is used as an indicator for the food and non-food provisioning service. In this study, we consider four crops, including fresh-fruit-bunch (FFB) from oil palm plantations, latex from rubber plantations, rice from rice fields and fruits from orchard plantations. The FFB yields differ among scenarios, depending on the scenario assumptions (Table 6.1). Based on the information from the Office of Agricultural Economics (OAE, 2012a, 2012b), the productivity of other crops is relatively stable in the past decade. We therefore assume for other crops that their yields remain at present levels in the future.

Second, for biodiversity conservation, we used mean species abundance (MSA) as an indicator. MSA is defined as the mean abundance of original species relative to their abundance in undisturbed ecosystems (Alkemade et al., 2013, 2009). In the GLOBIO 3 model, LUC is considered as an important driver to disturb the mean abundance of original species in natural ecosystems. We therefore derived mean species abundance that is specific for each type of land-use (MSA_{LU}) from the GLOBIO 3 (Alkemade et al., 2013, 2009). In this study, the MSA_{LU} for natural forests without disturbance from LUC is set equal to 1. A wide range of grassland and scrubland exists in Thailand, but most of these are managed grasslands, including converted forests. Following a conservative approach, an MSA_{LU} of 0.1 is assigned to grassland and scrubland. We also assigned an MSA_{LU} of 0.1 to cropland, as these are highly managed as well. The corresponding MSA_{LU} values of each land-use unit defined in this study are presented in Appendix B (Table B3).

Third, carbon stocks (in ton C) are used to define the carbon storage service. The carbon stock specific for each type of land-use is estimated based on the stock difference method described in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Volume 4 on Agriculture, Forestry and Other Land use (IPCC, 2006a). We derived the carbon stocks of different land-use units from our previous study (Saswattecha et al., 2016a); we used Araya et al. (Araya et al., 2015) for carbon stocks of bare land.

Sectoral model

To quantify the environmental pollution caused by palm oil production in our study, we developed a sectoral model to account for emissions from plantations and mills and developed it based on the environmental system analysis approach. It aims to assess the effects of options for reducing environmental impacts of palm oil production (Saswattecha et al., 2016b). Six environmental impact categories are taken into account in the sectoral model; global warming, acidification, eutrophication, photochemical ozone formation, human toxicity and freshwater toxicity (Figure 6.1). Our model also includes possible side-effects of mitigation options on other emissions, which can be both positive (decreasing emissions) and negative (increasing emissions). 26 mitigation options, categorised into eight independent groups of options, are analysed in the model (Table 6.3 for a list of mitigation options). We evaluated the effects of combinations for these options on yields, inputs (e.g. fertiliser use and energy) and emissions. A multiplicative approach is used when more than one mitigation options are assumed to be applied (Pluimers, 2001). The combined effect of multiple options is thus calculated as the product of their respective reduction and increase factors. Different combinations of mitigation options are therefore selected in the future scenarios, reflecting different environmental management strategies (Table 6.3). In section 6.3, we describe our scenario assumptions in more detail.

Appendix E2 - Description of the base year (2012) and four future scenarios

Base year (2012)

We analysed the base year (2012) to quantify the environmental impacts of current environmental management of palm oil production in Thailand. We use 2012 as a basis for comparison with the BAU 2050 scenario. Our previous study indicates that during 2009-2012, the annual expansion rates of the oil palm area was around 2%. Almost two-thirds of the new oil palm areas were established on cropland. In particular, rubber plantations were replaced by oil palm plantations (Table B1 in Appendix B). However, there was also some conversion of natural ecosystems (Saswattecha et al., 2016). Later in 2013, land-use zoning for oil palm plantations was developed by MOAC (MOAC, 2013). Thus oil palm expansion from 2009-2012 took place without considering land-use and land management. By 2012, the total oil palm planted area was 0.70 million ha, producing around 19 ton FFB/ha, while the oil extraction rate was 17% (OAE, 2016a).

For simplicity, we assumed that in 2012 none of mitigation options were yet applied in the plantations. Currently, more than 80% of oil palm plantations in Thailand are smallholders' plantations (Dallinger, 2011; Rewtarkulpaiboon, 2015). The majority of these plantations do not follow best or good management practices due to lack of knowledge and budget (Saswattecha et al., 2015b). Farmers randomly apply fertilisers and glyphosate is commonly used together with weed cutting machine among farmers for weed control. Fresh-fruit-bunches (FFB) are commonly harvested around week 18 when the fruits are ripe and delivered to the palm oil mills (AgriSource, 2005). In 2012, some mitigation options had already been implemented in some of the plantations, but not to a large extent. For example, some plantations applied optimum doses of fertilisers, mulched empty fruit bunches (EFB) and harvested only ripe fruits. This happened in particular in plantations that are owned by mills.

In palm oil mills, the main environmental concerns are associated with POME generation, solid waste generation and air emissions from boilers. Two environmental regulations are important for the Thai palm oil industry: (1) the 1992 National Environmental Quality Promotion and Preservation Act, and (2) the 1992 Factory Act. To comply with these acts, POME is typically treated by anaerobic open lagoons to mainly remove COD. As a side effect, large amounts of methane (CH_4) are emitted from the open lagoons. As a result of the policy to promote the use of renewable energy from biogas (DEDE, 2012a), about 60% of palm oil mills in Thailand currently apply biogas capture technologies to convert CH_4 to electricity(Saswattecha et al., 2016b). However, the capacity of transmission lines to connect to the grid are not sufficient (Dallinger et al., 2013). This slowed down the implementation of biogas capture systems in mills.

Solid waste generated in mills such as nutrient-rich decanter cakes can be used in other industries to produce animal feed. Fibres and shells contain heating value, therefore fibres are internally used in boilers while shells are used in other factories as biomass fuel. Empty fruit bunches EFB is currently used for mulching in the plantations (30% of EFB generated in Thailand), combustion (20%), and mushroom cultivation (10%) (DEDE, 2012b; Papong et al., 2004; Saswattecha et al., 2016b). However, only about 40% of EFB is left untreated (DEDE, 2012b). Mills are also sources of air pollution and PM emissions from the boilers typically exceed the standards (Chavalparit, 2006; PCD, 2016; Rashid et al., 1998). Today, some mills use the boilers that are equipped with cyclones to remove PM emissions but this is not happening to a large extent.

From the above it is clear that some mitigation options have already been implemented in mills. We therefore assume that biogas capture systems are applied in 60% of the palm oil mills in Thailand for 2012.palm oil For EFB disposal, we also assume that 40% of EFB is left abandoned whereas 30% of EFB is mulched in the plantations, 20% of EFB is used for combustion, and 10% for mushroom cultivation (Table 6.3).

Business as Usual scenario (BAU)

The BAU scenario assumes that environmental management of palm oil production in Thailand remains the same at the current practice up until 2050. We assume that expansion of oil palm plantations happens without consideration for LUM or land suitability. In addition, no new environmental policies and plans are assumed to be implemented. Oil palm plantations would continue to expand by 2% per year until 2050. We thus assume that the MOAC plan for LUM of oil palm expansion is not implemented because of a lack of law enforcement. Potential LUC effects caused by the expansion of oil palm plantations in this scenario are assumed to be similar as in 2012 (i.e. 60% is replacing cropland, 20% grassland and scrubland, 10% abandoned rice fields, 5% forests and 5% other agricultural land). All new oil palm areas in BAU 2050 are small-scale plantations. No new large-scale plantations by companies are developed due to land limitations. The environmental management practices in the plantations and mills as described for 2012 are also assumed to be implemented in BAU 2050. This scenario assumes that there is no continuation of policies to support renewable energy from biogas and biomass. The number of mills implementing biogas capture systems (60% of the mills in Thailand) and EFB-combustion (20% of EFB generated in Thailand) will remain unchanged until 2050. This also applies for mulching of EFB because no new large-scale plantations will be developed in the BAU 2050 scenario (Table 6.3).

Current Policy scenario (CP)

The CP scenario is meant to show implications of the current plans of the Ministry of Agriculture and Cooperatives (MOAC) plan, assuming that the targets to promote biodiesel production would continue to increase until 2050, while no new regulations and policies are employed. This scenario reflects the most likely future environmental impacts of the Thai palm oil industry. MOAC set the targets to increase the area of oil palm plantations up to 1.2 million ha, increase FFB yields up to 22 ton/ha and increase oil extraction rate up to 20% in 2026 (OAE, 2014). Based on this, we assume that the oil palm plantation will increase up to 2.1 million ha, the FFB yields will increase up to 27 ton/ha and oil extraction rate will increase up to 24% by the year 2050. We assume that LUM for expanding oil palm areas would follow the land-use zoning developed by MOAC (MOAC, 2013). The main focus of this zoning is to replace other cropland in the South to oil palm plantations, where suitable land for oil palm cultivation is currently used for rubber plantations and rice fields (FAO, 2010). We also assume that the land suitability for oil palm cultivation is considered in the LUM. Thus, only cropland that is classified as moderately to highly suitable for oil palm cultivation is the main focus for oil palm expansion (Table B2 in Appendix B). We assume that in the CP 2050 scenario all natural forests are closely monitored and well protected. The environmental management practices in the plantations and the mills will follow the same practices as employed in the BAU 2050 scenario (Table 6.3). This is because our assumption that no new policies are implemented in this scenario.

Strong Growth scenario (GRT)

The demand for sustainable palm oil production from European countries has been increasing rapidly (MFA, 2015). So far, almost 32,000 metric tonnes of palm oil in Thailand have been certified according to the Roundtable of Sustainable Palm Oil (RSPO) standard (RSPO, 2015). This indicates that there is an opportunity for Thailand to export palm oil to European countries if there are appropriate policies and plans in place. We therefore developed this GRT scenario assuming that the Thai government aims to export palm oil. Based on the MOAC strategic plans, we assume that the oil palm plantations will continue to expand up to 3.4 million ha, FFB yields increase up to 35 ton/ha and oil extraction rate improve up to 24% in the GRT 2050 scenario. We also assume that the MOAC oil palm zoning for 2013 will continue to be effective until 2050. On the top of this zoning, the demand for sustainable palm oil production from the international market is affecting LUM. The RSPO standard requires a new planting to avoid using land that contains high carbon stocks (i.e. forests and peatland). Therefore, the LUM in the GRT scenario assumes (1) replacing cropland that are suitable for oil palm cultivation (Table B2 in Appendix B), and (2) protecting all natural forests are assumed in the GRT scenario (Table 6.2).

Moreover, the RSPO standard requires the practitioners to account, manage and mitigate greenhouse gas emissions during palm oil production. On the other hand, other pollutants (i.e. SO_2, NOx, PM and VOC) are not accounted for. This affects environmental management in the plantations and mills. Since RSPO is a voluntary scheme, implementation of mitigation options in the GRT scenario is mainly driven by the costs of implementation rather than its effectiveness. Therefore, we assume that only the most paying options that are effective (or cost effective) are implemented in the GRT scenario. Currently, about 80% of palm oil in Thailand is produced in large-scale and medium-scale palm oil mills (DIT, 2016). In the GRT scenario, we assume furthermore that all large-scale and medium scale palm oil mills in Thailand employ biogas capture systems in 2050 as a result of following the RSPO standard (Table 6.3).

Note that approximately 20% of palm oil mills in Thailand are small-scale mills that have no or little interest in the RSPO standard (DIT, 2016).

Green Development scenario (GRT)

The Green Development scenario assumes implementation of improved environmental management practices consistent with sustainable (or green) palm oil production. This scenario aims to increase FFB yields up to 35 ton/ha and improve oil extract rate up to 24% by the end of 2050. Our earlier study shows that oil palm expansion in other cropland, in particular rubber plantations, would lead to a clearance of natural forests as an indirect LUC effect of oil palm expansion (Saswattecha et al., 2016). We therefore assume that in this scenario LUM for expanding oil palm area would focus on non-cropland (i.e. grassland and scrubland and abandoned-land) to avoid indirect deforestation. In this regard, only non-cropland in the provinces that we classified as suitable for oil palm cultivation are selected (Table B3 in Appendix B). We identified provinces that are suitable for oil palm by overlaying land suitability for oil palm plantations from Anuraktiphan (Anuraktiphan, 2010) with the water stress index studied by Gheewala et al. (Gheewala et al., 2014). Note that conversion of other cropland to oil palm plantations still exists but at limited area. Only areas classified as highly suitable for oil palm are converted (Table B2 in Appendix B) in order to maximise the FFB yields. In the end, it will result in expanding oil palm areas up to 1.67 million ha in 2050.

To improve the current environmental management practices, we assume that Thai environmental regulations will become more stringent and law enforcement will become more effective by 2050. Therefore, the most effective options in each option groups are assumed to be implemented in the GRN scenario.

Table E2.1 Land-use-change effects of oil palm expansion (% of new oil palm area) in the Business as Usual (BAU) scenario, adopted from our previous study (Saswattecha et al., 2016a)

Land-use	Land-use-change effect	
	Previous study (2009-2012)	This study
Cropland		
- Rubber	28%	30%
- Rice	11%	10%
- Orchard	17%	20%
Natural ecosystems		
- Forest	5%	5%
- Mangrove	0.4%	n.a.
- Wetlands and peat lands	0.2%	n.a.
- Unused land (i.e. grassland and scrubland)	17%	20%
Abandoned land		
- Abandon ricefield	13%	10%
Other		
- Water	9%	n.a.
- Built-up area		
- Others agriculture		

n.a. – Not applicable. We ignored this land-use type in this study because it is insignificant for oil palm expansion.

Table E2.2 Cropland that are highly and moderately suitable for oil palm development, adopted from the Land Development Department (Anuraktiphan, 2010).

Suitability class	Land-use type	Potential Area (ha)	
		Irrigation zone	Rainfall zone
High suitability	rubber	6,040[a]	40,629[a]
	Rice	5,582*	128,035[a]
	Orchard	1,324[a]	-
	Total	**12,946**	**168,664**
Moderate suitability	rubber	98,438[a]	1,362,343[b]
	Rice	372,190*	2,051,504[b]
	Maize	-	606,734[b]
	Total	**575,911**	**4,020,581**

* *Apart from rice fields in the irrigation zone, we assume that cropland in the high and moderate suitability classes will be converted to oil palm plantations in the Current Policy, Strong Growth and Green Development scenarios.*

[a] *Our LUC analysis assumes that this land-use unit will be totally converted to oil palm plantations in the Current Policy, Strong Growth and Green Development scenarios.*

[b] *To meet the set targets of oil palm expansion in the Current Policy, Strong Growth and Green Development scenarios, our LUC analysis assumes that some areas of this land-use unit will be converted oil palm plantations. An estimated 65% of missing areas are from rubber, 25% of missing area are from rice and 10% of missing areas are from maize.*

Table E 2.3 Available areas of non-cropland in selected provinces that contain areas of high, moderate and low suitability classes for oil palm. These provinces are selected based on land suitability (Anuraktiphan, 2010) and water stress index (Gheewala et al., 2014).

Province	Area of non-cropland (ha)			
	Grassland	Scrubland	Abandoned mining pits and bare land	Abandon rice
NORTH				
Chiang Mai	5,804	18,349	1,630	2,891
Chiang Rai	6,993	13,084	749	216
Lamphun	2,032	10,689	1,443	2,856
Lampang	1,909	9,737	538	1,248
Uttaradit	215	6,939	60	58
Phitsanulok	2,912	28,532	574	2,126
Tak	1,233	10,889	568	60
Kamphaeng Pheth	433	4,952	1,471	244
Nakhon Sawan	1,640	18,504	1,538	982
Phetchabun	4,395	27,880	84	214
Uthai Thani	831	6,047	167	396
SUM	28,397	155,601	8,824	11,294
CENTRAL				
Saraburi	3,206	11,313	568	3,846
Nakhon Nayok	6,511	3,561	267	1,720
Phetchaburi	4,453	27,449	1,000	1,388
SUM	14,171	42,323	1,834	6,954
EAST				
Prachinburi	14,650	14,203	909	2,052
Chachengsao	1,814	9,300	2,178	2,962
Trat	2,370	12,993	365	4,467
SUM	18,834	36,496	3,452	9,481
NORTHEAST				
Loei	6,529	15,301	283	128
Nong Kai	2,064	9,213	55	503
Udon Thaini	11,786	35,832	3,231	14,532
Nakhon Phanom	2,226	22,941	278	950
Ubon Ratchathani	11,943	71,749	548	11,254
SUM	34,548	155,036	4,396	27,367
SOUTH				
Chumphon	3,244	13,595	286	2,020
Surat Thani	2,342	15,535	398	9,496
Ranong	2,089	2,103	544	263
Phang Nga	633	5,569	1,676	907
Phuket	820	736	1,864	434
Krabi	822	3,871	12	1,823
Nakhon Si Thammarat	23,152	16,381	772	15,273
Trang	1,105	4,226	152	3,749
Pattalung	1,018	2,368	75	3,140
Satun	-	977	4	789
Songkla	3,345	19,898	720	17,827
Pattani	194	2,956	13	6,881
Yala	1,733	10,076	1,314	1,605
Narathiwat	4,814	16,371	308	3,094
SUM	45,311	114,660	8,138	67,301

Appendix E 3 Potential land-use-change and its effects on carbon storage, biodiversity conservation and food and non-food provisioning services.

Table E 3.1 Potential land-use-change effects in different scenarios.

Land-use that converted to oil palm plantations	Area (ha)				
	2012*	BAU 2050	CP 2050	GRT 2050	GRN 2050
Cropland					
- Existing oil palm	620,000	701,760	701,760	701,760	701,760
- Rubber plantations	25,200	240,317	692,641	1,574,784	46,669
- Rice fields	8,400	80,106	338,625	677,911	128,035
- Orchard plantations	16,800	160,211	1,324	1,324	1,324
- Maize fields	-	20,026	84,236	219,950	-
- Cassava fields	-	20,026	-	-	-
Natural ecosystems					
- Forest	4,200	40,053	-	-	-
- Grassland and scrubland	16,800	160,211	160,211	160,211	645,377
Abandoned land					
- Abandoned rice fields	8,400	80,106	80,106	80,106	122,396
- Abandoned mining pits and bare land	-	-	-	-	26,644

** LUC in this scenario is caused by oil palm expansion during 2009-2012 in the Tapi river basin in Thailand and was derived from our previous study (Saswattecha et al., 2016a). See Table B1 for more details.*

Table E 3.2 Potential effects of land-use-change caused by oil palm expansion on carbon storage services in different future scenarios. The carbon stocks specific for each type of cropland are derived from Saswattecha et al. (Saswattecha et al., 2016a)

Land-use	Scenarios				
	2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Cropland					
Rubber	-2,505,472	-23,893,134	-68,864,792	-156,570,532	-4,639,995
Rice	500,324	4,771,281	20,169,318	40,377,991	7,626,072
Orchard	694,932	6,627,135	54,767	54,767	54,767
Maize[a]	-	1,192,820	5,017,298	13,100,768	-
Cassava[a]	-	1,192,820	-	-	-
Natural ecosystems					
Forest	-783,206	-7,468,949	-	-	-
Grassland and scrubland	694,932	2,876,175	2,876,175	2,876,175	11,586,065
Abandoned land					
Abandoned rice	500,324	1,438,088	1,438,088	1,438,088	2,197,311
Abandoned mining pits & bare land[b]	-	-	-	-	3,043,396

[a] Carbon stocks of this cropland is assumed to be as same as the carbon stocks of rice fields.
[b] Only carbon stocks (41.2 ton C/ha) in soil is considered in our analysis (Araya et al., 2015).

Table E 3.3 Potential effects of oil palm expansion on biodiversity conservation services in different future scenarios. Corresponding mean species abundance for each type of land-use is presented in Table C4.

Land-use	Relative change of mean species abundance due to land-use-change				
	2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Cropland					
Rubber	-	-	-	-	-
Rice	-	-	-	-	-
Orchard	-	-	-	-	-
Maize	-	-	-	-	-
Cassava	-	-	-	-	-
Natural ecosystems					
Forest	-945	-36,048	-	-	-
Unused land	-	-	-	-	-
Abandon land					
Abandon rice	420	4,005	4,005	4,005	6,120
Abandon minning pits & bare land	-	-	-	-	1,332

Note '-' indicates no change in biodiversity conservation service while 'negative values' indicates the biodiversity loss.

Table E 3.4 Corresponding land-use in GLOBIO 3 and its MSA_{LU} (Alkemade et al., 2009).

Land-use in this study	Land-use in GLOBIO 3	MSA_{LU}
Cropland		
Rubber	Intensive agriculture/High external input agriculture or conventional agriculture	0.1
Rice	Intensive agriculture/High external input agriculture or conventional agriculture	0.1
Orchard	Intensive agriculture/High external input agriculture or conventional agriculture	0.1
Maize	Intensive agriculture/High external input agriculture or conventional agriculture	0.1
Cassava	Intensive agriculture/High external input agriculture or conventional agriculture	0.1
Natural ecosystems		
Forest	Primary vegetation/Minimal disturbance, where flora and fauna species abundance are near pristine	1
Grassland and scrubland	Man-made pastures/Forests and woodlands that have been converted to grasslands	0.1
Abandoned land		
Abandon rice	Built-up areas/Areas more than 80% built up	0.05
Abandon mining pits and bare land	Built-up areas/Areas more than 80% built up	0.05

Table E 3.5 Potential effect of land-use-change caused by oil palm expansion on food and non-food provisioning service.

Scenarios	Relative change of crop production due to expanding oil palm area (million ton)						
	FFB	**CPO**	**Rice**	**Maize**	**Cassava**	**Fruits**	**Latex**
2012	1.33	2.43	-0.03	-	-	-0.10	-0.04
BAU 2050	14.28	2.43	-0.24	-0.08	-0.43	-0.99	-0.39
CP 2050	40.00	11.25	-1.02	-0.35	-	-0.01	-1.14
GRT 2050	69.19	19.59	-0.61	-	-	-0.01	-2.48
GRN 2050	30.91	10.26	-0.39	-	-	-0.01	-0.24

Note '-' indicates no change while 'negative values' indicates the loss in crop production

Appendix E 4 Aggregated emissions of crude palm oil production in the four scenarios

Table E4 Aggregated emissions of crude palm oil production

a) Global warming (unit 10^3 ton CO_2eq/year)

Sub-system	Activity		2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Oil palm plantations	Soil preparation	Diesel	0.69	1	4	5.07	2.52
	Fertiliser management	N fertiliser	363	778	2,252	2,800	1,391
		P fertiliser	45	97	281	350	174
		K fertiliser	54	115	334	415	186
	Weed Control	Glyphosate	11	23	67	83	21
		Gasoline	22	46	134	146	36
	FFB transportation	Diesel	27	58	169	303	140
Palm oil mills	Palm oil extraction	Diesel	2	4	11	23	11
		Electricity	5	10	28	56	27
		Fibre	26	55	159	166	80
		Kaolin	5	11	31	62	30
	Water treatment	Alum	0.08	0.17	0.50	1	0.48
		Sodium sulphite	0.19	0.41	1	2	1
		Sodium carbonate	0.16	0.35	1	2	0.98
	Wastewater treatment	POME	960	2,056	5,951	15,947	9,563
	Waste disposal	EFB	1,178	2,523	7,303	12,112	-17,665
		SUM	**2,698**	**5,779**	**16,727**	**32,472**	**6,001**

b) Acidification (unit ton SO_2eq/year)

Sub-system	Activity		2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Oil palm plantations	Soil preparation	Diesel	34	72	209	249	124
	Fertiliser management	N fertiliser	712	1,525	4,415	5,489	2,728
		P fertiliser	1,058	2,266	6,559	8,155	4,053
		K fertiliser	177	379	1,098	1,365	612
	Weed Control	Glyphosate	37	80	231	287	71
		Gasoline	40	86	250	271	67
	FFB transportation	Diesel	152	324	939	1,639	750
Palm oil mills	Palm oil extraction	Diesel	91	194	562	1,129	542
		Electricity	7	15	45	90	43
		Fibre	1,499	3,210	9,291	9,709	266
		Kaolin	20	42	121	244	117
	Water treatment	Alum	1	3	8	17	8
		Sodium sulphite	5	11	32	65	31
		Sodium carbonate	0.49	1	3	6	3
	Wastewater treatment	POME	n.a.	n.a.	n.a.	n.a.	n.a.
	Waste disposal	EFB	-644	-1,379	-3,991	32,130	-59,949
		SUM	**3,190**	**6,831**	**19,773**	**60,844**	**-50,535**

n.a. - Not applicable

c) Eutrophication (unit ton PO_4^{3-}eq/year)

Sub-system	Activity		2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Oil palm plantations	Soil preparation	Diesel	8	18	52	62	31
	Fertiliser management	N fertiliser	1,288	2,759	7,985	9,927	4,934
		P fertiliser	19	40	117	145	72
		K fertiliser	26	56	162	201	90
	Weed Control	Glyphosate	3	5	16	19	5
		Gasoline	4	9	25	27	7
	FFB transportation	Diesel	38	80	233	405	185
Palm oil mills	Palm oil extraction	Diesel	22	48	139	280	134
		Electricity	1	2	7	14	7
		Fibre	258	552	1,598	1,670	28
		Kaolin	2	5	14	28	13
	Water treatment	Alum	0.04	0.08	0.24	0.49	0.24
		Sodium sulphite	0.05	0.12	0.34	0.68	0.33
		Sodium carbonate	0.04	0.09	0.25	0.50	0.24
	Wastewater treatment	POME	2	3	10	19	9
	Waste disposal	EFB	2,980	6,382	18,474	85,466	-8,715
		SUM	**4,651**	**9,960**	**28,831**	**98,265**	**-3,199**

d) Photochemical ozone formation (unit ton C_2H_4eq/year)

Sub-system	Activity		2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Oil palm plantations	Soil preparation	Diesel	8	16	47	56	28
	Fertiliser management	N fertiliser	64	137	396	493	245
		P fertiliser	15	33	94	117	58
		K fertiliser	27	59	170	211	95
	Weed Control	Glyphosate	9	20	57	71	18
		Gasoline	704	1,507	4,363	4,742	1,178
	FFB transportation	Diesel	30	63	183	327	151
Palm oil mills	Palm oil extraction	Diesel	21	44	127	256	123
		Electricity	0	1	3	5	2
		Fibre	1,432	3,068	8,880	9,279	224
		Kaolin	2	3	10	20	9
	Water treatment	Alum	0.03	0.06	0.16	0.33	0.16
		Sodium sulphite	0.04	0.10	0.28	0.56	0.27
		Sodium carbonate	0.22	0.47	1.37	2.75	1.32
	Wastewater treatment	POME	279	597	1,727	4,428	2,584
	Waste disposal	EFB	1,086	2,326	6,733	2,270	23,343
		SUM	**3,677**	**7,874**	**22,793**	**22,279**	**28,059**

e) Human toxicity (unit ton $C_6H_4Cl_2$eq/year)

Sub-system	Activity		2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Oil palm plantations	Soil preparation	Diesel	84	179	518	616	306
	Fertiliser management	N fertiliser	1,466	3,139	9,085	11,295	5,613
		P fertiliser	391	838	2,426	3,016	1,499
		K fertiliser	283	606	1,753	2,180	978
	Weed Control	Glyphosate	38	81	234	291	72
		Gasoline	58	123	357	389	97
	FFB transportation	Diesel	382	818	2,368	4,147	1,900
Palm oil mills	Palm oil extraction	Diesel	224	481	1,391	2,796	1,342
		Electricity	11	23	67	134	64
		Fibre	4,123	8,829	25,558	26,708	275
		Kaolin	24	52	151	304	146
	Water treatment	Alum	0.67	1	4	8	4
		Sodium sulphite	1	2	7	14	7
		Sodium carbonate	0.50	1	3	6	3
	Wastewater treatment	POME	n.a.	n.a.	n.a.	n.a.	n.a.
	Waste disposal	EFB	1,606	3,440	9,957	77,112	-42,642
		SUM	**8,692**	**18,614**	**53,880**	**129,017**	**-30,337**

n.a. - Not applicable

f) Freshwater ecotoxicity (unit kg $C_6H_4Cl_2$eq/year)

Sub-system	Activity		2012	BAU 2050	CP 2050	GRT 2050	GRN 2050
Oil palm plantations	Soil preparation	Diesel	n.a.	n.a.	n.a.	n.a.	n.a.
	Fertiliser management	N fertiliser	n.a.	n.a.	n.a.	n.a.	n.a.
		P fertiliser	n.a.	n.a.	n.a.	n.a.	n.a.
		K fertiliser	n.a.	n.a.	n.a.	n.a.	n.a.
	Weed Control	Glyphosate	954	2,043	5,914	7,353	1,827
		Gasoline	n.a.	n.a.	n.a.	n.a.	n.a.
	FFB transportation	Diesel	n.a.	n.a.	n.a.	n.a.	n.a.
Palm oil mills	Palm oil extraction	Diesel	n.a.	n.a.	n.a.	n.a.	n.a.
		Electricity	n.a.	n.a.	n.a.	n.a.	n.a.
		Fibre	n.a.	n.a.	n.a.	n.a.	n.a.
		Kaolin	n.a.	n.a.	n.a.	n.a.	n.a.
	Water treatment	Alum	n.a.	n.a.	n.a.	n.a.	n.a.
		Sodium sulphite	n.a.	n.a.	n.a.	n.a.	n.a.
		Sodium carbonate	n.a.	n.a.	fn.a.	n.a.	n.a.
	Wastewater treatment	POME	n.a.	n.a.	n.a.	n.a.	n.a.
	Waste disposal	EFB	n.a.	n.a.	n.a.	n.a.	n.a.
		SUM	**954**	**2,043**	**5,914**	**7,353**	**1,827**

n.a. - Not applicable

Summary

SUMMARY

Global demand for palm oil has increased as it is essential for numerous products including feedstocks for food, fuel and also pharmaceutical industries. This also holds for Thailand which is the world's third largest palm oil producing country. To meet this increased demand, more land to accommodate increasing oil palm cultivation is needed. However, there is insufficient consideration of the effects of this expansion on ecosystem services, as well as maintaining remaining ecosystems in existing land use planning. Therefore, expanding oil palm area poses a risk through forest clearance, meaning that, as a result, many ecosystem services provided by forests are in decline. Moreover, the increased demand for palm oil is also multiplying the level of environmental pollution of the oil palm plantations and palm oil mills.

Clearly, increased palm oil production causes several environment problems. Most existing studies on environmental impact assessments of palm oil production in Thailand pay attention to the impact of global warming alone, while other environmental problems (i.e. loss of ecosystem services, acidification, eutrophication, smog formation, human toxicity and freshwater ecotoxicity) are overlooked. Several options to reduce the environmental impacts ave been studied and proposed to the palm oil industry. However, none of the existing studies have investigated the cost-effectiveness of these options. Such information is crucial for decision makers (i.e. policy makers and palm oil entrepreneurs) to explore possibilities for improving environmental performance towards sustainable palm oil production in Thailand.

The objectives of this thesis are to analyse environmental impacts of the oil palm sector in the past and future, and to explore the possibilities for improving the environmental sustainability of the palm oil sector in Thailand. These objectives have been met through an integrated environmental assessment coupling a landscape model and sectoral model. This can be seen as the novelty of this thesis.

Firstly, I analysed the effects of oil palm expansion on ecosystem services in the Tapi river basin, Thailand, between 2000 and 2012 (Chapter 2). The effects on ecosystem services depend very much on what type of land use has been changed to oil palm plantations. To understand historical patterns of land use change caused by oil palm expansion, I developed a landscape model to spatially analyse direct and indirect land use change caused by oil palm expansion in the Tapi river basin for the period 2000-2012. I learned that oil palm plantations have expanded to a large extent. Predominantly, this rapid plantation expansion was associated with the replacement of other cropland in the past decade, an issue seen specifically with rubber plantations. After 2009, natural forests were also cleared. Surprisingly, deforestation strongly increased as an indirect effect of oil palm expansion after 2009. This indicates that available arable land for oil palm expansion has become limited. Furthermore, I assessed the land use change effects on selected ecosystem services to better support decision makers when developing strategies to improve land use management. Three ecosystem services were investigated; including food and non-food provisioning services, biodiversity conservation and carbon storage. I learned that the oil palm expansion increased the production of fresh fruit bunches, but decreased the production of other crops (i.e. latex, rice and fruits) in the basin. This expansion also led to losses in biodiversity

because the forests, a natural habitat for many species, were cleared. The effects on carbon storage depend on the type of land use change. There is net carbon sequestration and storing when unused land, rice fields and orchards are replaced by oil palm plantations. But, there are net carbon emissions when oil palm plantations are replacing forested land and rubber plantations. I believe that the outcome of this analysis is useful support for decision makers when developing a definitive land use plan for new oil palm areas while minimising impacts on ecosystem services in the future.

Secondly, I evaluated the environmental impacts of palm oil production in the past. To do this, I developed a sectoral model to assess several environmental impacts of palm oil production in the Tapi river basin (Chapter 3). This analysis considered the operations in the plantations and the palm oil mills. A partial life cycle assessment was combined with environmental performance indicators in the model. I found that there are five activities contributing to multiple environmental impacts. They include (1) use of fertilisers, (2) weed control, (3) burning fibre in the boilers, (4) palm oil mill effluent (POME) treatment, and (5) empty fruit bunch (EFB) treatment. The use of fertilisers in the plantations is found to be a main contributor to global warming and eutrophication. Weed control in the plantations is found to be a main contributor to ozone formation and freshwater ecotoxicity. Burning fibres in boilers is found to be a main contributor to acidification, ozone formation and human toxicity. Treatment of POME and EFB is found to be the main contributor to global warming and ozone formation.

The Roundtable on Sustainable Palm Oil (RSPO) certification, an emerging environmental management tool, was considered in the analysis to better understand how these environmental impacts could be reduced. In this regard, I distinguished between different management practices of palm oil producers in relation to the RSPO certification scheme: non- RSPO, potential RSPO and RSPO certified producers. The analysis shows that the RSPO certified producers cause lower environmental impacts as they implement cleaner technologies; such as treating POME with biogas capture system, which goes beyond the RSPO requirements. Implementing a biogas capture system in the palm oil mills mainly resulted from the national renewable policy and plans. This indicates that RSPO certification alone is not enough to ensure sustainable palm oil production. Associated policy and plans to support the palm oil sector is, therefore, important.

Third, I analysed the cost-effectiveness of possible options for reducing environmental impacts. To do this, the sectoral model previously developed was expanded to evaluate the potentials to reduce the environmental impacts of the identified options as well as their associated costs (Chapter 4). In this regard, the cost-effective analysis tool was coupled with the sectoral model. This modified model includes the key sources of emissions that contribute to the environmental impacts identified earlier, and covers options for reducing the aforementioned impacts. The side effect of reduction options was also taken into account in the model. In total, 26 options in eight groups were identified and evaluated with respect to their effectiveness and cost-effectiveness in reducing environmental impacts. I found that EFB combustion for power generation, wet scrubbers and heating fibre prior to use in the boilers are the most effective in reducing a range of impacts. This is because these options are associated with reducing or avoiding acidifying, eutrophying and toxic compounds and photochemical ozone precursors. Amongst these options, EFB combustion leads to the largest reduction, but this comes at relatively high costs. Alternatively, some options provide a positive return (i.e. benefits exceed costs). These options are considered a paying option. From this analysis, I learnt that mulching EFB in the oil palm plantations, harvesting ripe fruits and maintaining specific species of cover crops in the plantations are found to be the most paying options. Moreover, I found that seven out of the 26 options are both paying options and effective in reducing environmental impacts. They are; maintaining specific species of cover crops, harvesting ripe fruits, mulching EFB, EFB composting, EFB pellet production, heating fibre prior use in the boilers and oil recovery from decanter cake. The outcome of this analysis may help decision makers in ranking reduction options that are in line with their preferred environmental strategies. For instance, if one focuses on reducing non-CO_2 greenhouse gas emissions (Chapter 5), the cost-effective ways to reduce these emissions are (1) mulching EFB to reduce need for nitrogen fertilisers, (2) installing biogas capture systems to reduce methane emissions from POME, and (3) EFB pellet production and EFB combustion for power generation to avoid methane emissions from landfilled EFB.

Lastly, I explored the possibilities to improve environmental sustainability of the Thai palm oil industry in the future (Chapter 6). In this regard, the landscape model and sectoral model previously built are combined through a scenario analysis. This analysis focuses on possibilities to reduce the effects of land use change on ecosystem services and environmental pollution of oil palm plantations and palm oil mills. Four scenarios for 2050 are developed to demonstrate potential reductions if the Thai government and palm oil producers improve their current plans and management practices; including Business as Usual (BAU), Current Policy (CP), Strong Growth (GRT) and Green Development (GRN). From the BAU scenario, I learnt that environmental impacts may double without additional improvement. Moreover, the current policy and plans to increase palm oil production without additional implementation of improvement options may considerably increase environmental impacts. This even leads to higher environmental impacts than in the BAU scenario by a factor of three. Additionally, implementing only the cost-effective options, as shown in the GRT scenario, is not enough to avoid an increase in environmental impacts, if the export of palm oil increases production faster than currently envisaged. To deal with the increased palm oil production, I found that the implementation of a combination of effective options, regardless of their costs (as assumed in the GRN scenario), would considerably reduce environmental impacts.

All in all, this thesis proved that performing the integrated environmental assessment through a combination of the landscape model and sectoral model is greatly rewarding. Such integrated assessment provides comprehensive information to support decision makers and enable them to better understand (1) how land use change affects ecosystem services, (2) what are the main contributors to environmental impacts, and, where environmental management should urgently improve, and (3) what technologies are the most cost-effective to reduce these impacts, depending on the user designated purpose. Currently, only a few technologies have been implemented to reduce environmental impacts, and these options are not the most effective choices. This clearly indicates that there are still opportunities for further improvement. Responsively, information on the various possibilities available to improve the environmental sustainability of the palm oil industry are provided in this thesis. Limiting oil palm expansion is imperative to avoid continued deforestation. Instead, improving FFB yields in existing oil palm plantations and increasing oil extraction rate in the existing mills are needed. Technically, it is possible to considerably reduce environmental impacts in the coming decades through the implementation of a combination of the most effective options; such as EFB combustion for power generation, wet scrubbers and heating fibre prior use in the boilers. However, the palm oil producers may prefer to make a choice for the paying and cost-effective options, such as mulching EFB, EFB composting, EFB pellet production, and oil recovery from decanter cake. The information from this thesis is therefore beneficial for decision makers when designing future environmental management strategies and general improvement within the palm oil industry and the country as whole

บทสรุป

น้ำมันปาล์มเป็นวัตถุดิบที่สำคัญในหลากหลายอุตสาหกรรม อาทิเช่น อุตสาหกรรมอาหาร อุตสาหกรรมเชื้อเพลิง อุตสาหกรรมยา ดังนั้น ความต้องการน้ำมันปาล์มทั่วโลกรวมถึงประเทศไทยซึ่งเป็นประเทศผู้ผลิตน้ำมันปาล์มรายใหญ่อันดับสามของโลก จึงเพิ่มสูงขึ้นอย่างรวดเร็ว การจัดสรรที่ดินเพื่อรองรับการเพิ่มขึ้นของการเพาะปลูกปาล์มน้ำมันนับเป็นสิ่งจำเป็นเพื่อตอบสนองความต้องการที่เพิ่มขึ้น ทว่าการวางแผนการใช้ที่ดินในปัจจุบัน ยังขาดการคำนึงถึงผลกระทบของการขยายพื้นที่ปลูกปาล์มน้ำมันต่อการบริการของระบบนิเวศและการรักษาระบบนิเวศที่ยังคงเหลืออยู่การขยายพื้นที่ปลูกปาล์มน้ำมันจึงเสี่ยงต่อการบุกรุกป่าไม้ และส่งผลเสียต่อการบริการของระบบนิเวศจากป่าไม้ต่าง ๆ นอกจากนี้ความต้องการน้ำมันปาล์มที่เพิ่มขึ้นยังส่งผลให้สวนปาล์มน้ำมันและโรงงานน้ำมันปาล์มปล่อยมลพิษสู่สิ่งแวดล้อมเพิ่มเป็นทวีคูณ

การเพิ่มขึ้นของการผลิตน้ำมันปาล์มส่งผลให้เกิดผลกระทบต่อสิ่งแวดล้อมอย่างเห็นได้ชัด ในปัจจุบันประเทศไทยมีหลายผลงานวิจัยที่ทำการศึกษาประเมินผลกระทบต่อสิ่งแวดล้อมของการผลิตน้ำมันปาล์ม แต่การศึกษาส่วนใหญ่จะให้ความสนใจกับปัญหาภาวะโลกร้อนเพียงอย่างเดียว ในขณะที่ปัญหาสิ่งแวดล้อมอื่น ๆ ถูกมองข้ามไป อาทิเช่น การสูญเสียการบริการของระบบนิเวศ ภาวะฝนกรด ปรากฏการณ์ยูโทรฟิเคชั่น การก่อตัวของโอโซน ความเป็นพิษต่อมนุษย์ และความเป็นพิษต่อระบบนิเวศน้ำจืด นอกจากนี้ ยังมีหลายงานวิจัยศึกษาถึงมาตรการในการลดผลกระทบต่อสิ่งแวดล้อมและนำเสนอให้แก่อุตสาหกรรมน้ำมันปาล์มหลากหลายตัวเลือก อย่างไรก็ตาม ในประเทศไทยยังไม่มีผลงานวิจัยใดทำการวิเคราะห์ต้นทุน-ประสิทธิผลของมาตรการต่าง ๆ เหล่านี้ ซึ่งข้อมูลดังกล่าวเป็นสิ่งสำคัญสำหรับผู้มีอำนาจตัดสินใจ เช่น ผู้กำหนดนโยบายและผู้ประกอบการ เพื่อวิเคราะห์ความเป็นไปในการพัฒนาการจัดการความยั่งยืนด้านสิ่งแวดล้อมของอุตสาหกรรมน้ำมันปาล์มไทย

ด้วยเหตุนี้ วิทยานิพนธ์ฉบับนี้มีวัตถุประสงค์เพื่อวิเคราะห์ผลกระทบต่อสิ่งแวดล้อมของอุตสาหกรรมน้ำมันปาล์มทั้งในอดีตและอนาคต และวิเคราะห์ความเป็นไปได้ในการพัฒนาการจัดการความยั่งยืนด้านสิ่งแวดล้อมของอุตสาหกรรมน้ำมันปาล์มไทย การศึกษาภายใต้วัตถุประสงค์เหล่านี้ได้ดำเนินการผ่านการประเมินด้านสิ่งแวดล้อมแบบบูรณาการ โดยผนวกแบบจำลองเชิงภูมิทัศน์ (landscape model) และแบบจำลองของภาคการผลิต (sectoral model) เข้าด้วยกัน แบบจำลองแบบบูรณาการนี้นับเป็นความคิดริเริ่มที่ท้าทายของวิทยานิพนธ์ฉบับนี้ที่ยังไม่ปรากฏในผลงานวิจัยอื่น ๆ

ประการแรก ผู้วิจัยได้วิเคราะห์ผลกระทบของการขยายพื้นที่ปลูกปาล์มน้ำมันต่อการบริการของระบบนิเวศในลุ่มน้ำตาปี ประเทศไทย ระหว่างปี 2543 และ 2555 (บทที่ 2) ผลกระทบต่อระบบนิเวศบริการขึ้นอยู่กับประเภทของการใช้ที่ดินที่ถูกเปลี่ยนมาใช้ปลูกสวนปาล์มน้ำมัน ผู้วิจัยได้พัฒนารูป

แบบจำลองเชิงภูมิทัศน์ขึ้นมาเพื่อให้เข้าใจถึงรูปแบบการเปลี่ยนแปลงการใช้ที่ดินจากการขยายตัวของสวนปาล์มน้ำมันในอดีตทั้งทางตรงและทางอ้อมในลุ่มน้ำตาปี ระหว่าง 2543 และ 2555 ผลการศึกษาพบว่าในช่วงทศวรรษที่ผ่านมามีการขยายตัวของสวนปาล์มน้ำมันอย่างรวดเร็วในวงกว้าง โดยส่วนใหญ่มีการเปลี่ยนจากพื้นที่เพาะปลูกพืชอื่น ๆ มาปลูกปาล์มน้ำมัน โดยเฉพาะสวนยางพารา หลังจากปี 2552 มีการบุกรุกพื้นที่ป่าไม้ตามธรรมชาติเพิ่มขึ้นเป็นจำนวนมาก อันเป็นผลสืบเนื่องมาจากผลกระทบทางอ้อมของการขยายตัวของสวนปาล์มน้ำมัน แสดงให้เห็นว่าพื้นที่รองรับการขยายตัวปาล์มน้ำมันในลุ่มน้ำตาปีมีจำกัด

นอกจากนี้ผู้วิจัยได้ประเมินผลกระทบของการเปลี่ยนแปลงการใช้ที่ดินต่อการบริการของระบบนิเวศ 3 ประเภท ได้แก่ การบริการให้ผลผลิตทางการเกษตรทั้งที่เป็นพืชอาหารและไม่ใช่อาหาร ความหลากหลายทางชีวภาพและการเก็บกักคาร์บอน ผลการศึกษาพบว่าการขยายพื้นที่สวนปาล์มน้ำมันส่งผลให้ผลผลิตทะลายปาล์มสดในลุ่มน้ำตาปีเพิ่มขึ้นแต่กลับลดผลผลิตของพืชอื่น ๆลง (เช่น น้ำยาง ข้าว และผลไม้) การขยายพื้นที่สวนปาล์มน้ำมันนี้ยังนำไปสู่การสูญเสียความหลากหลายทางชีวภาพเนื่องจากมีการบุกรุกป่าไม้ซึ่งเป็นแหล่งที่อยู่อาศัยตามธรรมชาติของหลายหลายสายพันธุ์ ส่วนผลกระทบต่อการเก็บกักคาร์บอน พบว่ามีการสะสมคาร์บอนสุทธิและการเก็บกักคาร์บอนเมื่อแทนที่พื้นที่นาข้าวและสวนผลไม้ด้วยการปลูกปาล์มน้ำมัน ในทางกลับกัน จะมีการปล่อยก๊าซคาร์บอนสุทธิเมื่อเปลี่ยนพื้นที่ป่าไม้และสวนยางมาปลูกปาล์มน้ำมันผู้วิจัยเชื่อว่าผลการศึกษานี้จะเป็นประโยชน์ต่อผู้มีอำนาจตัดสินใจในการพัฒนากลยุทธ์ในการวางแผนบริหารจัดการการใช้ที่ดินสำหรับขยายพื้นที่สวนปาล์มน้ำมันให้มีความเหมาะสมมากขึ้น ในขณะที่ลดผลกระทบต่อระบบนิเวศบริการในอนาคต

ประการที่สอง ผู้วิจัยได้พัฒนาแบบจำลองของภาคการผลิตขึ้นมาเพื่อประเมินผลกระทบต่อสิ่งแวดล้อมของการผลิตน้ำมันปาล์มในลุ่มน้ำตาปีในอดีตที่ผ่านมา (บทที่ 3) โดยนำเอาหลักการประเมินวัฏจักรชีวิตผลิตภัณฑ์บางส่วน (partial life cycle assessment) ร่วมกับตัวชี้วัดประสิทธิภาพด้านสิ่งแวดล้อม (environmental performance indicators) มาใช้ในการวิเคราะห์ และพิจารณาขอบเขตการศึกษาเฉพาะภาคการผลิตในสวนปาล์มน้ำมันและในโรงงานสกัดน้ำมันปาล์ม จากผลการศึกษา พบว่า (1) การใช้ปุ๋ย (2) การควบคุมวัชพืช (3) การเผาไหม้เส้นใยในหม้อนึ่งไอน้ำ (4) การบำบัดน้ำทิ้งโรงงานน้ำมันปาล์ม (POME) และ (5) การจัดการทะลายปาล์มเปล่า (EFB) เป็น 5 กิจกรรมสำคัญที่ส่งผลกระทบต่อสิ่งแวดล้อมการใช้ปุ๋ยในสวนปาล์มน้ำมันจะก่อให้เกิดปัญหาภาวะโลกร้อนและปรากฏการณ์ยูโทรฟิเคชั่นส่วนการควบคุมวัชพืชในสวนปาล์มน้ำมันจะก่อให้เกิดปัญหาการก่อตัวของโอโซนและความเป็นพิษต่อระบบนิเวศน้ำจืด ส่วนการเผาไหม้เส้นใยปาล์มในหม้อนึ่งไอน้ำจะก่อให้เกิดปัญหาภาวะฝนกรด การก่อตัวของโอโซนและความเป็นพิษต่อมนุษย์ ส่วนการบำบัด POME และการจัดการ EFB จะก่อให้เกิดปัญหาภาวะโลกร้อนและการก่อตัวของโอโซนเช่นกัน

นอกจากนี้ ผู้วิจัยได้พิจารณานำเอามาตรฐานการผลิตน้ำมันปาล์มอย่างยั่งยืนน้ำมัน (Roundtable on Sustainable Palm Oil) ซึ่งนับว่าเป็นเครื่องมือในการจัดการด้านสิ่งแวดล้อม มาใช้ในการวิเคราะห์เพื่อให้เข้าใจถึงความสามารถในการลดผลกระทบต่อสิ่งแวดล้อมผ่านการรับรองมาตราฐาน RSPOใน การวิเคราะห์ดังกล่าว โดยได้จำแนกประเภทผู้ผลิตน้ำมันปาล์มออกเป็น 3 กลุ่มเพื่อให้สอดคล้องกับการรับรองมาตรฐาน RSPO ได้แก่ (1) กลุ่มที่ไม่ได้รับการรับรองมาตรฐาน RSPO (2) กลุ่มที่มีศักยภาพได้รับการรับรองมาตรฐาน RSPO (3) กลุ่มที่ได้รับการรับรองมาตรฐาน RSPO ผลการศึกษาแสดงให้เห็นว่าผู้ผลิตที่ได้รับการรับรองมาตรฐาน RSPO ก่อให้เกิดผลกระทบต่อสิ่งแวดล้อมต่ำกว่าผู้ผลิตกลุ่มอื่น ๆ เพราะว่าผู้ผลิตกลุมนี้มีการใช้เทคโนโลยีสะอาดในกระบวนการผลิตที่นอกเหนือไปจากข้อกำหนดในมาตรฐาน RSPO เช่นการบำบัดPOME ด้วยระบบดักจับก๊าซชีวภาพซึ่งเป็นผลโดยตรงจากการส่งเสริมของภาครัฐตามนโยบายและแผนพัฒนาพลังทดแทนและพลังงานทางเลือกแห่งชาติผลการศึกษานี้บ่งชี้ว่ามาตรฐาน RSPO เพียงอย่างเดียวไม่เพียงพอที่จะทำให้การผลิตน้ำมันปาล์มอย่างยั่งยืนเกิดขึ้นได้ ดังนั้น นโยบายและแผนงานที่เกี่ยวข้องที่จะสนับสนุนภาคอุตสาหกรมน้ำมันปาล์มจากทางภาครัฐจึงเป็นสิ่งสำคัญ

ประการที่สาม ผู้วิจัยได้วิเคราะห์ถึงความคุ้มค่าของมาตรการลดผลกระทบต่อสิ่งแวดล้อมหลายมาตรการ โดยนำเอาเครื่องมือการวิเคราะห์ต้นทุน-ประสิทธิผล (cost-effectiveness analysis) เข้ามารวมในแบบจำลองของภาคการผลิต ที่พัฒนาก่อนหน้านี้ เพื่อประเมินศักยภาพในการลดผลกระทบต่อสิ่งแวดล้อมและต้นทุนของมาตรการต่าง ๆ (บทที่ 4) เพราะฉะนั้น แบบจำลองดังกล่าวจะสามรถครอบคลุมทั้งประเด็นทั้งแหล่งปล่อยมลพิษสู่สิ่งแวดล้อมและศักยภาพในการลดมลพิษของมาตรการต่าง ๆ รวมทั้งผลข้างเคียงของมาตรการเหล่านั้นจากการศึกษามาตรการต่าง ๆ รวมทั้งสิ้น 26 มาตรการ พบว่ามาตรการการเผาไหม้ EFB เพื่อผลิตกระแสไฟฟ้าการติดตั้งสครับเบอร์แบบเปียก (wet scrubbers)และการให้ความร้อนเส้นใยปาล์มก่อนที่จะเผาไหม้ในหม้อนึ่งไอน้ำ เป็นมาตรการที่มีประสิทธิภาพในการลดผลกระทบต่อสิ่งแวดล้อมมากที่สุดเพราะมาตรการเหล่านี้สามารถลดหรือหลีกเลี่ยงสารมลพิษที่ก่อให้เกิดปัญหาภาวะฝนกรดปรากฏการณ์ยูโทรฟิเคชั่น สารก่อให้เกิดโอโซนและสารที่เป็นพิษต่อมนุย์ ในบรรดาตัวเลือกเหล่านี้ การเผาไหม้ EFB เพื่อผลิตกระแสไฟฟ้าสามารถลดผลกระทบต่อสิ่งแวดล้อมได้มากที่สุด แต่จะมีค่าใช้จ่ายที่ค่อนข้างสูง นอกจากนี้ มาตรการบางมาตรการสามารถสร้างผลตอบแทนที่ดี กล่าวคือ มีผลประโยชน์เกินค่าใช้จ่าย ผลการศึกษาบ่งชี้ว่ามาตรการที่สร้างผลตอบแทนให้สูงที่สุด ได้แก่ (1) การใช้ EFB คลุมดินในสวนปาล์มน้ำมัน (2) การเก็บเกี่ยวแต่ผลทะลายปาล์มสดที่สุกเท่านั้น และ (3) การเลือกปลูกพืชคลุมดินบางสายพันธุ์ในสวนปาล์มน้ำมัน จากมาตรการที่ศึกษาทั้งหมด 26 มาตรการ พบว่ามีเพียง 7 มาตรการที่มีความคุ้มค่าสูงสุด กล่าวคือ สามารถสร้างทั้งผลตอบแทนที่ดีและมีประสิทธิภาพในการลดมลพิษสูง ได้แก่ (1) การใช้ EFB คลุมดินในสวนปาล์มน้ำมัน (2) การเก็บเกี่ยวแต่ผลทะลายปาล์มสดที่สุกเท่านั้น (3) การเลือกปลูกพืชคลุมดินบางสายพันธุ์ในสวนปาล์มน้ำมัน (4) การผลิตปุ๋ยหมักจาก EFB (5) การผลิต EFB เม็ด (6) การให้ความร้อนเส้นใยปาล์มก่อนที่จะใช้ในหม้อนึ่งไอน้ำ และ (7) การเพิ่มการ

ผลิตน้ำมันปาล์มจากการดึงกลับน้ำมันตกค้างในกากตะกอนขี้เค้ก ผู้วิจัยหวังว่าผลการศึกษาที่ได้จากการวิเคราะห์นี้จะสามารถช่วยผู้มีอำนาจตัดสินใจในการจัดอันดับตัวเลือกในการลดมลพิษให้สอดคล้องกับกลยุทธ์การจัดการด้านสิ่งแวดล้อมตามที่ต้องการ อาทิเช่นถ้ามุ่งเน้นที่การลดก๊าซเรือนกระจก ที่ไม่ใช่ CO_2 (บทที่ 5) มาตรการที่มีประสิทธิภาพในการลดการปล่อยก๊าซเรือนกระจกเหล่านี้ คือ (1) การใช้ EFB คลุมดินในสวนปาล์มน้ำมัน เพื่อลดการใช้ปุ๋ยไนโตรเจน (2) การติดตั้งระบบดักจับก๊าซชีวภาพเพื่อลดปล่อยก๊าซมีเทนจาก POME และ (3) การผลิต EFB เม็ด และการเผาไหม้EFB เพื่อผลิตกระแสไฟฟ้าเพื่อหลีกเลี่ยงการปล่อยก๊าซมีเทนจากการกอง EFB ทิ้งไว้

ประการสุดท้าย ผู้วิจัยได้วิเคราะห์หาความเป็นไปได้ในการพัฒนาการจัดการความยั่งยืนด้านสิ่งแวดล้อมของอุตสาหกรรมน้ำมันปาล์มไทยในอนาคต (บทที่ 6) โดยผนวกแบบจำลองเชิงภูมิทัศน์และแบบจำลองเชิงอุตสาหกรรมที่สร้างขึ้นก่อนหน้านี้เข้าด้วยกัน การวิเคราะห์นี้จะมุ่งเน้นที่ความเป็นไปได้ในการลดผลกระทบจากการเปลี่ยนแปลงการใช้ที่ดินต่อการให้บริการของระบบนิเวศและการลดการปล่อยมลพิษสู่สิ่งแวดล้อมจากสวนปาล์มน้ำมันและโรงงานสกัดน้ำมันปาล์ม ในการนี้ ผู้วิจัยได้จำลองสถานการณ์สำหรับการผลิตน้ำมันปาล์มในปี 2593 มา 4 สถานการณ์ ได้แก่ สถานการณ์ตามปกติ (Business as usual (BAU)) สถานการณ์ตามนโยบายปัจจุบัน (Current policy (CP)) สถานการณ์การพัฒนาอย่างรวดเร็ว (Strong growth (GRT)) และสถานการณ์การพัฒนาอย่างเป็นมิตรต่อสิ่งแวดล้อม (Green development (GRN)) เพื่อแสดงให้เห็นถึงศักยภาพของอุตสาหกรรมน้ำมันปาล์มไทยในการลดผลกระทบต่อสิ่งแวดล้อม หากรัฐบาลปรับทิศทางการกำหนดนโยบายและผู้ประกอบการปรับการบริหารจัดการในกระบวนการผลิตในปัจจุบัน จากสถานการณ์ BAU พบว่าผลกระทบต่อสิ่งแวดล้อมอาจเพิ่มขึ้นเป็นสองเท่าหากไม่มีการพัฒนาการจัดการด้านสิ่งแวดล้อมในปัจจุบันให้ดีขึ้น ทั้งในระดับนโยบายและกระบวนการการผลิตน้ำมันปาล์ม ส่วนสถานการณ์ CP แสดงให้เห็นว่านโยบายในปัจจุบันที่มุ่งเน้นการเพิ่มการผลิตน้ำมันปาล์มเพียงอย่างเดียวโดยไม่คำนึงถึงการพัฒนาการจัดการด้านสิ่งแวดล้อมทั้งระดับนโยบายและกระบวนการการผลิตน้ำมันปาล์มในปัจจุบันให้ดีขึ้น อาจเพิ่มผลกระทบต่อสิ่งแวดล้อมแบบก้าวกระโดดซึ่งอาจจะเพิ่มมากกว่าในสถานการณ์ BAU ถึงสามเท่าตัว ถึงแม้ว่าจะมีการปรับใช้มาตรการลดมลพิษที่มีความคุ้มค่าสูงสุดในกระบวนการผลิต (ตามที่แสดงในสถานการณ์ GRT) แต่ก็ยังไม่เพียงพอที่จะหลีกเลี่ยงผลกระทบต่อสิ่งแวดล้อมที่เพิ่มขึ้นจากการเร่งเพิ่มการผลิตน้ำมันปาล์มเพื่อส่งออกในอนาคต เพื่อรับมือกับการผลิตน้ำมันปาล์มเพิ่มขึ้น ผู้วิจัยพบว่าการปรับใช้มาตรการลดมลพิษที่มีประสิทธิภาพหลายมาตรการพร้อมกันโดยไม่คำนึงถึงต้นทุน (ตามที่สันนิษฐานไว้ในสถานการณ์ GRN) จะช่วยลดผลกระทบต่อสิ่งแวดล้อมลงอย่างยิ่งยวด

สุดท้ายนี้ วิทยานิพนธ์ฉบับนี้ได้พิสูจน์ให้เห็นว่าการดำเนินการประเมินผลกระทบต่อสิ่งแวดล้อมแบบบูรณาการผ่านการผสมผสานของแบบจำลองเชิงภูมิทัศน์และแบบจำลองของภาคการผลิต ประสบความสำเร็จเป็นอย่างมาก เพราะการประเมินแบบบูรณาการดังกล่าวได้ให้ข้อมูลแบบองค์รวมที่ครบถ้วนเพื่อใช้สนับสนุนผู้มีอำนาจตัดสินใจให้เข้าใจถึง (1) รูปแบบการเปลี่ยนแปลงการใช้ที่ดินที่ส่งกระทบผลกระทบต่อระบบนิเวศบริการ (2) กิจกรรมที่ส่งผลกระทบต่อสิ่งแวดล้อมที่สำคัญ ที่ควรได้รับการปรับปรุงอย่างเร่งด่วน (3) มาตรการที่มีความคุ้มค่าสูงในการลดผลกระทบสิ่งแวดล้อม ทั้งนี้ขึ้นอยู่กับวัตถุประสงค์การใช้งานของผู้ใช้ ในขณะนี้มีเพียงไม่กี่มาตรการที่ถูกนำไปในใช้อุตสาหกรรมน้ำมันปาล์มเพื่อลดผลกระทบต่อสิ่งแวดล้อมซึ่งมาตรการเหล่านี้ยังไม่ใช่มาตรการที่มีประสิทธิภาพในการลดผลกระทบที่ดีที่สุด แสดงให้เห็นว่าอุตสาหกรรมน้ำมันปาล์มไทยยังมีโอกาสในการพัฒนาการผลิตให้ดียิ่งขึ้นในวิทยานิพนธ์ฉบับนี้ ได้ชี้บ่งให้เห็นถึงความเป็นไปได้ที่จะพัฒนาการจัดการความยั่งยืนด้านสิ่งแวดล้อมของอุตสาหกรรมน้ำมันปาล์มไทย กล่าวโดยสรุปคือ การจำกัดการขยายตัวของสวนปาล์มน้ำมัน โดยมุ่งเน้นที่การเพิ่มผลผลิตทั้งในสวนปาล์มน้ำมันและโรงงานสกัดน้ำมันที่มีอยู่เดิม มีความจำเป็นอย่างมากเพื่อหลีกเลี่ยงการตัดไม้ทำลายป่าอย่างต่อเนื่อง ในทางเทคนิคมีความเป็นไปได้ที่อุตสาหกรรมน้ำมันปาล์มไทยจะลดผลกระทบต่อสิ่งแวดล้อมอย่างยิ่งยวดในอีก 30 ปีข้างหน้า ผ่านการดำเนินการใช้มาตรการลดมลพิษที่มีประสิทธิภาพมากที่สุดหลายมาตรการรวมกันอาทิเช่นการเผาไหม้ EFB เพื่อผลิตกระแสไฟฟ้าการติดตั้งอุปกรณ์สครับเบอร์แบบเปียก และการให้ความร้อนเส้นใยปาล์มใช้ก่อนเผาไหม้ในหม้อนึ่งไอน้ำ อย่างไรก็ตามผู้ผลิตน้ำมันปาล์มอาจเลือกใช้เพียงแค่มาตรการที่มีความคุ้มค่าสูง หรือมาตรการที่ให้ผลตอบแทนสูงเท่านั้น เช่น การใช้ EFB คลุมดิน การใช้ EFB ผลิตปุ๋ยหมัก การผลิต EFB เม็ด และการเพิ่มการผลิตน้ำมันจากการดึงกลับน้ำมันตกค้างในกากตะกอนขี้เค้ก ผลการศึกษาจากวิทยานิพนธ์ฉบับนี้จึงเป็นประโยชน์สำหรับผู้มีอำนาจตัดสินใจในการกำหนดนโยบายและวางแผนกลยุทธ์ในการจัดการด้านสิ่งแวดล้อมในอนาคตและการปรับปรุงกระบวนการผลิตน้ำมันปาล์มทั้งอุตสาหกรรมและทั้งประเทศโดยรวม

About the Author

Ms. Kanokwan Saswattecha was born on 27 December 1982 in Bangkok, Thailand. She received her BSc Degree in Health Sciences at Thammasat University, Thailand in 2005. Kanokwan is a flexible person and is always open for any opportunities that may come along. Later, she received a scholarship from the Royal Thai Government to study Environmental Engineering and Management at the Asian Institute of Technology (AIT), Thailand and received her MSc degree in 2007. Her studies focused on air quality monitoring and air pollution abatement. During her study, she received an opportunity to work as an intern for two months at the Korea Water Resources Corporation. This opportunity has broadened her view and experience on water resource management and water treatment technologies.

After her graduation, Kanokwan worked in various fields of work (i.e. environmental consulting company, research institute and development organization). She gained valuable working experiences and a set of well-grounded skills, including analytical, organizational and communication skills. In September 2012, she received an opportunity to pursue a PhD position at the Environmental System Analysis group, Wageningen University, The Netherlands. Her study is a part of a research program called 'Towards Environmentally Sustainable and Equitable Palm Oil' or SUSPENSE, funded by the Interdisciplinary Research and Education Fund (INREF) of Wageningen University. Her PhD thesis aims to explore possibilities to contribute to a more sustainable palm oil development for Thai palm oil sector in the future. In this regard, she developed an integrated model for sustainable palm oil development; coupling a landscape model and sectoral model. She hopes that her model will be useful for other industrial sectors to seek for possibilities to improve their environmental performance towards sustainable development.

During her PhD research, Kanokwan was involved in several education and supervision activities. She supervised a Masters Degree student who worked on estimation and evaluation of options to reduce future greenhouse gas emissions from palm oil mills in Thailand. She also participated various international conferences. Now, Kanokwan is looking forward to new challenges in her scientific career.

List of publications

Published peer-reviewed articles:

Saswattecha K, Kroeze C, Jawjit W, Hein L. 2015. Assessing the environmental impact of palm oil produced in Thailand. J Clean Prod. 100:150–169.

Saswattecha K, Cuevas Romero M, Hein L, Jawjit W, Kroeze C. 2015. Non-CO 2 greenhouse gas emissions from palm oil production in Thailand. J Integr Environ Sci. 8168:1–19.

Saswattecha K, Hein L, Kroeze C, Jawjit W. 2016. Effects of oil palm expansion through direct and indirect land use change in Tapi river basin, Thailand. Int J Biodivers Sci Ecosyst Serv Manag.

Saswattecha K, Kroeze C, Jawjit W, Hein L. 2016. Options to reduce environmental impacts of palm oil production in Thailand. J Clean Prod.

Published reports:

Dallinger J, **Saswattecha K**, Sinsuphan P. 2013. Policy Assessment and Recommendations on Sustainable Bioenergy in Thailand. Ecole Polytechnique Fédérale de Lausanne (EPFL). Lausanne, Switzerland.

Conference proceedings:

Saswattecha K, Hein L, Kroeze C, Jawjit W. 2016. Land use change effects of oil palm expansion on ecosystem services in Tapi river basin, Thailand. In: Proceedings of the 8th International Congress on Environmental Modelling and Software, July 10-14, Toulouse, FRANCE. ISBN: 978-88-9035-745-9

Submitted articles:

Saswattecha K, Kroeze C, Jawjit W, Hein L (under revision) Improving environmental sustainability of Thai palm oil production in 2050. J Clean Prod.

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born on 27 December 1982 in Bangkok, Thailand

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Wageningen, 13 February 2017

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K O N I N K L I J K E N E D E R L A N D S E
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The SENSE Research School declares that **Ms Kanokwan Saswattecha** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 39.3 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2013)
- Research in context activity: 'Initiating and organising a policy forum and stakeholder consultation on 'Sustainable Biofuel Registration and Implementation', Bangkok, Thailand' (2013)
- Complex dynamics in human-environment system (2013)

Other PhD and Advanced MSc Courses

- Introduction to global change, Wageningen University (2012)
- Action oriented research training, Wageningen University (2012)
- Techniques for writing and presenting a scientific paper, Wageningen University (2012)
- Improve your writing, Wageningen University (2012)
- Geo-information tools, Wageningen University (2013)

External training at a foreign research institute

- Application of R programme in data management and analysis, Walailak University, Nakhon Si Thammarat, Thailand (2013)

Management and Didactic Skills Training

- Supervising MSc student with thesis entitled 'Greenhouse gas emissions from crude palm oil mills in the Tapi river basin (Thailand) and options for control' (2013)

Oral Presentations

- *Land use change effects of oil palm expansion in Tapi river basin, Thailand.* 8th International Congress on Environmental Modelling and Software (iEMSs), 10–14 July 2016, Toulouse, France
- *Improving environmental sustainability of Thai palm oil production in 2050.* 14th Annual Roundtable Conference on Sustainable Palm Oil (RSPO), 7-10 November 2016, Bangkok, Thailand

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