Oil palm (*Elaeis guineensis*) production in Indonesia:

carbon footprint and diversification options

Ni’matul Khasanah

Propositions

1. Higher oil palm yields per unit of land through increased fertilizer use will reduce the drive to expand plantation area, but can increase the carbon footprint of palm oil.
   (this thesis)

2. Mixed cropping systems with oil palm as 'land sharing' practice can achieve 'land sparing' through Land Equivalent Ratios above 1.0.
   (this thesis)

3. Peat subsidence results may depend on the weight and footprint of the researchers visiting the observation site.

4. Sustainability of a landscape as a commons depends on how the '*common but differentiated responsibilities*' expressed in the Rio de Janeiro Earth Summit, 1992 are linked to respective capabilities.

5. Performance-based incentive schemes between ecosystem services providers and beneficiaries are most effective when understood by all as a conservation and livelihoods coinvestment.

6. In baking, gaps between model and reality don't hinder a sweet tooth, offering a nice distraction for an overstretched PhD students' mind.

Propositions belonging to the thesis, entitled

Oil palm (*Elaeis guineensis*) production in Indonesia: carbon footprint and diversification options

Ni'matul Khasanah
Wageningen, 9 April 2019

Oil palm (*Elaeis guineensis*) production in Indonesia:

carbon footprint and diversification options

Ni'matul Khasanah

Thesis committee

Promotor
Prof. Dr Meine van Noordwijk
Special Professor Agroforestry
Wageningen University & Research

Co-promotor
Dr Maja A. Slingerland
Associate professor, Plant Production Systems Group
Wageningen University & Research

Other members
Prof. Dr Carolien Kroeze, Wageningen University & Research
Prof. Dr H. Martin Junginger, Utrecht University
Dr Gede Wibawa, Riset Perkebunan Nusantara, Indonesia
Dr Jan Verhagen, Wageningen University & Research

This research was conducted under the auspices of the of the C. T. de Wit Graduate school of Production Ecology and Resource Conservation

Oil palm (*Elaeis guineensis*) production in Indonesia:
carbon footprint and diversification options

Ni'matul Khasanah

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 9 April 2019
at 11 a.m. in the Aula.

Ni'matul Khasanah

Oil palm (*Elaeis guineensis*) production in Indonesia: carbon footprint and diversification options,
205 pages.

PhD thesis, Wageningen University, Wageningen, the Netherlands (2019)
With references, with summary in English

ISBN: 978-94-6343-569-7
DOI: https://doi.org/10.18174/467425

Abstract

Oil palm (*Elaeis guineensis*) is a uniquely valuable palm as source of low-cost vegetable oil. However, the success and method of its expansion (monoculture plantation) especially in biodiversity-rich Indonesia and Malaysia have made it one of the most controversial crops of the world. One of the policy consequences of the boycotts and debate is the Renewable Energy Directive (RED) of European countries that sets binding targets for the emission savings to be achieved when oils are used as feedstock of biofuel. Exporting countries such as Indonesia need to have reliable data on the carbon footprint of their product across production systems and the products' lifecycle. Diversification of oil palm plantations starts to gain attention as a strategy to increase farmer resilience. The objectives of this thesis were (1) to estimate the carbon footprint of palm oil production in Indonesia when it is used as biofuel and express it as CO_2 equivalent and emissions saving, and (2) to explore mixed oil palm systems as diversification strategy to increase farmer benefit and to reduce the carbon footprint. Through a survey and sample collection in more than 20 plantations distributed over Sumatra, Kalimantan and Sulawesi we analysed the palm oil life cycle. Using the Biofuel Emission Reduction Estimator Scheme (BERES) emissions savings were differentiated by carbon debt (land use change) and current practices. Process-based modelling using WaNuLCAS (Water, Nutrient and Light Capture in Agroforestry System) helped explore intercropping systems beyond current practice. Results show that it is possible to achieve the high emission savings target with palm oil to comply with the RED requirement. Of companies with 'good agricultural practice' 40% and 25% of production can meet the 35% (2015) and 60% (2018) emissions savings standards, respectively. The larger the areas that were converted from high-C stock forest, the larger the fraction of peat, the larger the emissions from fertilizers, transportation and processing (incl. methane) and the lower the yield of Fresh Fruit Bunches (FFB), in a mix of production situations that is accounted for jointly (as is the case for 'company' level assessments), the harder it is to achieve emission savings. While fertilizer application increases FFB yield, it also increases N_2O emissions. Selected mixed oil palm systems can provide considerable economic and environmental system improvements. The Land Equivalent Ratio of mixed oil palm – cacao systems can be 1.4, showing a superior way to achieve land sparing as a goal of efficient use of land, relative to monocultures for each commodity separately. Diversification should be a valid counterpart of current intensification research and policies to help make palm oil more sustainable from both social and environmental perspectives.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AGC	Aboveground carbon
BD	Bulk density
BERES	Biofuel Emission Reduction Estimator Scheme
C_{org}	Organic carbon content
C_{org_ref}	Organic carbon content-reference
CPO	Crude palm oil
EFB	Empty fruit bunch
FFB	Fresh fruit bunch
FPIC	Free and prior informed consent
GHG	Greenhouse gasses
HCS	High carbon stock
ICRAF	World agroforestry centre
IPCC	Intergovernmental panel on climate change
IPOC	Indonesia palm oil committee
ISPO	Indonesian sustainable palm oil
LCA	Life cycle assessment
LER	Land equivalent ratio
LER_m	Land equivalent ratio-multifunctionality
LER_p	Land equivalent ratio-production
LER_r	Land equivalent ratio-regulation
MSPO	Malaysian sustainable palm oil
NPV	Net present value
OER	Oil extraction rate
P&C	Principle and criteria
PKO	Palm kernel oil
P_{SWEET}	Sustainable weighting of ecology and economic trade-offs'
RACSA	Rapid carbon stock assessment
RED	Renewable energy directive
RSPO	Roundtable on sustainable palm oil
WaNuLCAS	Water, Nutrient and Light Capture in Agroforestry System

Chapter 1

General Introduction

1.1. Background

Oil palm (*Elaeis guineensis*) is a uniquely valuable palm originating in Africa, producing oil that can be used for a wide range of food and non-food end products, and also as biofuel feedstock. The success and method of its expansion, however, have made it one of the most controversial crops of the world, with strongly negative and positive opinions competing for attention. Between 'worst case' examples that attract negative press and 'best practice' examples that are cited by the industry in defence is a wide 'management swing potential' (Davis et al., 2013) on both social and environmental dimensions. Science-based evaluations of consequences of the diverse practices on the ground and exploration of options beyond the standard monocultures remain scarce. The direct cost of oil production from palms (less than USD 300 per ton of oil) is lower than that of other vegetable oils such as sun flower, soybean, coconut and rapeseed (USD 300 – 600 per ton of oil) (Carter et al., 2007). For plantation owners and farmers, oil palm is a more profitable tree crop than other commodities such as rattan and rubber and positive welfare effects and a high return to land and labour have been well documented (Belcher et al., 2004; Feintrenie et al., 2010a; Rist et al., 2010). These unique characteristics explain the increased demand for palm oil and have attracted global expansion of oil palm plantations (Sheil et al., 2009; Woittiez et al., 2017). Two countries, Indonesia and Malaysia currently produce more than 85% (54% for Indonesia and 31% for Malaysia) of the worlds' palm oil (Index Mundi, 2017).

However, the private benefits may be accompanied by social costs. Expansion of oil palm plantations often causes deforestation or conversion of species-rich agroforests on both mineral and peat soils (Koh and Wilcove, 2008; McCartney, 2010; Koh et al., 2011; Carlson et al., 2012; Villamor et al., 2014), and especially in the forest margin frontiers, lead to land conflicts (Sirait, 2009). Global concerns aligned with local, social and ecological issues has led to consumer boycotts. To avoid such, a number of standards and certification responses like roundtable sustainable palm oil (RSPO) or Malaysian sustainable palm oil (MSPO) or Indonesian sustainable palm oil (ISPO) have emerged (Mithöfer et al., 2017), aiming to regain trust for certified producers (van Noordwijk et al., 2017; Hidayat et al., 2018). A third cycle of environmental and social RSPO rules packaged in the set of Principles and Criteria (P&C)[1] was recently (November 2018) ratified and adopted. It tightened the requirements that must be obeyed for a company to obtain RSPO certification. The set of changes included a ban on palm oil producers planting on peat of any depth and a total ban on deforestation. The Government of Indonesia meanwhile implemented a three-year 'moratorium' (Presidential Instruction No 8/2018 on the Delay

[1] https://rspo.org/key-documents/certification/rspo-principles-and-criteria

and Evaluation of Permits and Elevated Productivity of Oil Palm Plantations)[2], that is a (belated) response to the global debate of the past decade.

The public debate on oil palm heated up by the increasing options for use of palm oil as non-food product. Emerging demand for palm oil from European countries followed from policies to reduce their attributed CO_2 emissions through the use of biofuels, with associated carbon emissions outside their books. By 2020, European countries aim to have 20% on average of the transport fuel come from renewable sources (Renewables Directive 2009/28/EC). However, this policy has raised concerns over net greenhouse gases emissions because the standard and accounting systems ignore emissions in the feedstock source areas (Searchinger et al., 2008, 2009). Based on earlier critiques, biofuels must (from 2018 onwards) lead to at least 60% emissions saving at global scale in order to be included in the EU policy, but the assessment of such emissions (at sector, national, company or plantation scale) is still debated.

Where export opportunities are at risk due to subsequent regulations in importing countries, palm oil exporting countries such as Indonesia need to have reliable data on the carbon footprint of palm oil to be used for biofuel. In addition, efforts as a strategy to increase farmer benefit and to reduce the risk such as diversification of oil palm plantations with other cash crops are starting to gain attention.

1.1.1. Palm oil production in Indonesia

This thesis focuses on palm oil production in Indonesia. For the past 40 years, driven by increased global demand of palm oil and higher yields or profitability, the area of oil palm plantation has significantly increased (up to 2007 by 10% every year on average and beyond 2007 by 6%) (Carter et al., 2007; Directorate general of estate crops, 2016a). At national scale the land area under oil palm is currently 6% of the whole country (190 M ha), challenging interpretations that it is the primary driver of deforestation (Sheil et al., 2009). According to data of the Tree Crop Estate Statistics of Indonesia (Directorate general of estate crops, 2016a), the expansion of oil palm plantation involves both large (88,847 ha in 1980 to 6.7 million ha in 2017) as well as smallholder scale production (from 6175 ha in 1980 to 4.7 million ha in 2017). However, various definitions of 'smallholders' link to the size of plantation and involvement in day-to-day plantation management, the existence of mills without plantations and medium-sized plantations without their own mills makes interpretation of existing statistics complex (Jelsma et al., 2017).

[2] https://www.thejakartapost.com/news/2018/09/20/groups-welcome-jokowis-palm-plantation-moratorium.html

In line with the massive pace of expansion, production of palm oil has, since 1980, increased from 0.72 to 35 million Mg in 2017 (Directorate general of estate crops, 2016a). Indonesia became the world's largest producer of palm oil[3] and more than 30% of the palm oil production is exported to India (49%), Europe (31%) and Singapore (8%) (Directorate general of estate crops, 2016a). Maintaining its status as the world's largest producer of palm oil, Indonesia has projected a production of 44 Mton by 2020 (Kwatiwada et al., 2018). This projection is supposed to be met by increasing production of existing plantation especially smallholder production rather than through the expansion of new plantation areas. The production of smallholder oil palm plantations in Indonesia is on average less than 15 Mg ha^{-1} yr^{-1} (Vermeulen and Goad, 2006; Molenaar et al., 2013; Lee et al., 2014) with some notable exceptions (Woittiez et al., 2017) which is 35 – 40% lower than large plantation (Suharto 2009 cited in GanLian, 2012). This level of production has yield gaps ranging from 2 – 4 Mg oil $ha^{-1}yr^{-1}$ in smallholder systems and from 1 – 3 Mg oil $ha^{-1}yr^{-1}$ in large plantations. Closing these yield gaps to only 80% of the water-limited yield could realistically increase global production by 15–20 million Mg oil yr^{-1}, the equivalent to clearing 4 – 6 Mha of new land (Woittiez et al., 2017).

More than 95% (57% large scale plantations and 38% smallholders) of oil palm expansion have so far occurred in lowland regions of Sumatra and Kalimantan (Directorate general of estate crops, 2016a). The expansion has catalysed rural development not only in developing infrastructure and providing employment but also in providing additional options for smallholder farmers. Data show that reduction in rural poverty is not only experienced by farm households (Gatto et al., 2017; Euler et al., 2017; Kubitza et al., 2018), but also reached non-farm households (Did et al., 2018). Initially smallholder oil palm growers were supported by government programs based on cooperation between large-scale plantations as *nucleus* and surrounding farmers as *plasm*a (Santoso, 2010). The *plasma* scheme refers to areas planted with oil palm that are initially managed by the core company (*nucleus*) during establishment, usually until the early production stage (4 – 5 years old) and then transferred to the farmers who still own the land or who will own the land if the nucleus-plasma concept became an embedded part of the transmigration (resettlement) program. However, in several parts of Kalimantan such schemes were implemented without free and prior informed consent (FPIC) of all involved (Colchester

[3] In 1935 the "Dutch indies" became the world's leading palm oil exporter, for the first time surpassing Nigeria, with 35% of global export, derived from 74,000 ha with an average yield of 2.4 t of oil per ha. (Rowaan,1936); when it regained the number one spot 75 years later the production area was more than a factor 100 larger.

and Chao, 2011) and conflicts arose when plantations were sold and new owners renegotiated terms of the initial contract (Sirait, 2009; Lee et al., 2014).

Furthermore, the growing importance of smallholders of various categories has been recognized by both the Indonesian Government and the private sector. But, in terms of certification of legality and adherence to social and ecological sustainability standards, the independent smallholders are the most complex as they are the most diverse and the cost of certification might not be economically feasible (Hutabarat et al., 2018). Given the area and total production involved, the various smallholder categories and their production practices (Jelsma et al., 2017) have become a major focus in the past decade (e.g. it was an ‘emerging’ topic in the study by Sheil et al., 2009). ‘Independent’ is a relative term, as such farmers are fully dependent on effective delivery contracts traders have with existing mills.

1.1.2. Palm oil carbon footprint

In line with concerns of end users of the products, the carbon footprint of palm oil in this thesis is defined as the net greenhouse gas (GHG) emissions per unit product. As unit of analysis for GHG emissions along the full chain products integrate GHG emissions per unit land, the yields obtained and further emissions (or losses of the accounting base) during processing, transport and conversion to the end-users’ product. It thus assesses emissions caused by palm oil production and processing for biofuel. The analysis thus uses a ‘life cycle analysis’ approach. Life cycle analysis is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing to the final consumer. Calculations of the palm oil carbon footprint for biofuel in this thesis consider three phases of the production process: (i) the initial conversion of preceding vegetation into an oil palm plantation, usually based on 'land clearing', leading to a 'carbon debt' defined as the difference between time-averaged C stock of the subsequent plantation and that of the preceding vegetation, (ii) the growth cycle of the oil palms (typically around 25 years) and its management and fertilization practices that lead to the yield, direct fertilizer-related emissions and an aboveground and belowground time-averaged C stock of oil palm that influences the carbon debt and repay time, (iii) post-harvest processing including transportation until the product reach the end user (van Noordwijk et al., 2013). These calculation phases imply that if a new plantation is established in an area with high carbon stock (natural forest and/or on peat soils), net emissions will be high (large carbon footprint). If oil palm is developed on mineral soils on lands already deforested, attributable emissions can be low (small carbon footprint). Intensification of production within existing oil palm plantations, e.g. by increasing fertilizer use, could either increase or decrease the carbon footprint per unit product, depending on context, scale and accounting method.

Footprint calculations for palm used as biofuel can be directly compared with the emission savings that are obtained when fossil fuels are substituted by 'renewable' liquid biofuels. The net emission saving is the basis for biofuel policies; it requires an accounting method that considers the above-mentioned three phases of the production process, as well as technical efficiencies at the final consumer end. As intensification using larger N fertilizer rates increase production as well as emissions, it is yet to be assessed which fertilizer rate minimizes the carbon footprint and maximizes the net emissions saving.

As part of the land sparing versus land sharing debate (Renwick and Schellhorn, 2016; Mertz and Mertens, 2017; Phalan, 2018) the merits of intensified monoculture production (high yields, but also direct environmental impacts of high input use) have been compared with those of diversified, 'ecologically intensified' production systems (lower yields, but better in terms of environmental services). As it refers to the amount of land needed to achieve the production of a range of products, the Land Equivalent Ratio (LER) is directly relevant for the 'land sparing' debate (Martin-Guay et al., 2018). Interestingly, the common finding that LER values above 1 are feasible in intercropping (Szumigalski et al., 2008), suggest that 'land sharing' may be the best way to achieve 'land sparing' as a goal of efficient use of land. As suggested recently (van Noordwijk et al., 2018), an extended LER_m index that includes all aspects of multifunctionality (beyond commodity production) might take the debate further into the analysis of existing landscape mosaics, that include a range of intensities of land use and monocultures as well as mixed cropping systems. To do so, a better understanding is needed of the rationales and methods for oil palm diversification, especially under smallholder management systems.

1.1.3. Diversification of oil palm plantation

Intercropping of oil palm and food crops has been studied for several decades, not only in its origin countries in Africa; but also in extended countries in Asia. The studies addressed various research topics: local perceptions and strategies on intercropping, production of food crops at early stage of oil palm growth and residual effect of intercropping on the yield and productivity of oil palm at later production stage (Salako et al., 1995; Orewa, 2008; Okyere et al., 2014; Putra et al., 2012; Nchanji et al., 2016). Diversification of oil palm plantation with cash crops may not only as a strategy to reduce level of smallholder livelihood vulnerability that has social and economic risks for depending on a single cash crop, but also as a strategy to increase oil palm production that grows in less suitable climate and soil conditions and to reduce ecological damage (Romero, 2018) that experiences by both large and small-scale plantations.

Oil palm can grow well in the area where temperature range from 24^{O}C to 28^{O}C, bright sunshine should not less than 6 hours per day, 80% of humidity and 2000 mm of rainfall per year that is evenly distributed without a marked long dry season. In term of soil, generally oil palm can grow on a wide range of soils. However, it grows best in not too alkaline or saline soil, well drained and rich in organic matter (Corley and Tinker, 2016; Woittiez et al., 2017).

In less suitable climate (longer dry periods) and soil (acid soil) conditions, male inflorescence production increases and female inflorescence decreases in response to water stress (Breure, 1982; Gawangkar et al., 2003; Adam et al., 2011) that lead to low fruit production after about 12 months (Corley and Tinker, 2016), and moreover oil palm develops relatively shallow roots on acid soils (Mutert, 1999a). In such conditions, mixed oil palm systems with other cash crops that have a deeper root system might be a strategy for increasing growth and yield of oil palm as deeper-rooted companion trees can maintain soil water content in the topsoil in dry periods through hydraulic equilibration (Bayala et al., 2008), hence avoiding male flowers. Furthermore, it provides additional other tree products per unit resources used, and reduces economic risks when product prices fluctuate and can also have positive environmental impact such as reduction in carbon footprint if it is good managed.

Figure 1.1. Mature monoculture oil palm in Lampung, Indonesia (left) and experimental plot of mixed oil palm in Tome Acu, Brazil (right)

To test the sustainability of diversified oil palm plantation, the Brazilian Agricultural Research Institute/Embrapa (together with other institutes and a local farmer community) has developed a 6 ha of mixed oil palm experiment that split into different treatment in term of land preparation (manual or mechanic), spacing (variants of double row spacing) and type of intercropped trees (direct economic value such as cacao and banana; soil fertility enhancing such as *Inga edulis*, *Gliricidia sepium* or legume cover crops). In this thesis, this experiment became the basic model in the exploration of various mixed oil palm systems.

1.2. Knowledge gaps

It is clear that global demand for palm oil has, in suitable climate zones, lead to a massive expansion of oil palm plantations, with a range of management and ownership regimes. In the two countries that currently dominate the world market, Indonesia and Malaysia, the expansion has had both positive (mostly in terms of welfare) and negative (mostly in terms of environment) impacts. Concerns for negative environmental and social effects of oil palm expansion, especially expressed in importer countries has led to 'issue attention cycles' (Mithöfer et al., 2017; van Noordwijk et al., 2017) that resulted in standards and certification schemes. Specifically related to the potential use as biofuel feedstock this has made the greenhouse gasses emission saving from palm oil production a topic of high relevance. Most of the palm oil greenhouse gasses emission studies using the life cycle analysis approach (Souza et al., 2010; de Vries, 2012; Kittithammavong et al., 2014; Siregar et al., 2015) have focused on the carbon footprint expressed in CO_2 equivalent; only a few have taken the next steps to derive an emission savings metric compared to the use of fossil fuel (Yee et al., 2009). This thesis estimates the carbon footprint using the same approach and expressed it in both CO_2 equivalent and emission saving to get the figure of palm oil production in Indonesia as basis data to meet the (European) market for biofuel feedstock.

Moreover, current sustainability standards focus on the initial land conversion, and the social and productivity side of plantations, but are not yet fine-tuned to smallholders. The latter often prefer mixed rather than monoculture production systems, for a variety of economic and social reasons. This includes food crops grown between the young palms in the early years (Figure 1.2), rather than the legume cover crops preferred in large-scale plantation, but may also target other tree crops such as cacao or pepper and possibly fruit and timber trees. For the mixed oil palm systems, most studies so far have focused on intercropping oil palm and food crops in the early years; this may involve trade-offs with subsequent palm oil yields if conditions in the palm are negatively affected. Beyond the existing systems studied, intercropping of oil palm and other tree crops that receives considerable attention among practitioners has not been widely explored yet. Gérard et al (2017), Stomph (2017) and Mignon (2018) initiated study on oil-palm yields in diversified plantations.

1.3. Overall objectives, research questions and hypotheses

The general research objectives of this study were (1) to estimate the carbon footprint of palm oil production in Indonesia when it is used as biofuel and express it as CO_2 equivalent and emission saving compared to the use of fossil fuel, and (2) to explore mixed oil palm systems as diversification strategy to increase farmer benefit and to reduce the carbon footprint. To achieve these objectives, five chapters (Figure 1.2) for five research questions (RQs) and hypotheses were formulated (Table 1.1).

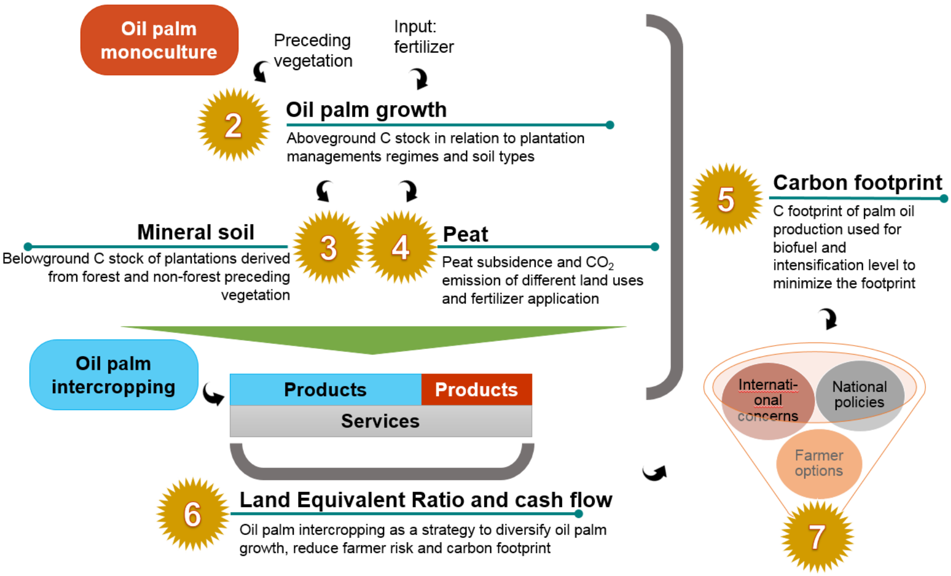

Figure 1.2. Relationship between the five research questions (and associated primary research chapters) of the thesis

1.4. Scope and approaches

This thesis focuses on the analysis of the carbon footprint of palm oil production in Indonesia, in relation to the emerging standards when it is used as biofuel. It also explores options of mixed oil palm systems as a diversification strategy to increase farmer benefit. A range of methods and approaches was applied to answer the questions and test the hypotheses (Table 1.2). As most of the published data are of a 'case study' nature, without explicit attention to the way data can be aggregated for assessments at regional or national scales, research in this thesis was explicit in its attention to sampling schemes for achieving representativeness across Indonesia. Yet, as explained in more detail in chapters 2 and 3, the voluntary nature of participation by oil palm companies made the results a reflection on what these companies see as 'achievable practices', rather than giving an unbiased view on current reality.

To answer research questions 1 and 2, survey and data collection (field measurements) were conducted in more than 20 selected plantations distributed in Sumatra, Kalimantan and Sulawesi (Figure 1.3). Selection of the plantations was based on stratifiers at both national level (plantation: derived from forest versus non-forest; soil type: mineral soils versus peat; the prevalence of oil palm in the surrounding area: <1, 1-5, 5-15%, as indication of options for independent smallholders through the 'distance to mill' variable) and plantation level (plantation management: nucleus, plasma, independent smallholder; soil type: mineral soils versus peat). Age during the crops' life cycle was also considered to provide the range of aboveground and belowground C stocks available in the area (related to the local oil palm expansion history). For the belowground (mineral soil) C stocks (research question 2), besides variation at both national and plantation levels, fine-scale variation between four different management zones (weeded circle, interrow, frond stacks, and harvest paths) commonly found in oil palm plantation was explored in its implications for soil carbon organic content (C_{org}) and soil bulk density (BD). As the mandated 0-30 cm soil C stock data are influenced by soil compaction, various corrections were applied to understand the fate of pre-existing and newly added soil carbon over a plantations life cycle where initial loss can be compensated by later gains.

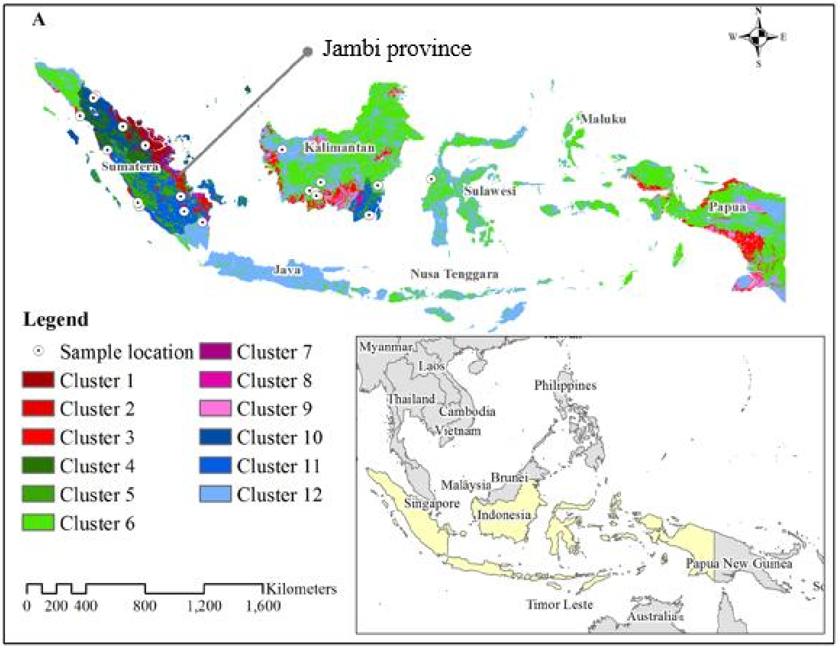

Figure 1.3. Site distribution of more than 20 surveyed plantations and province where peat subsidence was conducted

Table 1.1. Five research questions (RQs) and hypotheses of the thesis

	Research questions	Hypotheses
1	What is the range of aboveground time-averaged C stocks (Mg C ha^{-1}) of various types of oil palm plantations in Indonesia? Sub questions: are there relevant differences between the three main plantation management conditions found in Indonesia: nucleus, plasma, and independent smallholders, and between soil types (mineral versus peat)?	Aboveground time-averaged C stock of oil palm plantation varies in relation to soil types and plantation management regimes
2	What is the belowground time-averaged C stock (Mg C ha^{-1}) on mineral soil of oil palm plantations in Indonesia? With as sub question: how does temporal variation of soil organic content (C_{org}, %) and soil bulk density (BD, g cm^{-3}) influence the results for the top 30 cm used in C accounting?	The belowground time-averaged C stock of plantations on mineral soil differs between those derived from forest and non-forest as preceding vegetation
3	How does variation in subsidence (cm yr^{-1}) and CO_2 emission (Mg CO_2 ha^{-1} yr^{-1}) rates of smallholder oil palm plantations on peat compare to that for other land-use types, in relation to conversion history (earlier compared to recent drainage), and fertilizer application?	There is variation in peat subsidence and CO_2 emission rate of different land uses due to differences in conversion history and fertilizer application
4	How is the carbon footprint of palm oil production in Indonesia, and attributed emission savings when used as substitute for fossil fuel, influenced by intensification level (fertilizer use); do environmentally and economically optimized intensification levels match the current carbon footprint per unit biofuel?	Palm oil used for biofuel and produced in plantations derived from low C stock land covers on mineral soils can achieve current targets for emissions saving when compared to the use of fossil fuel, when fertilizer levels are adjusted
5	Can development of mixed oil palm systems be a strategy to diversify oil palm production, reduce farmer risk and reduce the attributed carbon footprint?	Selected mixed oil palm systems achieve land saving through a land equivalent ratio above 1, improve farmer benefits and reduce the carbon footprint compared to monoculture oil palm

Table 1.2. Focus of analysis and approaches to address the five questions

		Approaches					
RQs	**Focus of analysis**	**Spatial analysis**	**Survey and data collection (field measurement)**	**Experimental plot**	**Life cycle analysis**	**Process based modelling**	**Scenario analysis**
1	Aboveground time-averaged C stock of oil palm plantation						
2	Belowground (mineral soil) time-averaged C stock of oil palm plantation						
3	Subsidence and CO_2 emissions of smallholder oil palm plantation and other land covers						
4	Carbon footprint of palm oil production and level of fertilizer application to minimizes the carbon footprint						
5	Agronomic options to diversify oil palm growth						

To answer research question 3, field experiments were established in different land cover types under smallholder management, with variation in conversion history (earlier compared to recent drainage) and fertilizer application in Jambi, Sumatra (Figure 1.3). Subsidence and groundwater levels were monitored for 2.5 years. The estimation of peat subsidence considered micro-topographical dynamics of the peat surface to address local heterogeneity of peat subsidence and test improved ways of representing this variation.

Figure 1.4. Measurement and collected sample of above and belowground C stock

To answer question 4, a life cycle analysis approach including scenario analysis was applied using the Biofuel Emission Reduction Estimator Scheme (BERES) (van Noordwijk et al., 2013). The approach considered three stages of palm production leading to CO_2-eq. emission: land conversion, palm oil production and use of external inputs, and post-harvest transport and processing. Comprehensive data including secondary data on fresh fruit bunch production and fertilizer application for the approach was collected during survey and data collection for research questions 1 and 2. Further analysis of yield and emission data in relation to fertilizer use identified ways to minimize the footprints (per unit product) and optimize fertilization from an environmental (footprint) and economic (cost-benefit analysis) perspective.

To answer question 5, the tree-soil-crop interaction and intercropping model, WaNuLCAS (Water, Nutrient and Light Capture in Agroforestry System) (van Noordwijk and Lusiana 1999; van Noordwijk et al., 2011) was used to explore and analyse various mixed oil palm systems and Biofuel Emission Reduction Estimator Scheme (BERES) (van Noordwijk et al., 2013) to calculate carbon footprint. The mixed systems were further analysed for land equivalent ratio multifunctionality (LER_m), economic performance indicators and environmental performance indicators.

Figure 1.5. Peat subsidence measurement

1.5. Outline of the thesis

This thesis consists of seven chapters and started with this general introduction chapter. The subsequent five primary research chapters (chapter 2 – 6) address the five research questions presented in section 1.3 and are followed by a general discussion and conclusions (chapter 7).

Chapter 2 reports measurements and quantification of the aboveground time-averaged C stock of oil palm (Mg C ha^{-1}) to answer research question 1. A survey was set up to cover the main production conditions across Indonesia. The measurements included oil palm biomass, understory vegetation, standing litter and necromass stock in oil palm and the vegetation it replaced. The quantification and analyses provided aboveground threshold values for oil palm land conversion to meet carbon-neutrality in this aspect of carbon footprint calculations (research question 4).

Chapter 3 presents the temporal trends of soil organic content (C_{org}, %) and soil bulk density (BD, g cm^{-3}) of mineral soils and analyses of time-averaged mineral soil C stock (Mg C ha^{-1}) for the same survey as used in Chapter 2. It analyses the data to answer research question 2. The chapter discusses changes in mineral soil C stock under oil palm plantations derived from forest or non-forest and provides recommendation for the assessment of mineral soil CO_2 emission in oil palm cultivation to be used in carbon footprint calculations (research question 4).

Chapter 4 aims to answer research question 3 by monitoring and analysing the annual rate of peat subsidence (cm yr^{-1}) and CO_2 emission (Mg CO_2 ha^{-1} yr^{-1}) of different land-use types under smallholder management. Analysis related conversion history to subsidence after drainage, and fertilizer application. The analyses provided a range of peat CO_2 emission estimates under smallholder management for an active conversion district in Jambi province.

Chapter 5 presents palm oil production in Indonesia from a green growth perspective or carbon footprint analyses if the palm oil is used for biofuel feedstock. This chapter analyses the level of fertilizer application in its relation to production and footprints, to derive the level of intensification that can minimize the footprint per unit biofuel, as answer to research question 4.

Chapter 6 explores intercropping scenarios in oil palm through simulations of tree-soil-crop interactions in water, nutrient and light capture. It compares the performance expected from various mixed oil palm systems as diversification strategy to increase farmer benefit and to reduce the carbon footprint, as answer to research question 5. Results are used to calculate a Land Equivalent Ratio for multifunctionality. By modifying the weighting factors for various functions this can be used to represent various stakeholder perspectives on mixed oil palm systems and support decisions on adoption of mixed oil palm systems. Beyond the carbon footprint per unit product, systems can be compared for efficient use of land (LER or Net Present Value (NPV)), for minimizing disturbance of water flows or nitrogen loading of the environment, for high returns to labour, for risk and for cost-benefit ratios, depending on global versus local perspectives and on views on labour, land or financial investment as primary ‘production factor’.

To close this thesis, chapter 7 discusses key findings, presents integration of all the chapters, and implications of the key finding of this thesis.

Chapter 2

Aboveground carbon stocks in oil palm plantations and the threshold for carbon-neutral vegetation conversion on mineral soils[4]

[4] *This chapter was published as*
Khasanah N, van Noordwijk M, Ningsih H. 2015. Aboveground carbon stocks in oil palm plantations and the threshold for carbon-neutral vegetation conversion on mineral soils. Cogent Environmental Science 1: 1119964

Abstract

The carbon (C) footprint of palm-oil production is needed to judge emissions from potential biofuel use. Relevance includes wider sustainable palm oil debates. Within life cycle analysis, aboveground C debt is incurred if the vegetation replaced had a higher C stock than oil palm plantations. Our study included 25 plantations across Indonesia, in a stratified study design representing the range of conditions in which oil palm is grown. From allometric equations for palm biomass and observed growth rates, we estimated the time-averaged aboveground C stock for 25-year rotations and 95%-confidence intervals to be 42.07 (42.04-42.10) Mg C ha^{-1} for plantations managed by company on mineral soil, 40.03 (39.75-40.30) Mg C ha^{-1} for plantations managed by company on peat, and 37.76 (37.42-38.09) Mg C ha^{-1} for smallholder oil palm on mineral soils. Oil palm can be established C debt-free on mineral soils with aboveground C stocks below these values; neutrality of mineral soil C pools was documented in a parallel study. Acknowledging variation in shoot:root ratios, the types of vegetation that can be converted debt-free to oil palm include grasslands and shrub, but not monocultural rubber plantations, rubber agroforest, and similar secondary or logged-over forests of higher C stock.

Key words: biomass, allometric equation, footprint, Indonesia sustainable palm oil, time-averaged carbon stock

2.1. Introduction

Oil palm (*Elaeis guineensis*) plantations and their expansion may well be the driver of deforestation in Indonesia that has the highest degree of public scrutiny (Sheil et al., 2009; McCartney, 2010; Carlson et al., 2012). In 1935, Indonesia became the global leader in palm-oil export, with a plantation area of 74,000 ha (Rowaan, 1936). Seventy-five years later it re-gained the number one position that it had lost to Malaysia, with a planted area of over 8 Mha, 100 times more than in 1935, but still less than 5% of its 193 Mha of land. Further expansion is planned but needs to reconcile with environmental regulations and consumer concerns.

The Renewable Energy Directive (RED) of the European Union includes a commitment to substitute part of the Union's transport fuel with biofuels as an environmentally friendly alternative to fossil fuels. For diesel engines, biofuels can be derived from vegetable oils such as palm oil, rapeseed and soybean (Demirbas, 2007; Tan et al., 2009). Similarly, environmental authorities in the USA have formulated standards for a minimum degree of net emission reduction for biofuel use (EPA, 2010). Currently, more than 80% of the world biodiesel production derives from rapeseed oil. However, palm-oil production costs are lower than that of other vegetable oils (Thoenes, 2006; Tan et al., 2009) and increased demand for palm oil as a source of biodiesel can be expected, if environmental regulations and import restrictions allow. Demand of palm oil has increased, as it is a source of fats and oil for food products (Tan et al., 2009) as well as biofuel feedstock to replace fossil fuel (Reijnders and Huijbregts, 2008; Tan et al., 2009). These multiple types of use have promoted expansion of oil palm plantation not only in Indonesia but also in Malaysia (Barlow et al., 2003; Koh and Wilcove, 2008; Danielsen et al., 2009), and at more modest scale elsewhere in the humid tropics. Indonesia and Malaysia still represent 90% of global production and trade of palm oil (Thoenes, 2006). Environmental issues in expansion of oil palm plantations include loss of biodiversity and the net emission of carbon dioxide per unit product, especially when peatlands are used and high carbon-stock forests are converted (Koh et al., 2008; Reijnders and Huijbregts, 2008). Carbon debts incurred at establishment of oil palm plantations can take decades or centuries to repay, depending on subsequent productivity, or have infinite pay-back times on peat soils where recurrent CO_2 emissions exceed the possible emission saving from the fossil fuel for which it was substituted (Germer and Sauerborn, 2008; Gibbs et al., 2008; Searchinger et al., 2008; Danielsen *et al*., 2009).

While the debate on biofuels has focused on a comparison of default characteristics between commodities, the 'management swing potential', or difference in environmental profile of a single commodity depending on the location and the way it is grown is now recognized (Davis et al., 2009, 2013). Based on current estimates, palm oil has the widest 'swing potential' as it is both among the best and the worst of current biofuels in terms of potential for emission saving. If oil palm is grown on lands already deforested, it is among the best (Hassan et al., 2011; George and Cowie, 2011; Choo et al., 2011; Siangiaeo et al., 2011). However, when it is grown on deeply drained peat soils converted from forest, it is among the worst (Sheil et al., 2009; Adachi et al., 2011; Nogueira, 2010; Davis et al., 2013). The wide swing potential is a challenge for current regulators who seek a single average value as characteristic per commodity. A single average value per commodity is needed for thresholds that can be used to certify the segments of the production system that meet environmental standards, as an alternative to treating all uniformly. In a life-cycle analysis, the potential carbon-debt incurred at land-use conversion (Fargione et al., 2008), the recurrent emissions in the production phase (linked to fertilizer use, drainage of wetlands and peat, among others), and the transport and processing phases jointly contribute to an overall footprint per unit product (Reijnders, 2011). We will here focus on thresholds for "carbon-neutral" or "debt-free" land conversion, derive the aboveground time-averaged C stock of oil palm plantations that can be used in the carbon-debt calculations within life cycle analysis. The life cycle concept, however, cannot be easily applied to vegetation with low management intensity or where the balance between continued degradation and recovery cannot be predicted. In practice, we used the average of measured values for a certain land cover class as its time-averaged value in such cases. Apart from accountability for recurrent emissions from fertilizer use and soil carbon loss (Khasanah et al., 2015a), the footprint of oil palm includes terms for the aboveground carbon debt due to conversion ($C_{AGB,P}$ - $C_{AGB,T}$), with $C_{AGB,P}$ the aboveground carbon stocks preceding conversion and $C_{AGB,T}$ the time-averaged value after conversion.

As an initial estimate of the time-averaged carbon stock of oil palm, Dewi et al. (2009) proposed a value of 40 Mg C ha^{-1}, based on a limited data set. If shoot:root estimates for oil palm can be assumed to be (at most) equal to that for other vegetation (Jourdan and Rey, 1997), the carbon-debt-free status applies for all biomass, with no changes in soil organic carbon (Khasanah et al., 2015a). However, the initial estimate of 40 Mg C ha^{-1} did not represent the full range of conditions found in oil palm plantations in Indonesia, as regards soil type and plantation management (nucleus, plasma, and independent smallholder). The term nucleus is used for the core area of a plantation managed by a company; the term plasma refers to surrounding areas of plantation that are initially managed by the core company during establishment, usually until the early production stage (4-5 years old) and then transferred to the farmers who own the land. In many cases, the plantation obtained land that was under community control and returns part as plasma to individual farmers. The term independent is used for a smallholding plantation managed by a farmer on land they control (whether legally owned or not) (Santoso, 2010), using planting material obtained in markets and selling produce to intermediaries or mills, without long-term contract. Koh et al. (2012) used an estimate of 24 Mg C ha^{-1} for aboveground biomass of oil palm averaged over a 25-year rotation, based on a limited data set of Murdiyarso et al. (2010).

A recent HCS+ proposal for self-regulation by the oil palm industry suggested that 75 Mg C ha^{-1}can be the threshold value for above-ground carbon (AGC) of land converted to oil palm – claiming that oil palm converted from land with aboveground carbon stocks below that value can be carbon neutral (Raison et al., 2015). Carbon neutrality can be evaluated at multiple scales. At product level, carbon neutrality may imply a 'footprint' of zero, which is only achievable if there are gains in parts of the accounting sheet that offset the unavoidable emissions that are part of production and transport. Where palm oil is used as biofuel, offsets can be derived from the emissions avoided by not using fossil fuels, but only if the fate of these non-used fuels is deemed to be outside of accountability of the biofuel user. Even so, carbon neutrality of biofuels is not feasible, and existing standards, such as those of the European Union and USA Environmental Protection Agency only require partial emission reduction relative to fossil fuel use, not carbon neutrality. A simpler form of carbon neutrality applies to the way land use and land use change is accounted for in IPCC compliant national accounting systems. Tier I and Tier II accounting systems, using global defaults and nationally appropriate values, respectively, calculate emissions from a comparison of time-averaged carbon stocks. Averaging the C stock over the life cycle of a land use system is appropriate if a landscape can be expected to contain proportional areas of each age class. That assumption is relaxed in Tier III accounting of losses and gains, but at substantially increased data demand and marginal change of the bottom line of the accounting system in most cases. Carbon neutrality in this sense is obtained when the time-averaged C stock of a new land use system is equal to that of its predecessor. To apply this concept, we thus need to quantify the C stock of oil palm over all stages of its life cycle. If the value obtained is less than 75 Mg C ha^{-1} the HCS proposal can be rejected in its claim of securing carbon neutrality. However, if accountability extends to a larger area than that planted, there may be compensation for carbon debts in the planted area as long as other areas are effectively recovering and achieving higher C stocks (Raison et al., 2015). Even so, the aboveground time-averaged C stock of oil palm is a critical value for any landscape-level calculations.

We thus initiated research to measure and assess the aboveground time-averaged C stock of oil palm across the three main management conditions found in Indonesia: nucleus, plasma, and independent smallholder. This study aimed to:

1. establish an allometric equation between oil palm height (m) and aboveground biomass (Mg per palm) applicable to different oil palm production conditions in Indonesia, potentially differentiated by soil type and management regime (nucleus, plasma, and independent smallholder),
2. estimate growth rates of aboveground oil palm biomass (Mg ha^{-1} $year^{-1}$) based on actual stand density and palm heights under the same range of conditions,

estimate the time-averaged aboveground C stock of oil palm plantations (Mg C ha^{-1}) including oil palm biomass, understory vegetation, standing litter stock and necromass stock, differentiated by the growing conditions.

2.2. Materials and Methods

2.2.1. Oil palm characteristics relevant to the study design

Oil palm (*Elaeis guineensis*) is an African palm that yields oil from the pulp of the fruit as well as from the kernels (seed) (Corley and Tinker, 2003) and is mostly planted from hybrid (*Tenera* = *Dura* × *Pisifera*) seed. It typically has a life cycle of about 25 years, when harvesting becomes difficult as the columnar trunks exceed 20 m. Oil palm is unbranched and the planting pattern (typically between 128 to 148 palms ha^{-1}) is designed to secure a closed canopy once pinnate-leaved frond reach their normal length of 3 – 5 m (Henson, 1999). It has a rigid development pattern with increments in stem height for every new frond that emerges in a 3-4 weekly interval, over time developing a flower in its axil that can, if not aborted due to a dry period, become a fruit bunch. The frond associated with a harvestable fruit bunch is removed, leaving a frond base on the stem that over time will decay (Henson, 2004). Under suboptimal conditions of water and/or nutrient supply, all flowers in newly developing inflorescences become male and the number of harvestable fruit bunches declines. To secure female flower and fruit development, high levels of fertilizer are typically used (Pahan, 2006), while locations with more than 1-2 dry months are sub optimal. On peat soils buffered water supply in dry periods is associated with lack of mechanical support, unless the peat is intensively drained and therefore sensitive to drought as well as rapidly decomposing and emitting CO_2 in the process. In the first year(s) after planting, there is enough light penetration to ground level for a leguminous cover crop to develop, which is shaded out over time and contributes nitrogen to the system in the process. Smallholders may intercrop with annual food crops in the first three years, instead of using a cover crop.

In contrast to rubber, coffee and cacao, the initial expansion of oil palm in Southeast Asia has been based on large-scale, centrally managed plantations, as the fruits need rapid processing once harvested. As economies of scale favour mills that cater for a planted area of the order of 10,000 ha, financial investment is substantial and the political connection needed to acquire land and credit has favoured large scale schemes (Budidarsono et al., 2013). As acquisition of quality and trustable planting material is difficult for smallholders and the crop has a strongly negative response to suboptimal management, the company-controlled 'nucleus' plantation management model continue to dominate in areas of new oil palm expansion. However, over time smallholder oil palm has emerged in two ways: as contract farms in outgrower schemes ('plasma') around nuclear plantations, often a pre-requirement for land acquisitions by plantations (Budidarsono et al., 2013), but also, in areas where there are enough mills, as independents with flexible marketing arrangements. The management types (nucleus, plasma, and independent smallholder) differed (potentially) in fertilizer application, use of organic inputs (pruned fronds and empty fruit bunches), and understorey vegetation maintenance. These differences are likely to have impact on the growth rates and aboveground carbon stocks during the production cycle.

To provide the range of aboveground C stocks, we derived stratifiers at national level and at plantation or landscape level for a sampling scheme. These stratifiers represent current condition of oil palm plantation in Indonesia. At the national level, we had three stratifiers to sample plantation or landscape: 1) plantation or landscape history (derived from forest versus non-forest (other vegetation or from preceding oil palm), 2) soil type (mineral soils versus peat), and 3) the prevalence of oil palm in the surrounding area (<1, 1-5, 5-15%), assessed at provincial level, as areas of high oil palm prevalence are likely to represent a longer history of the crop, potentially selected for the most suitable climatic conditions, and may have the best knowledge and processing infrastructure. At the plantation or landscape level, we applied three stratums to sample oil palm stands: 1) plantation management (nucleus, plasma, independent smallholder), 2) soil type (mineral soils versus peat), and 3) age during the crops' life cycle.

2.2.2. Study and sampling design

2.2.2.1. Plantation or landscape selection

At the national level, the study was designed to sample plantation or landscapes that represent the primary variation in oil palm production environment in Indonesia. It was differentiated by the three stratifiers mentioned. Factorial combinations across the three strata led to 12 (= 3 × 2 × 2) clusters. As the study was part of a program designed to increase the capacity of the Indonesian oil palm sector to understand and assess its own carbon footprints, the selection of plantation or landscapes to be sampled in the various strata was based on voluntary nominations by plantation companies. As described in Khasanah et al. (2015a), all participating companies were guaranteed confidentiality of plantation-level data, while they all received a report in which their performance was compared with the data set. This procedure, managed by an agency associated with the Ministry of Agriculture, was chosen to protect commercially sensitive information and stimulate voluntary nominations.

While nominations for some categories (non-forest history on mineral soil) were readily obtained, peat-based plantations were underrepresented. Selection of plantation or landscapes was based on *a priori* information provided by the companies, which was not in all cases confirmed in the subsequent fieldwork. In the end, we were able to sample 8 of the 12 clusters identified, in a total of 25 oil palm plantation or landscapes surrounding a plantation agreeing to be part of the research (Table 2.1). Despite all efforts to secure access to the full range of conditions, willingness to participate may indicate that the company expected to represent "good practice" in oil palm management. The current data may therefore reflect what is possible in oil palm with current practice, rather than being the unbiased average of present conditions. Figure. 2.1 presents the spatial distribution of the selected 25 oil palm plantation or landscapes across Indonesia, in twelve provinces: 7 provinces in Sumatra (16 plantations), 4 provinces in Kalimantan (8 plantations), and 1 province in Sulawesi (1 plantation).

2.2.2.2. Plot selection within selected plantations or landscapes

Within each selected plantation or landscape in each cluster and in discussion with the plantation company hosting the study, a number of plots were selected, making use of the available range of conditions: 1) plantation management (nucleus, plasma, independent smallholders), 2) soil type (mineral soils versus peat), and 3) age during the crops' life cycle. In terms of preceding vegetation and soil type, multiple clusters could be sampled in some of the plantations or landscapes. In most cases, there was limited choice in the plot ages, depending on the period since the nucleus plantation was developed. Table 2.1 presents the distribution of the selected 25 oil palm plantations or landscapes by cluster, as well as associated replicate plots (totalling 180 sampling plots), characterized by age and management style.

Table 2.1. Study design with the actual number of plots sampled across plot age, management style, preceding vegetation, soil type and oil palm prevalence in the surrounding province

Plantation parameters			Cluster	Number of plantation or landscape	Plantation management[1)]	Number of sampled plots per age category (year)			
Preceding land cover	Soil	Prevalence of oil palm (% of area in province)				0-8	9-16	17-25	Total
Forest	Peat	5–15	1	2	N	2	2	4	8
					P	1	-	-	1
					I	1	-	-	1
		1–5%	2	2	N	4	-	-	4
					P	-	-	-	-
					I	-	-	-	-
		<1%	3	1	N	5	4	1	10
					P	-	1	-	1
					I	-	-	-	-
	Mine-ral	5–15	4	3	N	2	5	10	17
					P	-	2	2	4
					I	-	-	-	-
		1–5%	5	3	N	6	8	7	21
					P	1	2	-	3
					I	2	1	-	3
		<1%	6	9	N	16	20	7	43
					P	4	4	1	9
					I	10	2	-	12

Preceding land cover	Soil	Prevalence of oil palm (% of area in province)	Cluster	Number of plantation or landscape	Plantation management[1)]	0-8	9-16	17-25	Total
Non-forest	Peat	5–15	7	-	-	-	-	-	-
		1–5%	8	-	-	-	-	-	-
		<1%	9	-	-	-	-	-	-
	Mine-ral	5–15	10	2	N	4	5	2	11
					P	-	-	-	-
					I	-	-	-	-
		1–5%	11	3	N	2	8	6	16
					P	4	6	3	13
					I	2	1	-	3
		<1%	12	-	-	-	-	-	-
		Total		25		66	71	43	180

Column groups: "Plantation parameters" spans Preceding land cover, Soil and Prevalence; "Number of sampled plots per age category (year)" spans 0-8, 9-16, 17-25 and Total.

1) (N = nucleus, P = plasma, I = independent)

Table 2.1 presents the classifications after the survey, rather than that based on *a priori* information. The 180 plots selected included 86% on mineral soil and 14% on peat, with 70%, 19% and 12%, under nucleus, plasma, and independent smallholder management, respectively. The age groups 0-8 years, 9-16 and 17-25 years were represented by 34%, 41% and 25% of the samples. For the plot distribution, 110 plots (61%), 65 plots (36%) and 5 plots (3%) were in Sumatra, Kalimantan and Sulawesi, respectively. This means our sample under represented Sumatra and over represented Kalimantan relative to data on planted area (64% in Sumatra (of which 53% in the two high-prevalence provinces of North Sumatra and Riau), 32% in Kalimantan and 4% elsewhere (with Sulawesi as the most important area), according to data for 2013 of the Tree Crop Estate Statistics of Indonesia (Directorate general of estate crops, 2014).

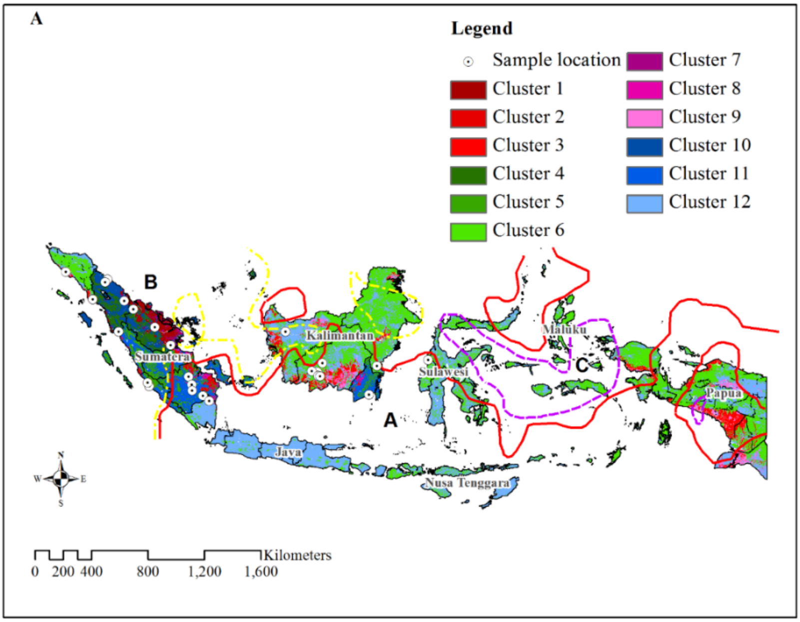

Figure 2.1. Spatial distribution of 25 oil palm plantations or landscapes selected for inclusion in this study. Notes: The colour definition refers to cluster definition in Table 2.1. Clusters 7, 8, 9, 12 were not sampled as there is no oil palm plantation under those clusters. Climate division based on Aldrian and Susanto (2003), Region A in red solid line, Region B in yellow short dashed line and dot, and Region C in purple long-dashed line.

The clusters 7-9 that could not be sampled would represent oil palm on peat not derived from a preceding forest, which most likely is very rare in Indonesia; cluster 12, plantations on mineral soil derived from non-forest in an area with very low oil palm prevalence, is similarly scarce in Indonesia. While the target of a fully balanced factorial design could not be achieved in the process as described, the data provide ample opportunity to study the importance of each of the stratifiers in isolation, and their possible interactions in the clusters (strata) of direct relevance.

2.2.3. Plantations or landscapes description

Based on the intra- and inter-annual variation in rainfall and the statistical correlation of rainfall with sea surface temperatures in the Pacific and Indian Ocean, Aldrian and Susanto (2003) recognized three climatic regions in Indonesia. Oil palm is currently grown in the two wettest of these regions (Figure 2.2), with region B that is in northwest Indonesia and stretches from northern Sumatra to north-western Kalimantan is a region where oil palm plantation mostly concentrated. While mean annual rainfall (2600 $mmyear^{-1}$) and the number of months with rainfall over 200 mm is 7 months is similar between regions A and B, the pattern of interannual variability differs. Region B has a tendency to a bimodal pattern without months of less than 100 mm rainfall on average, combined with low sensitivity to El Nino patterns of interannual variability in the Pacific and modest response to the Indian Ocean dipole (Niedermeyer et al., 2014) have created a climate in northern Sumatra that is eminently suitable for oil palm. Region A is in southern Indonesia and stretches from south Sumatra to Timor, southern Kalimantan, Sulawesi and part of Papua. Its unimodal rainfall has a relatively dry period between May to September that in interaction with interannual variability can reduce oil palm yields, depending on the degree of water buffering by the soil. The highest 'oil palm prevalence' at provincial level (5-15%) coincided with climate region B for this study, while the data for 'oil palm prevalence below 5% where derived from climate region A.

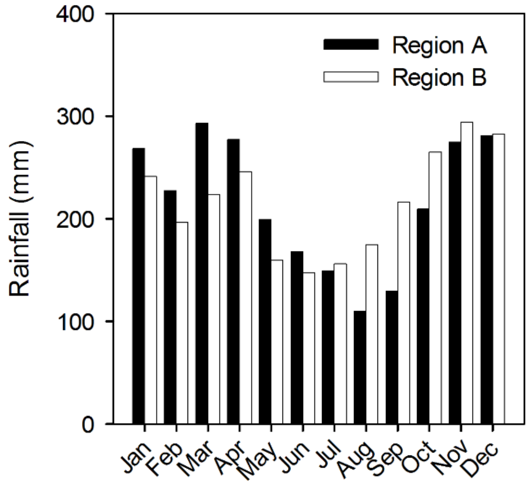

Figure 2.2. Mean monthly rainfall of all plantations presented based on climate regions A and B as derived by Aldrian and Susanto (2003).

With regard to soil type, 86% of the sample plots had mineral soil, with 55% and 19% categorized as Ultisols and Inceptisols, respectively. Other soil types encountered less frequently were Spodosols, Oxisols and Entisols. Across these soil types, variation in soil texture and pH account for differences in soil carbon content that can exceed the effects of land cover (forest, non-forest categories) (van Noordwijk et al., 1997). Soil carbon data obtained at plot level in the mineral soils are described in a parallel manuscript (Khasanah et al., 2015a)).

2.2.4. Sampling methodology

2.2.4.1. Establishing allometric equation for estimating oil palm biomass

Specific efforts were made to derive allometric equation between palm height and palm biomass (as stem diameter is a poor predictor of biomass in palms, Dewi et al., 2009 and Khalid et al., 1999) appropriate for the full set of conditions.

In developing an allometric equation for estimating oil palm biomass, 10 oil palms were selected, measured and sampled in each of the 180 plots, using partially destructive sampling. Selection of the 10 oil palms in each plot followed the standardized selection scheme used in establishing Leaf Sampling Units (LSU) for fertilizer recommendation (some of the details varied between plantation companies). The total biomass of oil palm was estimated by partitioning the biomass into three components: trunk; frond; and old frond base remaining on the stem.

Trunk biomass, trunk biomass was estimated by measuring trunk height (from ground level to the base of leaf number 41 (counting from most recently emerged frond), which under normal management is the lowest leaf maintained in the canopy (if leaves are removed after harvest of the fruit bunch) and trunk diameter at 150 cm trunk height. A cylindrical shape of the trunk allowed an estimate of trunk biomass as:

$$Y = 0.25 \times \pi \times \mathrm{D}^2 \times H \times \rho \qquad [1]$$

where, Y = trunk biomass (kg per palm), H = palm height (m), D = palm diameter (m), and ρ = wood density (kg m^{-3}) (with average value 395) (Porankiewicz et al., 2006).

Frond biomass, frond biomass was estimated by calculating the total number of fronds and taking a sample of frond number 17 to determine average dry weight of a representative single frond (Corley and Tinker, 2003).

$$FB = N \times DW \qquad [2]$$

where, FB = frond biomass (kg per palm), N = number of frond, DW = weight of single frond (kg) = 1.146 × ($DW_{petiole}$ + DW_{rachis} + $DW_{leaflet}$), 0.146 = correction factor, part of petiole still attached to the trunk, with estimation based on three samples.

Frond bases biomass, frond bases biomass was estimated by calculating cumulative frond bases and taking samples of three frond bases to determine averaged dry weight of single frond bases.

$$FB_s = N \times DW \qquad [3]$$

where, FB_s = total frond bases biomass (kg per palm), N = number of frond bases still present, DW = weight of a single frond base (kg).

Allometric equation, all biomass components were combined and a regression equation was established on the basis of trunk height, testing linear ($Y=Y_{mean} + b \times (X - X_{mean})$) and power function ($Y = Y_{mean} \times (X/X_{mean})^b$) models.

2.2.4.2. Estimating aboveground carbon stock of oil palm plantation

In the 25 selected plantations or landscapes the full range of existing land cover and land use types was sampled for its aboveground carbon stocks, using standard methods (Hairiah et al., 2011). However, we had to adjust the standard methods for oil palm considering the regularly spaced planting pattern, the specific 'management zones' around each palm, and the non-standard tree architecture.

Estimation of the aboveground carbon stock of oil palm plantations (Mg C ha^{-1}) includes four pools: oil palm biomass; standing litter stock comprising pruned fronds; understorey vegetation; and preceding necromass stock (dead wood) (Dewi et al., 2009).

Oil palm biomass, trunk height of selected 24 oil palms was measured in each plot and biomass was estimated using the allometric equation developed here. The selection of 24 oil palms in each plot also followed the standardized scheme for establishing Leaf Sampling Units for fertilizer recommendation. Results were scaled up to a hectare basis by multiplication with actual tree density 138 palms ha^{-1}.

Understorey vegetation and standing litter stocks, the basic methods were as described in Hairiah et al. (2011). Understorey vegetation and litter stocks were estimated by taking samples using a 0.5 m x 0.5 m sample frame. The sampling was done around 10 palms in four management zones: 1. weeded circle, often used for fertilizer application in young stages; 2. interrow/grass zone, in some cases in nucleus plantations used for application of empty fruit bunches (EFB) returned from the mill; 3. frond stack where pruned leaves are piled up (if not spread throughout zone 2) and decompose; and 4. harvest paths, subject to compaction. Details had to be adjusted to local management practice. All of the understorey and litter inside the sample frame were removed and then separated between stem and leaves before being dried at 80°C for 48 hours and weighed. A weighted mean for the four management zones was derived based on the proportions of each management zone under the specific situation found in the plantation.

***Necromass stocks*,** necromass was sampled in a transect across the plot, adjusted to local conditions where bulldozer clearing had established regularly spaced windrows. Height and diameter of the dead wood was measured and the necromass production was estimated using the following equation:

$$DW = (\pi/4) \times \rho \times H \times D^2 \qquad [4]$$

where, DW is dry weight of dead wood (g), ρ is the wood density (g cm^{-3}), estimated from live wood density for the trees involved plus the degree of decomposition assessed by handling it; H is height/length of dead tree (cm); D is diameter of dead tree (cm). Results were scaled up to a hectare basis using the effective sampling transect area.

The carbon stock of each pool then was estimated by multiplying the biomass of each pool with assumed organic carbon content. Organic carbon contents were assumed to be 0.47 for palm biomass and understorey vegetation, 0.5 for necromass (dead wood) and 0.4 for the standing litter stock (conform the standards used by the European Commission, 2010).

2.2.5. Time-averaged aboveground carbon stock of oil palm plantation

Time-averaged aboveground biomass of oil palm was estimated by developing an allometric equation of palm biomass (Mg ha^{-1}) as a function of palm age (plot-level assessment of mode, ignoring possible gap filling in early stages) (year). A similar procedure was applied to estimate time-averaged necromass stock. While the time-averaged understorey biomass and standing litter stock was derived from average value of 180 measured plots.

The time-averaged total aboveground carbon stock of oil palm plantation was then estimated comprehensively by developing an allometric equation of total carbon stock (Mg C ha^{-1}) of plantation, taking into account all pools of the plantation as a function of palm age (year).

Confidence intervals of the time-averaged total aboveground carbon stock of oil palm plantation were estimated using the following steps:

1. Derive a random b of the linear or power form of the palm allometric equation using normal probability distribution:
   $random\ b = N(b, se)$
   where b is an intercept of the linear or power equation and se is the standard error estimate derived for this equation. The data had been centralized before regression analysis, so the intercept could be derived as $Y_{mean} - b \times X_{mean}$ for linear equations and as $Y_{mean}/(X_{mean})^b$ for power curves,
2. Estimate plot-level palm biomass by applying the random b to all palms measured, add data on the understorey, necromass and litter,
3. Repeat steps 1 and 2 for all plots in the current category of soil and management type,
4. Derive the parameters of a total aboveground C stock regression on plot age for this part of the data set and evaluate the time-averaged C stock for a 25-year rotation, as:
   $$C_{AGB,T} = Y_{mean} - b \times X_{mean} + b \times \frac{t_{cycle}}{2} \quad [5]$$
   where Y_{mean} is mean of measured total aboveground carbon stock, X_{mean} is mean of measured age of palm and t_{cycle} is the duration of one cycle of oil palm (here taken as to be 25 years),
5. Repeat step 4 100 times and report mean and ± 1.96 × standard deviation as 95% confidence interval,
6. Repeat steps 4 – 5 for other combinations of soil and management types.

2.3. Results

2.3.1. Allometric equation to estimate oil palm biomass

Figure 2.3 correlates palm height (m) and palm biomass (Mg per palm) for different soil types. A power model for palm biomass (Figure 2.3B) proved to account for a slightly larger fraction of the variance than a linear increment model for palms on mineral soils. On peat soils, however, the linear equation (Figure 2.3A) accounted for a great fraction of variance accounted for (as seen from the r^2 value).

The allometric data indicated no significant difference owing to preceding land cover and plantation management, but some differentiation owing to soil type. Oil palm growth on peat had a similar biomass increment per unit height increment to that on mineral soil (about 0.09 Mg per m palm height), but had a 30% lower intercept in the resulting linear equation. Applying the power equation derived for mineral soil conditions and a linear regression for peat soil palms, suggests that palm biomass relative to palm height is higher on peat than on mineral soil for the first three years after planting (while tree height increments per time are less on peat due to lack of mechanical stability). For further calculations, we used the linear regression for both mineral and peat soils.

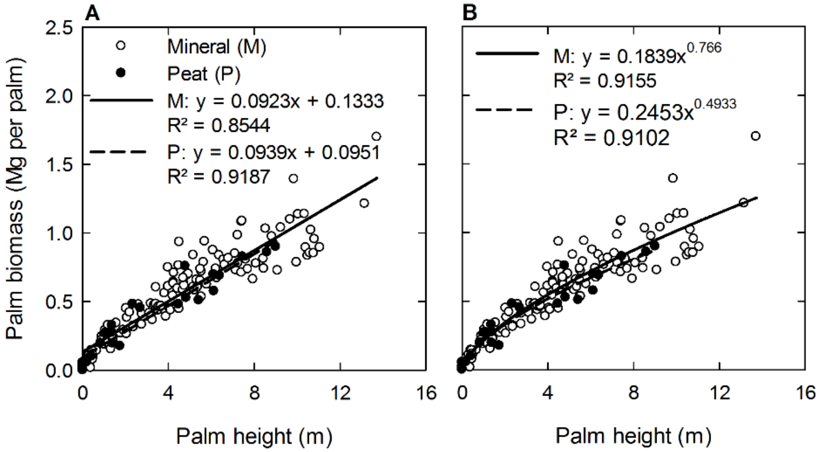

Figure 2.3. Linear model (A) and power model (B) between palm height (m) and palm biomass (Mg per palm) at different soil types.

2.3.2. Time-averaged aboveground carbon stock

2.3.2.1. Time-averaged aboveground carbon stock of each pool

Oil palm, Table 2.2 presents different equations for estimating palm biomass (Mg ha^{-1}) as a function of palm age (year). The first model is based on linear regression while the second model is based on a power regression. Under nucleus management, both on mineral and peat soils, the power equation accounted for a larger part of the variance, while under plasma/independent management on mineral soil (no data for peat soils in this class), the linear equation had a higher r^2 value.

Figure 2.4 shows the correlation between age of palm (year) and palm biomass (Mg ha^{-1}) with different soil types and plantation management and presents a linear regression for palm growth on mineral soils under plasma/independent management conditions and a power regression for palm growth on mineral and peat soil under nucleus management as the chosen, best-performing model. The chosen model was used to estimate time-averaged aboveground carbon stock of oil palm over one cycle of a plantation (typically 25 years).

The aboveground accumulation in oil palm biomass under nucleus management was estimated to be 5.85 Mg ha^{-1} year^{-1} and 4.88 Mg ha^{-1} year^{-1} for oil palm on mineral and peat soils, respectively (Figure 2.4). The aboveground accumulation of oil palm biomass on mineral soil under plasma and independent management was estimated to be 5.35 Mg ha^{-1} year^{-1} or 12.5% lower compared to nucleus management (Figure 2.4).

Taking this growth rate and using carbon presented in section 2.4, the time-averaged carbon stock of oil palm over one life cycle (25 years) under nucleus management was found to be 38.78 ± 0.17 Mg C ha^{-1} and 37.30 ± 0.57 Mg C ha^{-1} growth on mineral and peat soils, respectively (Table 2.2). Time-averaged carbon stock of oil palm under plasma/independent management and growth on mineral soil was found to be 35.28 ± 0.38 Mg C ha^{-1}.

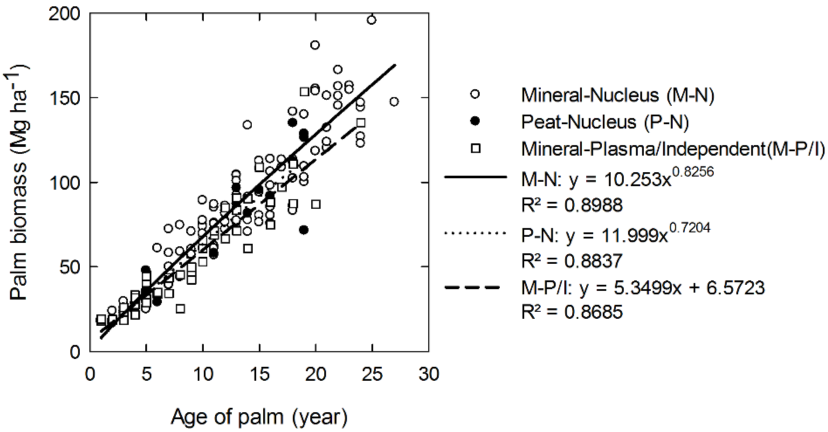

Figure 2.4. Correlation between age of palm (year) and palm biomass (Mg ha^{-1}) under different soil type and plantation managements

Understorey**,** Figure 2.5A shows the correlation between age of palm and understorey biomass (Mg ha^{-1}) under different plantation management styles. The data indicated no clear pattern of understorey biomass with increasing age of palm and there is no statistically significant difference between soil types, estate management and initial land cover to understorey vegetation. By using default carbon concentrations (section 2.4), the time-averaged carbon stock of understorey over one life cycle of an oil palm plantation (25 years) is about 0.52 ± 0.45 Mg C ha^{-1} (Table 2.2).

Standing stock of litter**,** Figure 2.5B shows the correlation between age of palm and litter production (Mg ha^{-1}) under different plantation management styles. Similar to understorey, litter production also indicates no clear pattern with increasing age of palm. By using carbon content presented in section 2.4, the time-averaged carbon stock of standing stock of litter over one life cycle of an oil palm plantation (25 years) under different management styles is significantly different: 2.36 ± 2.40 Mg C ha^{-1}, 1.83 ± 1.21

Mg C ha^{-1} and 0.96 ± 0.49 Mg C ha^{-1} for nucleus, plasma, and independent smallholder management, respectively (Table 2.2). Where this practice is used, recycling of empty fruit bunches into the plot contributes to a higher standing stock of litter, but its contribution to the total carbon stock of the plantation is small.

Necromass, necromass/dead wood was only found in plantations with forest as the previous land cover. Figure 2.6 indicates a weak negative trend of necromass/dead wood with time owing to decomposition (Mg ha^{-1}) suggested by low R^2 value (0.0279), however, the average rate of dead wood decomposition around 0.254 Mg ha^{-1} year^{-1} can be taken for further calculation of time-averaged C stock. Taking this decomposition rate and using 0.5 as its C content, the time-averaged carbon stock of necromass over one life cycle of an oil palm plantation (25 years) is around 3.42 ± 0.47 Mg C ha^{-1} (Table 2.2).

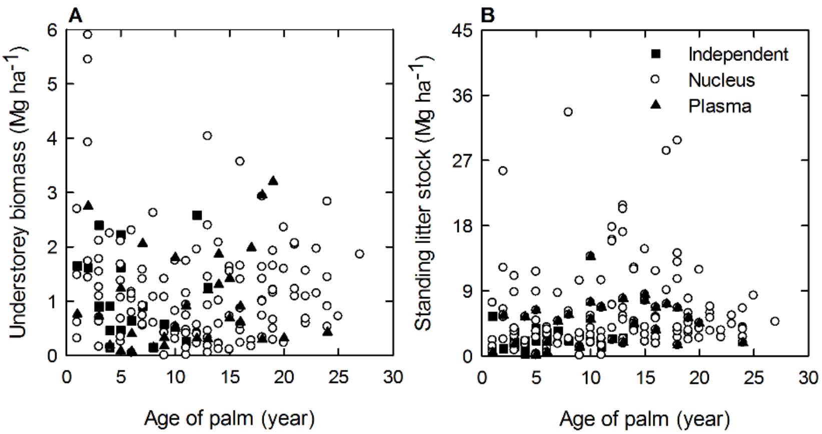

Figure 2.5. (A) Correlation between age of palm and understory; and (B) Standing litter stock. Both expressed in (Mg ha^{-1}) under different plantation management conditions.

2.3.2.2. Time-averaged aboveground carbon stock of oil palm plantation

Table 2.3 presents different model (linear and power) to estimate the time-averaged total aboveground carbon stock of oil palm plantations with different soil types and plantation management. Both in mineral and peat soil in all plantation management, linear model has higher r^2. The time-averaged carbon stock of oil palm under nucleus management and its 95% confidence interval is 42.07 (42.04 – 42.10) Mg C ha^{-1} and 40.03 (39.75 – 40.30) Mg C ha^{-1} on mineral and peat soils, respectively. The time-averaged total aboveground carbon stock of oil palm plantations established on mineral soil under plasma or independent management was estimated at 37.76 (37.42 – 38.09) Mg C ha^{-1}.

Table 2.2. Regression coefficients of two growth models for palm biomass Y (Mg ha^{-1}) based on age A (years after planting) and the resultant time-averaged carbon-stock estimate for a 25-year rotation of oil palms, understorey, standing litter and necromass.

Growth equation	Soil type	Plantation management[1)]	a	b	R^2	Time-averaged carbon stock per pool (Mg C ha^{-1})
Oil palms						
Model I: $Y = aA + b$	Mineral	Nucleus	6.1147	6.1917	0.8757	38.83 ± 0.03[2)]
		Plasma/independent	5.3499	6.5723	0.8685	35.28 ± 0.38[2)]
	Peat	Nucleus	5.6104	6.5672	0.8758	36.41 ± 0.33[2)]
Model II: $Y = aA^b$	Mineral	Nucleus	10.253	0.8256	0.8988	38.78 ± 0.17[2)]
		Plasma/independent	11.311	0.7203	0.852	34.85 ± 0.49[2)]
	Peat	Nucleus	11.999	0.7204	0.8837	37.30 ± 0.57[2)]
Understorey						
		Nucleus				0.52 ± 0.47[3)]
		Plasma				0.46 ± 0.43[3)]
		Independent				0.50 ± 0.35[3)]
		Average				0.52 ± 0.45[3)]
Standing stock of litter						
		Nucleus				2.36 ± 2.40[3)]
		Plasma				1.83 ± 1.21[3)]
		Independent				0.96 ± 0.49[3)]
Necromass (dead wood)						
		Ex-forest	10.368	-0.2542	0.0279	3.42 ± 0.47[2)]

1) Attribute followed by the same letter are not significantly different at $p<0.05$
2) Time-averaged carbon stock over one cycle (25 years) ± standard deviation.
3) Averaged over a cycle of 25 years ± standard deviation of plot-level measurements

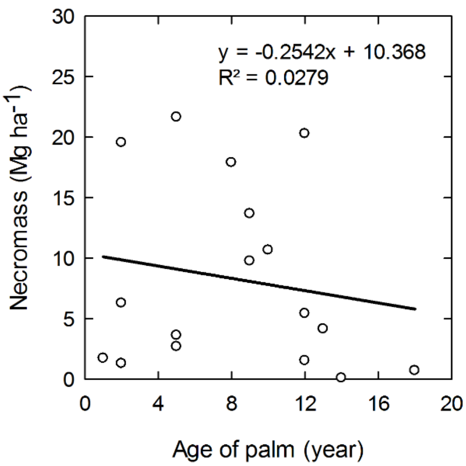

Figure 2.6. Correlation between age of palm and necromass (Mg ha^{-1}).

2.4. Discussion

Biomass accumulation of oil palm on mineral and peat soils as a function of trunk height can be well described by a linear regression equation. These results were consistent with other studies reported by Khalid (1999), Corley and Thinker (2003) and Henson (2004). Overall, this study revealed that soil type and plantation management styles result in different time-averaged carbon stocks in oil palm plantations. Time averaged C stocks range from 37.8 to 42.1 Mg C ha^{-1} for the clusters described here. These values include the frond bases attached to the trunk, understorey vegetation, litter production and necromass; and 90 – 95% of the time-averaged aboveground carbon stock is in the oil palm biomass. This figure is based on an average density of 138 palms per ha and will have to be modified for plantations with significantly lower palm density, or different rotation length.

If we assume, in the absence of a full assessment of stratum weights, that the average across our samples in the various clusters represents typical conditions for Indonesian palm oil production, the resulting estimate of time-averaged C stock is slightly higher than obtained in previous studies. Previous studies have been generally based on smaller data sets. Germer and Sauerborn (2008) estimated a value around 29.69 Mg C ha^{-1} (based on 51 studied plots); Henson (2003) 36 Mg C ha^{-1}; Palm et al. (2004) 36.4 Mg C ha^{-1}; and Dewi et al. (2009) 36.95 Mg C ha^{-1}(based on 13 studied plots). Palm density, the inclusion of all aboveground carbon-stock pools, soil types and variations in management can be major sources of different results. Most of the literature did not provide complete information on the terms included. The present data set has a much broader empirical basis than the values published before.

A value of 36 Mg C ha^{-1} has been used as basis for estimates of historical carbon emissions due to oil palm development in Southeast Asia (Agus et al., 2013b). For ease of use and in view of the level of precision of terrestrial carbon-stock data, we propose that a value of 40 Mg C ha^{-1} in aboveground stocks can still be used as the threshold for carbon debt-free land conversion. For that reason, our results lead to a clear rejection of the 75 Mg C ha^{-1} proposal of Raison et al. (2015) as threshold value for aboveground carbon (AGC) of land that can be converted to oil palm with a claim to be carbon neutral at plot level. Whether or not landscape-level compensation can justify use of the term 'carbon neutral' is open to debate.

Existing data on shoot:root ratios suggest that oil palm is not substantially different from the 4:1 ratios assumed for humid tropical forest vegetation on mineral soils (IPCC, 1996), although in young palms ratios can be higher (Syahrinudin, 2005) and in mature forests lower (Mokany et al., 2006). The aboveground threshold for debt-free conversion can, with assumed equivalence of shoot:root ratios, also be applied to total biomass. Consequences of oil palm management on soil carbon, as further step in the life cycle assessment of a carbon footprint, are discussed in a companion paper (Khasanah et al., 2015a). The results of soil carbon study suggested that there is no change in mineral soil carbon stock under oil palm plantations derived from forest or non-forest in Indonesia.

The types of vegetation that can be converted debt-free to oil palm include grasslands (3.4 Mg C ha^{-1}) and shrub (34.4 Mg C ha^{-1}), but not monocultural rubber plantations (44.1 Mg C ha^{-1}), rubber agroforest (176.6 Mg C ha^{-1}), and similar secondary or logged-over forests (65.4 – 218.8 Mg C ha^{-1}) of higher C stock (Khasanah et al., 2012; Hairiah et al., 2011; Agus et al., 2013a). In view of variation of the shoot:root ratios, grassland have shoot:root ratios around one third of oil palm (0.7 – 0.8) (Syahrinudin, 2005), however, aboveground biomass of grassland (3.4 Mg C ha^{-1}) is much less than oil palm.

According to Dewi [*pers comm*, November 2013] the land area that is considered suitable for palm oil and considered as green oil palm in Indonesia is substantial but does not fully allow for a doubling of the current oil palm area of 6.58 Mha, as planned by the Ministry of Agriculture. With a modest carbon debt of up to 20 Mg C ha^{-1} it is still possible to meet current EU RED thresholds and this may allow a doubling of the current area provided no other competing land uses take priority. In practice, oil palm is in some areas replacing paddy rice, as observed in Riau province (Budidarsono et al., 2013) and such conversion can be free of carbon debt, but is a sensitive issue in Indonesia's food security debate.

Table 2.3. Time-averaged total aboveground carbon stock of oil-palm plantations with different soil types and plantation management.

Growth equation	Soil type	Plantation management	a	b	R^2	Time-averaged total carbon stock ($Mg\ C\ ha^{-1}$)[1)]
Model I: $Y = aA + b$	Mineral	Nucleus	2.8167	6.8648	0.8478	42.07 ± 0.03
		Plasma/independent	2.5449	5.0007	0.8441	37.76 ± 0.33
	Peat	Nucleus	2.5822	7.074	0.8404	40.03 ± 0.27
Model II: $Y = aA^b$	Mineral	Nucleus	6.6671	0.7318	0.8426	42.32 ± 0.19
		Plasma/independent	6.5858	0.6615	0.8054	36.36 ± 0.54
	Peat	Nucleus	8.7558	0.5836	0.8161	41.71 ± 0.67

1) Averaged over a cycle of 25 years ± standard deviation of plot-level measurements

The dominance of relatively small land patches (25–100 ha) in the carbon-debt-free potential area suggests that future establishment of oil palm in these areas might have to adopt a small-scale production system, as has emerged in Southern Thailand, peninsular Malaysia, and Sumatra as a business model, rather than the pioneer large-scale models used in Sabah, Sarawak, and Kalimantan on the island of Borneo. Most of the larger patches identified were located in West Kalimantan province. A shift to oil palm production that meets environmental standards may coincide with a shift in the socio-economic characteristics of oil palm production in Indonesia (Budidarsono et al., 2013).

Beyond the carbon debt based on a comparison of aboveground biomass of preceding vegetation and oil palm, changes in soil pools, recurrent emissions due to fertilization as other emission factors and data on the harvested yield to be used as denominator, are needed before footprints can be assessed (van Noordwijk et al., 2013).

2.5. Conclusions

Oil palm can be established free of (aboveground) carbon debt where it replaces vegetation with a time-averaged carbon stock of 37.76 ± 0.33 Mg C ha^{-1} – 42.07 ± 0.03 Mg C ha^{-1}. Soil type and plantation management account for the variation in estimates where details are known. Establishing oil palm plantations in areas with higher preceding carbon stock (values above 40 Mg C ha^{-1} as ballpark figure) will lead to net release of carbon to the atmosphere, with changes in soil pools, recurrent emissions due to fertilization as other emission factors and the harvested yield to be used as denominator needed before footprints can be assessed.

Chapter 3

Carbon neutral? No change in mineral soil carbon stock under oil palm plantations derived from forest or non-forest in Indonesia[5]

[5] *This chapter was published as*
Khasanah N, van Noordwijk M, Ningsih H, Rahayu S. 2015. Carbon neutral? No change in mineral soil carbon stock under oil palm plantations derived from forest or non-forest in Indonesia. Agric. Ecosyst. Environ 211: 195–206

Abstract

Sustainability criteria for palm oil production guide new planting towards non-forest land cover on mineral soil, avoiding carbon debts caused by forest and peat conversion. Effects on soil carbon stock (soil C stock) of land use change trajectories from forest and non-forest to oil palm on mineral soils include initial decline and subsequent recovery, however modelling efforts and life-cycle accounting are constrained by lack of comprehensive data sets; only few case studies underpin current debate. We analysed soil C stock (Mg ha^{-1}), soil bulk density (BD, g cm^{-3}) and soil organic carbon concentration (C_{org}, %) from 155 plots in 20 oil palm plantations across the major production areas of Indonesia, identifying trends during a production cycle on 6 plantations with sufficient spread in plot age. Plots were sampled in four management zones: weeded circle (WC), interrow (IR), frond stacks (FS), and harvest paths (HP); three depth intervals 0-5, 5-15 and 15-30 cm were sampled in each zone. Compared to the initial condition, increases in C_{org} (16.2%) and reduction in BD (8.9%) in the FS zone, was compensated by decrease in C_{org} (21.4%) and increase in BD (6.6%) in the HP zone, with intermediate results elsewhere. For a weighted average of the four management zones and after correction for equal mineral soil basis, the net temporal trend in soil C stock in the top 30 cm of soil across all data was not significantly different from zero in both forest- and non-forest-derived oil palm plantations. Individual plantations experienced net decline, net increase or U-shaped trajectories. The 2% difference in mean soil C stock in forest and non-forest derived oil palm plantations was statistically significant ($p<0.05$). Unless soil management changes strongly from current practice, it is appropriate for C footprint calculations to assume soil C stock neutrality on mineral soils used for oil palm cultivation.

Key words: biofuel, carbon footprint, Elaeis guineensis, life cycle analysis, soil carbon sequestration, sustainable palm oil

3.1. Introduction

Current use of palm oil from Southeast Asia as biofuel is far from carbon neutral (Reijnders and Huybregts, 2008; Sheil et al., 2009; Agus et al., 2013a). It is part of the 12–15% of total anthropogenic carbon emissions due to deforestation (Houghton et al., 2010; Van der Werf et al., 2009). Current use of peat soils causes CO_2 emissions that far exceed the amount sequestered in harvested products (Hooijer et al., 2010; Couwenberg et al., 2010; Hergoualc'h and Verchot, 2011). Carbon debts due to conversion can continue to increase on peat soils at a rate exceeding the reductions of fossil energy release that palm oil products can substitute for, causing (near) infinite 'pay-back' times (van Noordwijk et al., 2014b). On mineral soils, an initial carbon debt to the atmosphere can be recovered by subsequent biomass development and harvestable yields if these offset fossil fuel use. Current understanding is that palm oil can be both the best and the worst known source of biofuel from a global C balance perspective, having the widest 'management swing potential' (Davis et al., 2013).

Oil palm expansion is a prominent cause of tropical deforestation and associated C emissions in many landscapes in Southeast Asia. Although total oil palm area is yet to cover 5% of Indonesia and deforestation rates have been at least 1% per year for the past 20 years (van Noordwijk et al., 2014a). Due to consumer pressure and environmental concerns of major stakeholders in the palm oil value chain, oil palm is being weaned from new forest conversion and use of peat soils under voluntary agreements of the Roundtable on Sustainable Palm Oil (http://www.rspo.org/; Tan et al., 2009; Laurance et al., 2010). Converting low vegetation C stock on mineral soils is seen as the future of sustainable palm oil, but its effects on soil carbon stock (soil C stock) have not been sufficiently quantified. The literature is based on isolated case studies and unconstrained modelling exercises at best (Adachi et al., 2011; Nair et al., 2011).

A number of authors reported that conversion to oil palm plantations on mineral soils can lead to a net gain of soil C stock (Germer and Sauerborn, 2008; Verhoeven and Setter, 2010; Flynn et al., 2011; Hassan et al., 2011; Patthanaissaranukool and Polprasert, 2011; Siangjaeo et al., 2011). Others, however, reported a net loss (Kotowska et al., 2015) or estimated loss to be 10% of the forest soil C stock (Busch et al., 2015). Empirical data of both initial C_{org} and trends over time during a production cycle of oil palm are needed to verify the claims that soil C stock will increase and to validate or improve the models used. Replicated trials with randomly assigned treatments carried through the relevant time scale (at least one rotation of 25 years) do not exist, and thus attention is needed to possible differences in soil type, texture and bulk density (BD) where survey data are used. A specific challenge is that with change in BD soil samples taken to constant depth may involve different layers of soil (Ellert and Bettany, 1995; Post and Kwon, 2000; Lee et al., 2009). Evidence relevant to the issue of net increase or decrease of soil organic carbon concentration (C_{org}) during an oil palm production cycle can come from observed spatial patterns, from processes that are understood in a quantitative sense, or a combination of the two.

Current national accounting systems of greenhouse gas rely largely on global or nationally derived 'default' data on relative effects of land use on soil C stock. As part of the 2nd IPCC review, Paustian et al. (1997) summarized known effects of land use change on C_{org} across climatic zones and soil types. Subsequent literature led to some refinement. Don et al. (2011) in a global meta-analysis of 385 studies on land-use change in the tropics found that the highest C_{org} losses were caused by conversion of primary forest into cropland (25%) and perennial crops (30%), but forest conversion into grassland also reduced soil C stock by 12%. If this would be a simple additive system, one might thus expect conversion of grasslands to perennial crops to lead to a decrease of C_{org} by about 18%, but a meta-analysis cannot compensate for sampling bias of the case studies that are reported in the literature. Another recent meta-analysis (Powers et al., 2011) focused on 'paired plot' literature and found little consistency in C_{org} change, with both 'forest to grassland' and 'grassland to forest' conversions leading to statistically significant C_{org} gain; this may raise doubts on the selection bias in the results that are published. Both reviews confirm that complete data sets that combine measurements of BD and C_{org} are scarce, and that spatial extrapolation is affected by unbalanced representation of tropical soil types. Given the current importance of having unbiased results underpinning global carbon accounting standards, the net change in soil C stock of conversion to oil palm mineral soils needs to be understood across the range of production conditions.

The world's main palm oil production areas are Sumatra and the Indonesian and Malaysian parts of Borneo, peninsular Malaysia and southern Thailand[6]. As oil palm is restricted to areas with minimum temperatures of 18^{o}C and does not respond well to climates with more than one dry month (Corley and Tinker, 2003), the primary expansion has been within an area of relatively homogeneous climate. Specifically for Sumatra, van Noordwijk et al. (1997) found effects similar to those of Don et al. (2011), except for lower C_{org} losses in conversion to cropland, potentially because permanently cropped upland soils are relatively scarce in Sumatra where intensification of shifting cultivation has

[6] The FAOstat data for 2012 (http://faostat3.fao.org) indicate a global production of 52.9 10^6 metric ton (valued at 21.6 10^9 USD), with 50.9%, 35.5%, 3.4% and 1.6% for Indonesia, Malaysia, Thailand and other Asia/Pacific countries, respectively. The remaining 9% of global production comes from W. Africa (3.8%) and Latin/Central America (4.8%).

generally moved towards permanent tree crops (van Noordwijk et al., 2008). *Imperata* grasslands and areas formerly used for shifting cultivation may not have substantially lower C_{org} than forests (Santoso et al., 1997). Soil C stock in tree plantations were reported to be 0–40% less than stocks in swidden cultivation, with the largest losses found in mechanically-established oil palm plantations (Bruun et al., 2009). The above-mentioned studies show that the effect of land use change on the trend of C_{org} remains unclear from studies of existing spatial patterns.

More process-oriented studies suggest that we can expect a decline of C_{org} inherited from preceding vegetation and a gradual build-up of C_{org} from the vegetation that replaces it. Based on carbon isotope differences between sugarcane residue and forest soil C pools, Sitompul et al. (2000) quantified the annual loss of forest C_{org} after conversion to sugarcane. The annual loss of forest C_{org} was 8.2% per year (± 2.8% per year) for an Ultisol (*Grossarenic Kandiudult*) in Sumatra, with differentiation between density fractions: 14-19% per year for macro-organic matter varying in degree of association with soil particles and hence in density, and lower rates for fine material associated with clay and silt. Similar initial decay rates can be expected for oil palm plantations, possibly reduced by microclimate modification and absence of soil tillage in oil palm, compared to sugarcane stands. As specified in the Century model (Sitompul et al., 2000) and confirmed in a Sumatra-wide data set (van Noordwijk et al., 1997), variation in soil clay and silt content is likely to influence the amount of C_{org} protected from decomposers by physical association with soil particles, leading to different C_{org} decomposition rates for the soil as a whole.

In further applying this conceptual model of breakdown and build-up, we expect that the decay of C_{org} inherited from preceding forest, grassland or other vegetation, is balanced by two types of organic inputs: aboveground litter, which can be readily quantified from the known leaf production (minus any biomass removals), and (fine) root turnover which is poorly quantified as yet. The spatial organization of oil palm plantations, where aboveground litter is typically accumulated in 'frond stacks' in between palms, differentiates the relative contributions of above- and belowground inputs, allowing some separation of the terms of the C_{org} change equation. Four different management zones are normally recognized: weeded circle (WC), frond stacks (FS), interrow (IR) and harvest paths (HP) (Corley and Tinker 2003; Law et al., 2009). Between plantations there is variation in the degree to which aboveground litter is stacked (to facilitate access to the plots) or spread out (to protect the soil), leaving only the HP and WC free of litter.

Specific questions for the current analysis of this data set are:

1. are there statistically significant positive or negative trends within oil palm plots in BD and C_{org} with age of oil palm for the four management zones in oil palm on mineral soil?
2. how does a correction for equal-soil-mineral basis of comparisons influence the estimated changes in soil C stock?
3. does the average soil C stock, weighted over the four management zones, increase or decrease with age of oil palm plots and is the change influenced by having forest or non-forest as recent land use history?
4. is variation between plantations in the shift from a negative to a positive trend of soil C stock with time and hence in time-averaged C stock attributable to known management practices?

3.2. Materials and methods

3.2.1. Demand-led research, confidentiality arrangements

As the Renewable Energy Directive of the EU ('EU RED'; EC, 2010) implies a need for comprehensive data on the C footprint of palm oil if this is to be exported to Europe and used for biofuel, the Indonesian Palm Oil Commission asked the World Agroforestry Centre to lead a study that would provide an initial database for comparisons and build capacity of the private sector to apply established methods. The study was implemented together with 20 plantations, recruited on a voluntary basis among all major oil palm producing companies in Indonesia. While confidentiality on the identity of participants was the basis for participation in a data collection of commercial importance in a politically sensitive arena, the data set as a whole represents an opportunity to analyse the temporal trends of C_{org} (%), BD (g cm^{-3}) and soil C stock (Mg C ha^{-1}) in the four different management zones. Aboveground C stock not only from of the same plantations, but also from other 5 plantations in peat soil is described in a parallel manuscript.

3.2.2. Study design and plantation selection

This study focused on the analysis of the temporal changes of BD, C_{org}, and soil C stock, in mineral soil in a total of 155 plots within 20 selected landscapes or plantations (Figure 3.1 and Table 3.1). Selection of the 20 landscapes or plantations and 155 plots was based on stratifiers we derived at national level to sample landscape or plantation and at landscape level to sample soil at various age of oil palm.

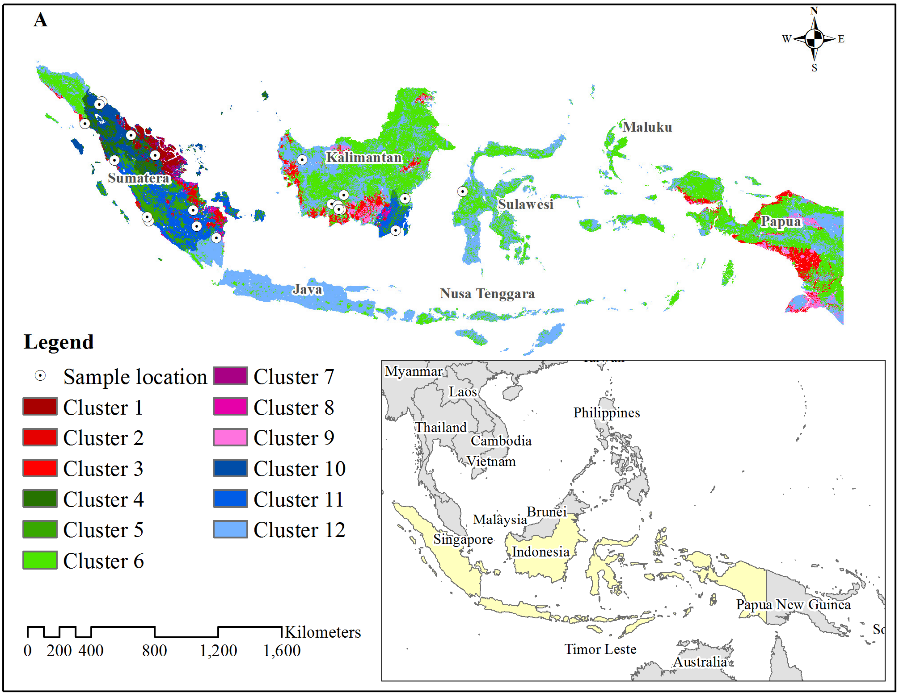

Figure 3.1. Spatial distribution of 20 oil-palm landscapes or plantations selected for inclusion in this study. The colour definition refers to cluster definition in Table 3.1.

At the national level, we had three stratifiers: 1) landscape or plantation history (derived from forest versus non-forest (other vegetation or from preceding oil palm), 2) soil type (mineral soils versus peat), and 3) the prevalence of oil palm in the surrounding area, assessed at provincial level, as areas of high oil palm prevalence are likely to represent a longer history of the crop, potentially selected for the most suitable climatic conditions, and may have the best knowledge and processing infrastructure. Climatic aspects are confounded with the other characteristics of this distinction, but the primary climatic distinction within the oil palm zone of Indonesia, in climatic zones A and B but not C as described by Aldrian and Susanto (2003), is in the frequency and strength of dry periods, which affects fruit rather than vegetative production. *A priori* expectations of effects of this climatic variation on soil C stock are thus limited.

At the landscape or plantation level, we distinguished between what in the commonly used terminology is termed the 'nucleus', a core plantation managed by a company, the 'plasma' or plantations initially managed by a company during establishment until the early production stage and then transferred to a farmer as the owner of the land (Santoso, 2010), and independents smallholder plantations (IFC, 2013). We thus used three additional strata: 1) plantation management (nucleus, plasma, independent smallholders), 2) soil type (mineral soils versus peat), and 3) age during the crops' life cycle.

Factorial combinations across the three criteria at the national level led to 12 (=3 × 2 × 2) clusters. In this paper, we analysed the focused study mentioned in mineral soil only (cluster 4, 5, 6, 10, 11 and 12 in Figure 3.1). Table 3.1 presents number of plot among stratifiers in mineral soil. From the 155 plots sampled, 112 plots (72%) and 43 plots (28%) were derived from forest and non-forest respectively; 108 plots (70%), 29 plots (19%) and 18 plots (12%) were under nucleus, plasma and smallholder management, respectively; 53 plots (34%), 64 plots (41%), 38 plots (25%) were in between 0-8, 9-16 and 17-25 age of oil palm, respectively.

3.2.3. Plantation landscapes description

Based on the intra- and inter-annual variation in rainfall and the statistical correlation of rainfall with sea surface temperatures in the Pacific and Indian Ocean, Aldrian and Susanto (2003) recognized three climatic regions in Indonesia. Oil palm is currently grown in the two wettest of these regions, with a centre of gravity in region B that is located in northwest Indonesia and stretches from northern Sumatra to north western Kalimantan. While mean annual rainfall (2600 mm $year^{-1}$) and the number of months with rainfall over 200 mm is 7 months is similar between regions A and B (Figure 3.2), the pattern of interannual variability differs. However, the average mean annual rainfall of those regions is not statistically significant ($P < 0.05$).

Region B has a tendency to a bimodal pattern without months of less than 100 mm rainfall on average, combined with low sensitivity to El Nino patterns of interannual variability in the Pacific and modest response to the Indian Ocean dipole (Niedermeyer et al., 2014) have created a climate in northern Sumatra that is eminently suitable for oil palm. Region A is located in southern Indonesia and stretches from south Sumatra to Timor, southern Kalimantan, Sulawesi and part of Papua. Its unimodal rainfall has a relatively dry period between May to September that in interaction with interannual variability can reduce oil palm yields, depending on the degree of water buffering by the soil. The highest 'oil palm prevalence' at provincial level (5 - 15%) coincided with climate region B for this study, while the data for 'oil palm prevalence below 5% where derived from climate region A.

With regards to soil type, the dominant soil in the 155 sampled plots was classified as Ultisols (55%) and Inceptisols (19%), respectively. Other soil types encountered less frequently were Spodosols, Oxisols and Entisols. Across these soil types, variation in soil texture and pH account for differences in C_{org} that can exceed the effects of land cover (forest, non-forest categories) (van Noordwijk et al., 1997). Soil organic carbon reference (soil C_{org_ref}) was then used to take into account the variation of soil types (section 3.2.4.3.).

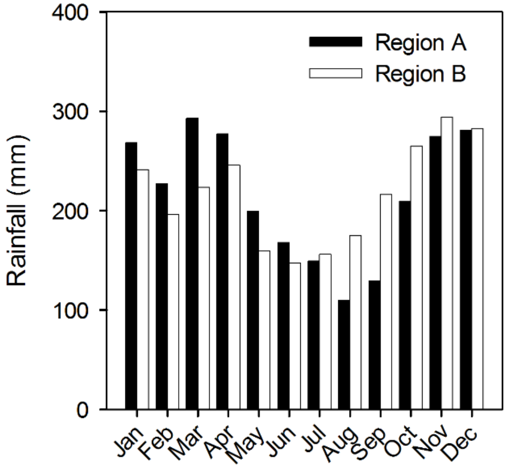

Figure 3.2. Mean monthly rainfall of all plantations presented based on climate regions A and B as derived by Aldrian and Susanto (2003).

3.2.4. Sampling design and calculation of soil carbon stock

3.2.4.1. Soil carbon stock measurement

This study represents what is considered to be, by the plantations, "good practice" management of oil palm plantation related to management of soil organic input. Typical "good practice" management of soil organic input is the plantation area normally distinguished into four different management zones: weeded circle (WC), frond stacks (FS), interrow (IR) and harvest paths (HP) (Figure 3.3B). WC zone is around palm trunk and occupy only 12% of total area. It is normally free of understorey for fertilizer application. During plantation establishment, legume cover crop is typically planted and the cover crop is allowed to grow only in IR zone (46% of total area) once the oil palm reach mature stage (> 3 years). Recycling management of yield residue such as Empty Fruit Bunches (EFB) is sometime also applied in the IR zone. Pruned frond is managed and piled in each alternate row (FS zone, it is about 30% of total area) with the harvest path of oil palm (12% of total area) kept free of litter. Soil sampling in each plot considered this organic input management zones, and recorded the site-specific variations in spatial extent of the zones.

Table 3.1. Study design with the actual number of plots sampled across plot age, management style, preceding vegetation, and oil palm prevalence in the surrounding area that assessed at provincial level. Cluster 1-3 and 7-9 are peat soil and excluded from the table as the paper focused on mineral soil.

Plantation parameters		**Cluster**	**Number of landscapes**	**N = nucleus, P = plasma, I = independent**	**Number of sampled plots per age category (year)**			
Preceding land cover	**Prevalence of oil palm (% of area in province)**				**0-8**	**9-16**	**17-25**	**Total**
Forest	5–15	4	3	N	2	5	10	17
				P	-	2	2	4
				I	-	-	-	-
	1–5%	5	3	N	6	8	7	21
				P	1	2	-	3
				I	2	1	-	3
	<1%	6	9	N	16	20	7	43
				P	4	4	1	9
				I	10	2	-	12
Non forest	5–15	10	2	N	4	5	2	11
				P	-	-	-	-
				I	-	-	-	-
	1–5%	11	3	N	2	8	6	16
				P	4	6	3	13
				I	2	1	-	3
	<1%	12	-	-	-	-	-	-
	Total		20		53	64	38	155

Soil C stock in each plot was estimated by measuring BD and analysing C_{org} (Hairiah, et al 2011) at 0 – 30 cm soil depth with intervals of 0-5 cm, 5-15 cm and 15-30 cm. The sampling was focused on the first 30 cm, besides the default for soil depth for soil C stock measurement provided by IPCC (2006) is 30 cm, it is also as the greatest proportion of the total root mass is confined to the top 30 cm of the soil surface (Ravindranath and Ostwald, 2008).

The BD was measured by taking samples using a 0.2 x 0.2 m sample frame around palm numbers 1, 3, 6, 9, 12, 15, 18, 21 in Figure 3.3A in four different management zones (Figure 3.3B). Hence the total sample per plot is 96 samples (8 palms × 4 management zones × 3 soil layers) or more than 10000 samples from the whole landscapes or plantations. Selected palms (1-24) in Figure 3.3A in each plot followed the standardized selection scheme used in establishing Leaf Sampling Units (LSU) for fertilizer recommendation (some of the details varied between plantation companies). Within these 24 trees, 8 palms were chosen to represent spatial distribution of the palm in each plot. The soil samples were oven-dried at 80°C in laboratory to determine the total dry weight.

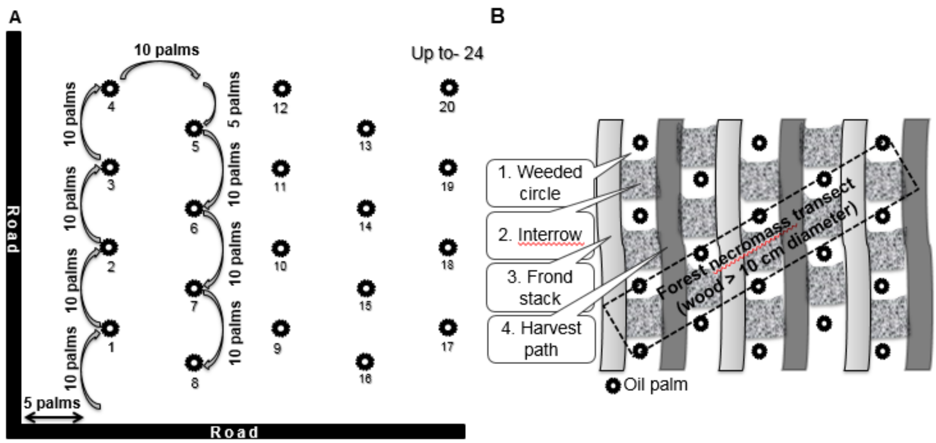

Figure 3.3. A. Scheme of selected palms where soil at four different management zones to be measured in each plot. B. Sampling measurement scheme of soil representing four spatial zones: Weeded circle (WC) or fertilizer application zone; Interrow (IR)/grass/empty fruit bunch (EFB) application zone; Frond stacks (FS) zone; and Harvest paths (HP) zone).

The soil's C_{org} was analysed by taking soil samples at the same position as BD measurement and composite from 8 trees. The composited soil samples were air-dried and sieved, ground to pass through a 2-mm sieve in laboratory prior to analysis using the Walkley and Black method. This method requires a correction factor for incomplete oxidation of organic C (Schulte, 1995; McCarty et al., 2010); we used a correction factor of 1.32 (Nelson and Sommers, 1996).

The soil C stock was then calculated as follow:

$$soil\ C\ stock_i = (BD_i \times D_i \times C_i)/100 \qquad (1)$$

$$BD_i = W_i/V_i \qquad (2)$$

where soil C stock$_i$ is soil carbon stock at depth *i* (g cm^2), BD$_i$ is soil bulk density at depth *i* (g cm^{-3}) = total dry weight of soil (W_i) divided by soil volume (V_i), D$_i$ is soil thickness at depth *i* (cm), and C_i is soil organic carbon at depth *i* (%).

Soil C stock at each sampling point was then up-scaled into per unit area of estimation (Mg C ha^{-1}) that was measured taking into account the area of each management zone per ha (weighted average).

3.2.4.2. Correction of soil carbon stock for equal mineral soil basis

Soil C stock that is quantified from BD, C$_{org}$ and soil depth is often over-estimated or under-estimated because of increasing BD due to minimum tillage (Badalikova, 2010) or decreasing BD due to large organic inputs. In the four different management zones of oil palm plantations (Figure 3.3B), the harvest path zone is a zone where BD increases and the interrow and frond stack zones are zones where it potentially decreases. Hence, correction is needed to ensure equal soil masses are compared for each different zone (Lee et al., 2009). We used the correction proposed by Ellert and Bettany (1995) to express results on an equal soil mass. Figure 3.4 clarifies its rationale.

The derivation of the equation for correcting carbon stock estimates is as follows. Let the mineral soil and C$_{org}$ content of a volume of soil that is sampled in three layers at time *t* be described by:

$$Min_t = \sum_{i=1}^{3} S_i \times BD_{t,i} \times \left(\frac{100-C_{t,i}}{100}\right), \text{ for each management zone} \qquad (3)$$

$$C\ stock_t = \sum_{i=1}^{3} S_i \times BD_{t,i} \times \frac{C_{t,i}}{100}, \text{ for each management zone} \qquad (4)$$

where Min_t = initial (for *t* = 0) or final (for *t* = *T*) mineral soil content between soil surface and depth *i*, g cm^{-2}; *C stock*$_t$ = initial (for *t* = 0) or final (for *t* = *T*) soil carbon stock between soil surface and depth *i*, g cm^{-2}; S_i = soil thickness of depth *i*, cm; $BD_{t,i}$ = soil bulk density of depth *i* at *t* = 0 or at *t* = *T*, g cm^{-3}; $C_{t,i}$ = soil organic carbon concentration of depth *i* at *t* = 0 or at *t* = *T* zone i, %.

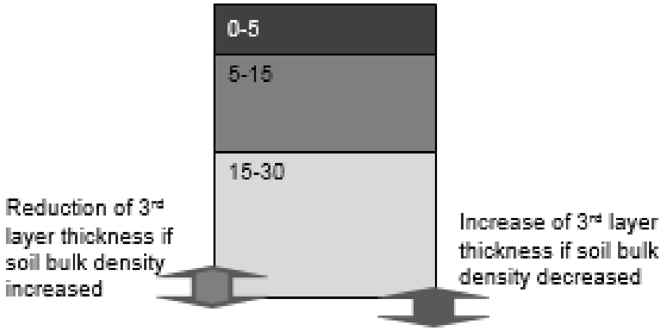

Figure 3.4. Diagram of the three soil layers and the type of correction needed to adjust for increase or decrease of soil bulk density

The correction factor (*CF*, %) to be added to $Cstock_{T(uncorrected)}$ is (for an example where three soil layers were sampled):

$$CF = \frac{(Min_0 - Min_T) \times \frac{C_{0,3}}{100 - C_{0,3}}}{(Min_0 - Min_T) \times \frac{C_{0,3}}{100 - C_{0,3}} + Cstock_{t,3}} \qquad (5)$$

$$Cstock_{corrected} = Cstock_{T(uncorrected)} \times (1 + CF) \qquad (6)$$

3.2.4.3. Estimation of texture-specific reference of soil carbon stock

To normalize the effect of soil texture on C_{org} of different soil classification, we calculated soil carbon stock reference (soil C $Stock_{ref}$) based on BD reference (BD_{ref}) (Wösten, et al (1998) and soil organic carbon reference (C_{org_ref}) (van Noordwijk et al., 1997).

BD_{ref} indicated maximum or reference of bulk density and can be used to see the status of soil compaction, which is ratio of measured bulk density and bulk density reference (BD/BD_{ref}). A value of the BD/BD_{ref} ratio bigger than 1 indicate compaction of soil. C_{org_ref} is a reference C_{org} level representative of forest soil. The ratio of C_{org} and C_{org_ref} can be used as an indicator for C_{org} sustainability. A value of the C_{org}/C_{org_ref} ratio above 1 indicates soil C stock improvement relative to forest soil conditions.

The estimation of C_{org_ref} used an equation developed by van Noordwijk et al, 1997 and subsequently refined (van Noordwijk, pers. comm.):

$$C_{ref(adjusted)} = (1.489\ x\ Z_{sample})^{-0.528} x\ exp(1.333 + 0.00994\ x\ Clay + 0.00699\ x\ Silt - 0.156\ x\ pH_{KCl} + 0.000427\ x\ elevation\ ) \qquad (7)$$

The estimation of BD_{ref} used an equation developed by Wösten, et al (1998) (cited in Suprayogo et al., 2003):

For clay + silt contents less than 50 and top soil

$$BD_{ref} = \frac{1}{\left(-1.984+0.01841\ x\ OM+0.032+0.00003576\ x\ (Clay+Silt)^2+\frac{67.5}{MPS}+0.424\ x\ Ln(MPS)\right)} \quad (8)$$

For clay + silt content less than 50% and sub soil

$$BD_{ref} = \frac{1}{\left(-1.984+0.01841\ x\ OM+0.00003576\ x\ (Clay+Silt)^2+\frac{67.5}{MPS}+0.424\ x\ Ln(MPS)\right)} \quad (9)$$

For clay + silt more than 50%:

$$BD_{ref} = \frac{1}{(0.603+0.003975\ x\ Clay+0.00207\ x\ OM^2+0.01781\ x\ Ln(OM))} \quad (10)$$

where clay = percentage of clay, silt = percentage of silt, OM = percentage of organic matter, BD = soil bulk density, g cm^{-3}, MPS = mean particle size of sand (default 290 μm).

3.2.4.4. Estimation of time-averaged soil carbon stock

Time-averaged C stock of oil palm plantation represents the soil C stock of an oil palm plantation over a life cycle (typically 25 years). The time-averaged C stock of oil palm plantations was estimated by developing an allometric equation of soil C stock, 0 – 30 cm soil depth (Mg C ha^{-1}) of plantation as a function of palm age (year). The soil C stock of plantation is average value of four management zones taking into account area of each management zone (weighted average).

3.2.5. A simple model of soil carbon stock

To understand the decrease and increase of soil C stock over time, a simple model was developed based on Sitompul, et al (2000). In the absent of soil organic input, the changes of soil C stock as follow:

$$Cstock_t = Cstock\_s_t + Cstock\_m_t + Cstock\_l_t \quad (11)$$

$$Cstock\_s_t = a(1-k_s)^t \quad (12)$$

$$Cstock\_m_t = b(1-k_m)^t \quad (13)$$

$$Cstock\_l_t = c(1-k_l)^t \quad (14)$$

where $Cstock_t$ is total soil C stock at time t; $Cstock\_s_t$, $Cstock\_m_t$, and $Cstock\_l_t$ are soil C stock of slow (or heavy), medium and fast (or light) pools, respectively at time t; a, b and c are initial soil C stock of slow (25 Mg C ha^{-1}), medium (15 Mg C ha^{-1}) and fast (15 Mg C

ha^{-1}) pools, respectively; k_s, k_m and k_l are decomposition rate of slow (0.142 per year), medium (0.185 per year) and fast (0.194 per year) pools, respectively.

The same calculation was then applied to the present of oil palm organic inputs. The amount of oil palm organic inputs is around 4.6 Mg ha^{-1} yr^{-1} and to increase over time to 10.9 Mg ha^{-1} yr^{-1}, by year 8 and it's distributed to slow (20%), medium (30%) and light (50%) pool, respectively.

3.2.6. Statistical data analysis

All soil BD, C_{org} and C stock data were analysed for single effect of the factors: plantation management (nucleus, plasma, and independent), soil classification (Ultisols, Inceptisols and others), landscape or plantation history (derived from forest or non-forest), management zones (weeded circle, interrow, frond stacks and harvest paths) and age of oil palm using SYSTAT 11. The analysis refers to 5% probability levels.

3.3. Results

3.3.1. Trends in soil bulk density (BD) and soil organic carbon (C_{org}) with age of oil palm per management zone

Figure 3.5A-5B shows the BD and C_{org} at various ages of oil palm and management zones in the top 30 cm of soil. Some measured plots under nucleus management and derived from forest had low BD and high C_{org}. These plots in fact had a layer of mature peat but of insufficient depth to be classified as peat soils. Overall, BD did not reveal any significant differences among types of plantation management, initial land cover, management zones and age of plantation ($p < 0.05$). By contrast, there were significant differences in C_{org} among types of plantation management, initial land cover, soil classification and management zones ($p < 0.05$) (Table 3.3).

Over a plantation life cycle, the BD increased by 6.6% (due to soil compaction) in the harvest path zone and decreased by 8.9 % in the frond stack zone compared to the initial condition. However, these trends could not be statistically distinguished from a no-effect null-hypothesis. The opposite trend was found in C_{org} over a life cycle, the C_{org} significantly increased by 16.2% in the frond stack zone and decreased by 21.4% in the harvest path zone.

3.3.2. Soil carbon stock before and after correction

Table 3.2 presents calculation of the correction factor for four management zones. In a zone where the soil became compacted (harvest path zone) and decreased in C_{org}, the estimated soil C stock should be decreased by 6.5% and in a zone that increased in C_{org}

and decreased the soil BD (frond stack zone) the estimated soil C stock should be increased by 6.1%.

Within this dataset, BD of the frond stack zone decreases (loose) and C_{org} of the frond stack zone increases with age of oil palm. While, BD of the harvest path zone increases (compacted) and C_{org} of the harvest path zone decreases with age of oil palm. These opposite trends make level of overall trend of soil C stock of oil palm plantation. This is reflected from the no significant different of weighted average of soil C stock among age of plantation ($P < 0.05$) (Figure 3.5C5). The correction factors do not substantially change the conclusion that there is no significant net change in soil C stock over an oil palm production cycle (Figures 3.6A and 3.6B).

3.3.3. Time-averaged of carbon stock of a plantation

The soil C stock in the top 30 cm soil depth was differ significantly among types of plantation/company management, initial land covers, soil types or management zones ($p < 0.05$). The soil C stock did not differ significantly with the age of the oil palm plantations ($P < 0.05$). This allowed us to estimate the time-averaged C stock of an oil palm plantation over a life cycle (25 years) based on the mean value of the weighted average of four management zones over the entire set of measurement points. The highest time-averaged C stock for the first 30 cm soil depth over a plantation life cycle was independent plantation, followed by nucleus and plasma plantation (Table 3.3).

Further analysis of the weighted average of soil C stock of forest and non-forest derived plantation, excluding the plantation that was already in the 2nd or 3rd cycle for the second category gave an interesting result as the net temporal trend of soil C stock in both forest and non-forest derived oil palm plantations was slightly negative (Figure 3.7A). The lowest 8 points all belong to the non-forest category, the means for forest and non-forest, 53.63 ± 15.98 and 49.86 ± 20.94 Mg C ha^{-1} were significantly different in a t-test ($p < 0.05$). However, soil C stock /soil C $stock_{ref}$ value is bigger than 1 with only some plot having values smaller than 1 (Figure 3.7B). This also indicates that current practices of maintaining soil organic input from fronds, cover crops, and empty fruit bunches (where applied) sustain the soil C stock.

3.3.4. Differences between plantations

For the six plantations with sufficient data over the life cycle of oil palm (Figure 3.8A) a mixed set of temporal response curves was obtained. These varied from the concave pattern of initial decline followed by recovery, to essentially linear and convex ones that peaked at ages of 15-20 years. Within these six plantations we did not have sufficient degrees of freedom to associate differences in temporal pattern to plot history or other factors.

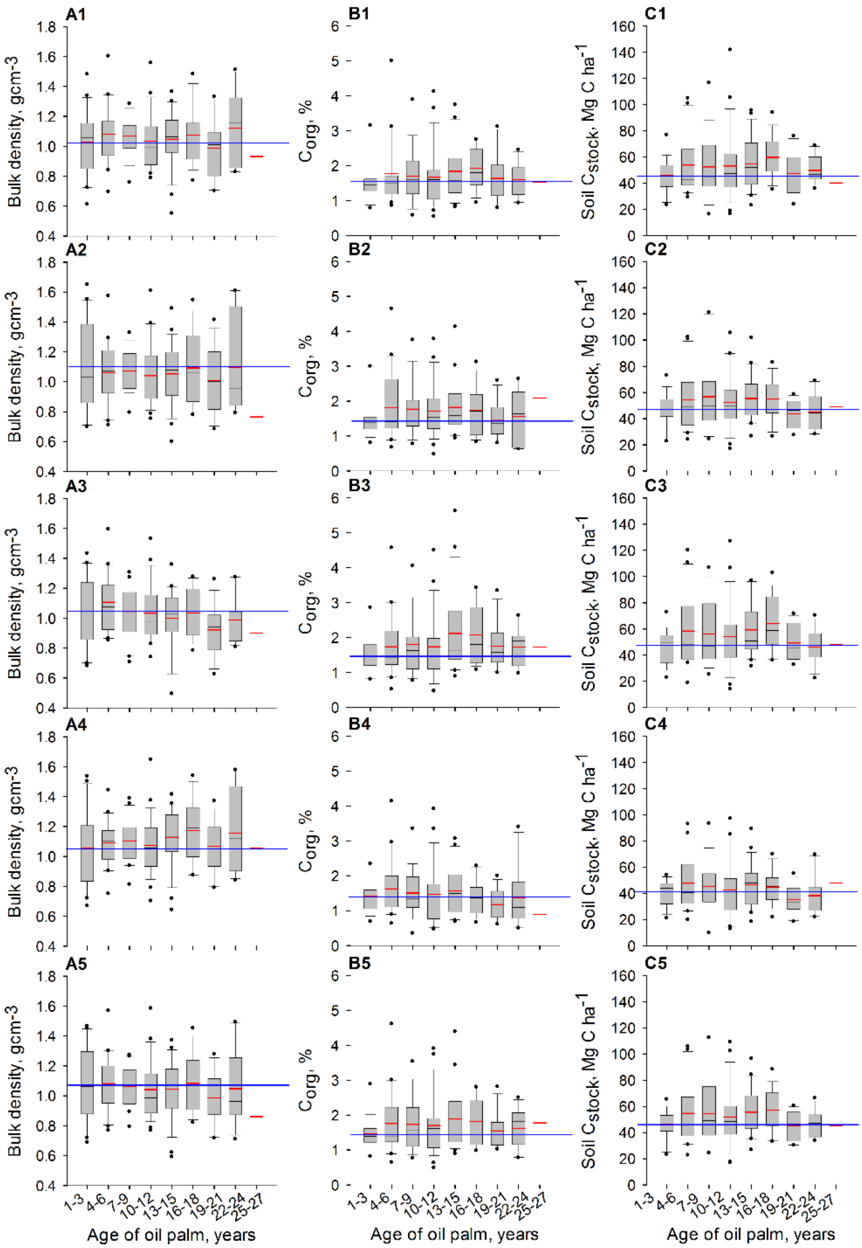

Figure 3.5. Soil bulk density (g cm-3) (A), soil organic carbon (%) (B), and corrected soil C stock (Mg C ha-1) at 0–30 cm depth at different oil palm ages and management zones. 1 = weeded circle (WC) zone, 2 = interrow zone (IR), 3 = frond stack (FS) zone, 4 = harvest path zone, and 5 for weighted average over four zones. Black and red line within the box marks the median and the mean. Blue line is a line at the mean of the first box (year 1-3), it can be easy to recognize weather the mean of the last box (year 25) increase or decrease compared to the first box.

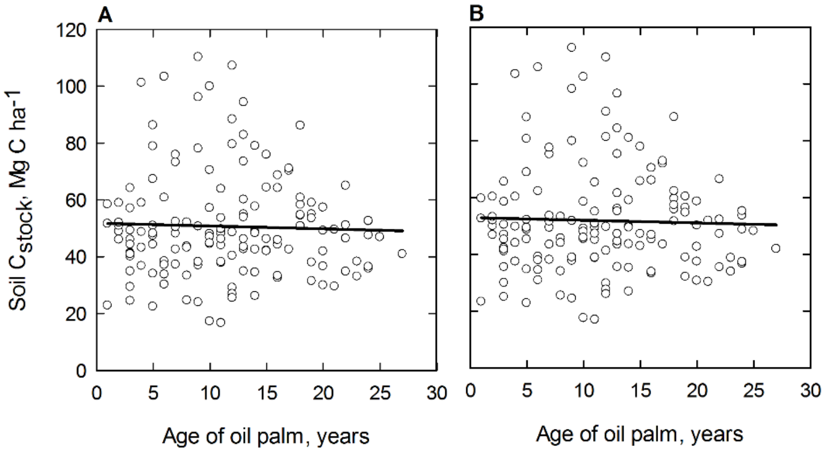

Figure 3.6. Weighted average of soil C stock of mineral soil at 0-30 cm depth at different oil palm ages, before (A) and after (B) corrections for sampling depth based on changes in soil bulk density.

3.4. Discussion

The research was designed to answer four questions that jointly allow recommendations on how to treat oil palm in national C accounting schemes and footprint calculations, depending on land use change history. In response to the first question regarding the trend of BD and C_{org} with age of oil palm for the four management zones, our data confirmed differentiation between the management zones within a plot. This implies that comparisons over time are not to be trusted unless the spatial sampling scheme acknowledges such differences in trends and compensates for them by appropriate weighting of sample locations.

Table 3.2. Calculation of the correction factor for four management zones.

Time	Zone	Soil thick-ness	Soil depth	BD g cm^{-3}	Soil C_{org} %	Mineral parts, g cm^{-2}	Organic part, g cm^{-2}	Correction factor 3-layer, %	Correction factor 1-layer, %
Initial (Year 0)	-	5	0-5	0.94	2.52	4.59	0.12	-	-
	-	10	5-15	1.13	1.74	11.15	0.20		
	-	15	15-30	1.21	1.12	17.91	0.20		
	-		**total**			**33.65**	**0.52**		
Year 25	Weeded circle	5	0-5	0.88	2.99	4.25	0.13	-0.8	-1.21
		10	5-15	1.14	1.79	11.21	0.20		
		15	15-30	1.25	1.11	18.57	0.21		
			total			**34.04**	**0.54**		
	Inter row	5	0-5	0.83	3.13	4.02	0.13	2.6	3.51
		10	5-15	1.09	1.75	10.73	0.19		
		15	15-30	1.19	1.07	17.70	0.19		
			total			**32.45**	**0.51**		
	Frond stack	5	0-5	0.72	3.57	3.49	0.13	6.1	8.86
		10	5-15	1.03	1.91	10.10	0.20		
		15	15-30	1.15	1.17	17.02	0.20		
			total			**30.61**	**0.53**		
	Harvest path	5	0-5	1.02	2.01	5.00	0.10	-6.5	-7.21
		10	5-15	1.19	1.39	11.75	0.17		
		15	15-30	1.29	0.86	19.23	0.17		
			total			**35.98**	**0.43**		

Over a plantation life cycle, C_{org} in the weeded circle, interrow, and frond stack increased by 5.6%, 5% and 16.2%, respectively. The increments in C_{org} in the circle must have been largely derived from root material (Lamade et al., 1996; Frazão et al., 2013) as the circle is maintained free of aboveground plant material. By contrast, the large input of pruned fronds led to an increase in C_{org} beneath the frond stack. Significant yet small changes in C_{org} between management zones were also reported by Fairhurst (1996) and Haron et al. (1998). As part of this exploration of the differentiation between zones corrections for comparisons at equal mineral soil mass (question 2) are indeed important. Without them, the differences would appear to be more pronounced, as lower BD and higher C_{org} concentration per unit soil dry weight tend to correlate. Of methodological interest is that a correction could also have been applied if the 0 - 30 cm soil layer had been sampled as a single layer, as some C sampling protocols suggest. If we compare the correction factors for 1-layer (0 - 30) or 3-layers (0-5, 5-15 and 15-30 cm depth intervals), however, the correction factors would be more extreme if a single layer had been sampled. The 3-layer scheme gives a smaller correction factor because the C_{org} of the deepest layer (which is used for the soil C stock correction) is known with greater precision.

In relation to our third question, increase or decrease of soil C stock with age of oil palm, we found evidence for a net decrease in the early part of the cycle, but not for the cycle as a whole. Several studies (Guo and Gifford, 2002; Schroth et al., 2002; Don et al., 2011; de Blécourt et al, 2013) reported that conversion of forest into agricultural systems, rubber or oil palm plantations leads to decreases in C_{org} in the surface 30 cm of soil, but most of these studies assessed the early parts of the tree crop's life cycle. The reduced inputs of organic matter in agricultural systems or oil palm plantations can, according to some authors, lead to a soil C stock that is threefold less than under natural forest (Schroth et al., 2002; Lamade and Bouillet 2005). Our results, however, show that the zone-averaged soil C stock in the top 30 cm soil depth did not change significantly with time or age of plantation in either forest or non-forest derived plantations. This lack of net effect can be understood as a balance between initial decline of the soil C inherited from preceding vegetation, and build-up of oil palm-derived soil C. The time-averaged soil C stock was 51.85 ± 18.95 Mg C ha^{-1}. This indicates that good management practice that includes retention of organic inputs from fronds, cover crops, and even yield residue can in balance sustain the soil C stock as also indicated by soil C stock /soil C $stock_{ref}$ value that is bigger than 1. However, use of EFB is mostly seen as form of waste disposal to oil palm fields near the mill, rather than as recycling to all plots (Bakar et al., 2011).

Table 3.3. Soil carbon stock of mineral soil in the top 30 cm of soil at different plantation/company managements, soil types, initial land covers, soil depths and management zones.

Factors		**Bulk density (g cm^{-3})[1)]**	**Soil C_{org} (%)[1)]**	**Time-averaged stock (Mg C ha^{-1})[1)]**
Plantation/ company management	Nucleus	1.04 ± 0.20	1.72 ± 0.75	51.60 ± 17.14
	Plasma	1.07 ± 0.21	1.60 ± 0.81	50.00 ± 22.02
	Independent	1.08 ± 0.17	1.76 ± 0.63	56.13 ± 20.42
Soil type	Inceptisol	1.02 ± 0.15	1.58 ± 0.80	45.53 ± 16.93
	Ultisol	1.07 ± 0.21	1.69 ± 0.55	53.45 ± 15.20
	Others	1.03 ± 0.22	1.91 ± 1.08	56.04 ± 27.04
Initial land cover	Forest	1.05 ± 0.22	1.72 ± 0.70	53.63 ± 15.98
	Other than forest	1.05 ± 0.16	1.63 ± 0.78	49.86 ± 20.94
Depth	0-5cm	0.88 ± 0.19	2.92 ± 1.37	
	5-15cm	1.11 ± 0.18	1.87 ± 0.88	
	15-30cm	1.07 ± 0.23	1.14 ± 0.54	
Management zone	1 (Weeded circle)	1.05 ± 0.19	1.71 ± 0.77	52.12 ± 20.80
	2 (Interrow)	1.06 ± 0.23	1.69 ± 0.75	51.99 ± 19.47
	3 (Frond stack)	1.03 ± 0.19	1.80 ± 0.87	54.77 ± 21.72
	4 (Harvest path)	1.10 ± 0.20	1.46 ± 0.70	43.08 ± 17.28
Time-averaged carbon stock for depth 0-30cm				51.85 ± 18.95

1. mean ± standard deviation

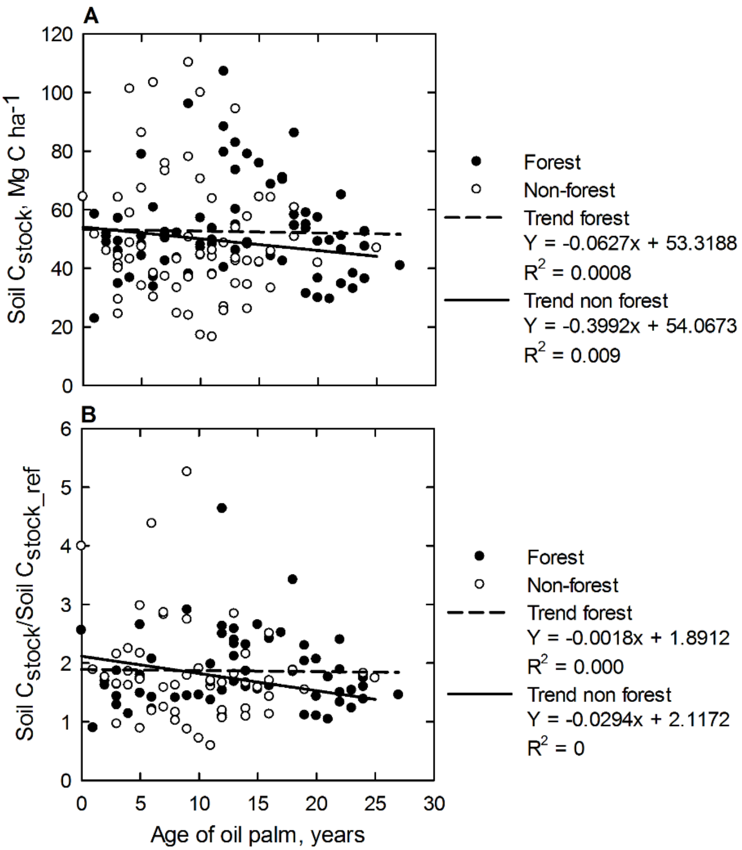

Figure 3.7. Soil carbon stock at 0–30 cm depth of forest-derived plantation and non-forest derived plantation at different oil palm ages (A) and ratio of soil carbon stock and soil carbon stock reference (B). Data at year 0 are coming from forest and non-forest land cover before conversion into oil palm.

Aboveground C stock in the same plantations was estimated and the time-averaged aboveground C stock varied around 40 Mg C ha^{-1} (Khasanah et al., 2012) and so the soil C stock to aboveground C stock ratio was around 1.25 : 1. The time-averaged soil C stock was relatively close to the 50.37 to 55.38 Mg C ha^{-1} in the top 30 cm of soil measured in temperate forests by Dar and Sundarapandian (2013). Compared with the aboveground C losses due to land conversion, belowground C losses are small (Sommer et al., 2000). Our findings that soil C stock do not change significantly with the age of plantation, and that no net soil C emissions were detected may be used to improve the life cycle C accounting of biodiesel derived from palm oil.

Regarding the fourth question, variation in the trend of soil C stock between plantations, our plantation level data (Figure. 3.8A) suggest that there is variation between plantations in temporal pattern that may be further explored. As comparison, a simplified model based on Sitompul et al. (2000) is presented in Figure 3.8B. A wide range of alternative model results can be obtained by varying initial allocation over the pools, e.g. related to soil texture, variations in decay rates for the pools, e.g. related to soil texture or soil water regime linked to drainage, and management of the palms that may influence the above- and belowground litter inputs and/or the temporal pattern of these inputs. Within a plausible parameter range both net increase and net decrease of soil C stock over a life-cycle is feasible.

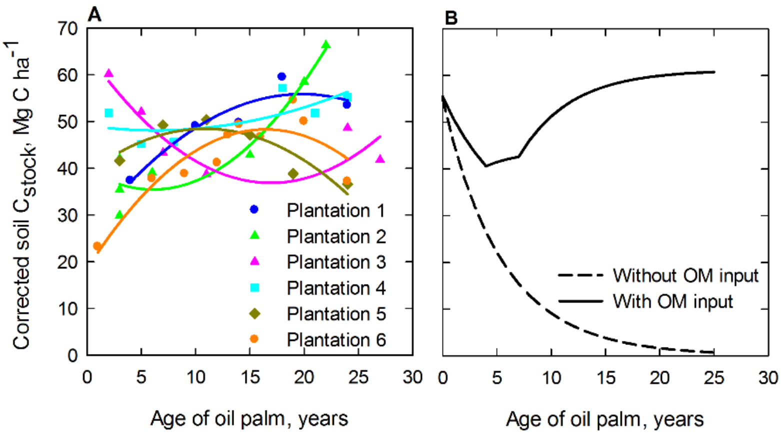

Figure 3.8. A. Nonlinear soil C stock trends in six plantations with sufficient age differentiation; B. Expected soil C stock for a simple model (based on Sitompul et al., 2000) of decline of inherited soil C stock and build-up of new soil C stockk based on oil palm above- and belowground residues.

A recent summary of soil C stock dynamics on agricultural soils described a 'soil C transition curve', with initial decline followed by recovery. Where net recovery has occurred under mainstream agricultural practice, it has generally been associated with an increase of organic inputs, above and/or belowground, and reduction of soil tillage (van Noordwijk et al., 2015a). It seems to be plausible that a similar dynamic occurs within each oil palm life cycle, and that both net increases and net decreases are possible outcomes, depending on details of site and management. The real 'proof of the pudding' of sustainability assessments is the long-term persistence of productivity. The plantations that were part of this survey that were in their 2nd or 3rd oil palm cycle was not clearly differentiated from the other data. The primary soil-related issue for such plantation appears to be the increased prevalence of the *Ganoderma* fungus (Corley and Tinker, 2003) rather than net loss of C_{org}. A more detailed specific sampling of these plantations may in future test hypotheses that relate changes in both *Ganoderma* and C_{org} to mycorrhiza development, beyond what our current data set could assert.

Overall, our data support conclusions of 'no net effect' for the response of soil carbon to well-managed oil palm plantations, compared to either a forest or a non-forest land use history. This conclusion is dependent on current management practices, and may need to be revised if practices change (e.g. by removal of fronds as source of biofuel). Carbon footprint calculations and national C accounting schemes can use a no-change assumption, while further exploration of the balance between decay and build-up of soil carbon may explain some of the apparent differences found between plantations.

3.5. Conclusions

The weighted average of corrected soil C stock in the top 30 cm across the four management zones from plantations with "good practice" management (as currently practiced in Indonesia) did, on average, not change significantly over the plantation cycle. These results imply that current retention in the field of organic plant residues and pruned fronds can recover from the initial loss and maintain soil C stock when assessed over a production cycle Thus, there was no detectable net carbon emission from soil at a scale relevant for national C accounting. Increments that are supposed to accrue for oil palm established in non-forest backgrounds were not evident. With current soil management practices, it is appropriate for life-cycle assessments to assume that soil C stock on mineral soils neither increase nor decrease due to oil palm cultivation.


N

Chapter 4

Subsidence and CO_2 emissions in a smallholder peatland mosaic in Sumatra, Indonesia[7]

[7] This chapter was published as
Khasanah N and van Noordwijk M. 2018. Subsidence and CO_2 emissions in a smallholder peatland mosaic in Sumatra, Indonesia. Mitig Adapt Strateg Glob Change. https://doi.org/10.1007/s11027-018-9803-2

Abstract

Most attention in quantifying carbon dioxide (CO_2) emissions from tropical peatlands has been on large-scale plantations (industrial timber, oil palm (*Elaeis guinensis*)), differing in drainage and land-use practices from smallholder farms. We measured subsidence and changes in bulk density and carbon organic content to calculate CO_2 emissions over 2.5 years in remnant logged-over forest and four dominant smallholder land-use types in Tanjung Jabung Barat District, Jambi Province, Sumatra, Indonesia: 1. simple rubber (*Hevea brasiliensis*) agroforest (>30 years); 2. mixed coconut (*Cocos nucifera*) and coffee gardens (*Coffea liberica*) (>40 years); 3. mixed betel nut (*Areca catechu*) and coffee gardens (>20 years); 4. oil palm plantation (1 year). We quantified changes in microtopography for each site for greater accuracy of subsidence estimates and tested the effects of nitrogen and phosphorus application. All sites had a fibric type of peat with depths of 50–>100 cm. A recently established oil-palm had the highest rate of peat subsidence and emission (4.7 cm yr^{-1} or 121 Mg CO_2 ha^{-1} yr^{-1}) while the remnant forest had the lowest (1.8 cm yr^{-1} or 40 Mg CO_2 ha^{-1} yr^{-1}). Other land-use types subsided by 2–3 cm yr^{-1}, emitting 70–85 Mg CO_2 ha^{-1} yr^{-1}. Fertilizer application did not have a consistent effect on inferred emissions. Additional emissions in the first years after drainage, despite groundwater tables of 40 cm, were of the order of belowground biomass of peat forest. Despite maintaining higher water tables, smallholder landscapes have CO_2 emissions close to, but above current IPCC defaults.

Keywords: agroforestry, CO_2 emissions, fertilizer application, peat subsidence, smallholder, tropical peatlands

4.1. Introduction

Indonesia has experienced the world's highest land-based carbon (C) emissions over the past decades owing to a combination of forest conversion (Margono et al., 2014), peatland drainage (Tata et al., 2014; Thorburn and Kull 2015) and land-clearing fires that escaped control (Turetsky et al., 2015). Indonesia has also, however, been an early champion of climate-change mitigation measures in the forest and peatland sectors (van Noordwijk et al., 2014a; Busch et al., 2015) and of an integrated policy environment for combining adaptation and mitigation aspects from local to national levels (Agung et al., 2014; Di Gregorio et al., 2017). In developing land-use policies, rather than separate policies for forestry and agriculture, the specific issue of tropical peatlands and the fires and haze caused by their conversion, has played an important role (Abood et al., 2015, Wijedasa et al., 2017, Larsen et al., 2018). Current scenario models (Mulia et al., 2014; Suwarno et al., 2018a, b) are, however, constrained by a lack of reliable data for emissions from existing smallholder land-use systems on peat.

Page et al. (2011b) estimated that 56% (24.8 Mha) of the global area of tropical peatlands is in Southeast Asia, mostly in Indonesia (20.6 Mha) and Malaysia (2.5 Mha). While recent estimates of peat areas in Africa and Latin America have increased (Gumbricht et al., 2017), most of the current carbon dioxide (CO_2) emissions from tropical peatland occur in Southeast Asia owing to high forest conversion rates. Approximately 35% of the Indonesian peatland area (7.2 Mha) is in Sumatra (Wahyunto et al., 2003), with other areas mainly in Kalimantan and Papua. As long as other land was available for conversion, peat swamps were mostly by passed by development, with smallholder mosaic agriculture nibbling at the edges. Large-scale conversion started in Indonesia and Malaysia in the 1990s, when conflicts over land tenure in other forest areas could be avoided by shifting to the peat-covered parts of the landscape. Large areas have been drained for agricultural use, mostly oil palm (*Elaeis guinensis*) and pulpwood plantations (Miettinen et al., 2016), producing continuous CO_2 emissions, subsidence and changes to the peat's characteristics owing to drainage.

To prevent subsidence and emissions, groundwater levels should be maintained between 40 cm below and 100 cm above the peat surface. This recommendation by Wösten et al. (2008) has been used as a generic policy standard in Indonesia. The rate of CO_2 emissions of large-scale plantations has been widely studied (Page et al., 2011a; Carlson et al., 2015; Sumarga et al., 2016; Wakhid et al., 2017) but little is yet known of the subsidence and emission dynamics in the specific context of smallholder mosaic landscapes. Nonetheless, mandated groundwater levels for rewetted peat landscapes are applied to smallholder landscapes as well as plantations. Technical drainage specifications are based on avoiding crop damage in the wettest places (typically in-between drainage canals), with a management trade-off between the distance of canals (and thus total length of canals) and the water table to be maintained in the canals (van Noordwijk et al., 2014b). Smallholder peatland mosaics have made different choices in this trade-off compared to large-scale operators with more technical means to make deeper canals further apart. In the current debate, opportunities for low-drainage, low-carbon-emission peatland livelihoods are highly sought after but have hardly been evaluated.

Tropical peats are mostly water. With 5–15% dry matter content, they are essentially a suspended litter layer of dead leaves, branches and occasional tree trunks arrested in early stages of decomposition, where structural coherence is primarily obtained from tree roots (Page et al., 1999). As anyone who has walked in a tropical peat swamp knows, beyond the roots one can sink deeply, before finding a branch or trunk that holds. Carbon accumulation in tropical peat, compared to other forest, occurs not because of high plant production but rather because of slow decomposition of roots and wood under anaerobic conditions (Chimner and Ewel 2005). Southeast Asian peat swamps can contain up to 10,000 years of litter accumulation in peat domes more than 10 m thick at their core. The carbon storage per metre of peat depends primarily on the bulk density, ranging 250–750 Mg ha^{-1} of C, which exceeds the aboveground C storage of tropical rainforests, accumulated at a rate of 0.5–1 mm yr^{-1} or 0.25–5 Mg C ha^{-1} yr^{-1} (Tiemeyer and Kahle, 2014; Kurnianto et al., 2015). When such peatlands are drained, the initial rate of subsidence is several centimetres per year owing to a combination of consolidation (increase in bulk density) and decomposition (releasing the net accumulation of 30–100 years (Wösten et al., 1997; Hooijer et al., 2010; Hooijer et al., 2012). The ratio between consolidation and decomposition tends to decrease with time (Frolking et al., 2010). Subsequent decomposition can both increase and decrease bulk density, in the absence of weight that leads to compaction (Hooijer et al., 2012). Aerobic microflora is responsible for the increase in decomposition rate after drainage (Nurulita 2016), initially with little help from the litter organisms that comminute litter in aerobic forest soils (Garcia-Palacios et al., 2016). The microflora may well be nutrient (nitrogen (N), phosphorus (P)) limited, as peat swamp-forests function at high C:N and C:P ratios. Some published evidence exists for N and P effects on temperate zone and tropical peat decomposition (Crill et al., 1994; Song et al., 2013; Jauhiainen et al., 2014; Reeza et al., 2014). Handayani (2009) documented an initial response of respiration after N addition to peat soils from Aceh (Sumatra). Maswar (2011) in a study of subsidence and emissions in recently opened peat swamps under various types of land use at the same site found emissions in the first 3–5 years after drainage to be substantially higher than in the subsequent period. The literature is clear on the decline over time of subsidence and decomposition rates but not on the process-level explanation (van Noordwijk et al., 2014b). As decomposing bacteria themselves don't keep track of time, explanations could be based on a changing quality of remaining substrate (once the more easily decomposable pools have been exhausted), the circumstances (return to wetter conditions after subsidence and structural collapse), or a combination of both. The total additional emissions in early years in the Maswar (2011) data amount to a pool size of 100–200 Mg C ha^{-1}, similar to the belowground biomass of the forest that preceded it.

The rate of peatland CO_2 emissions is large but so is the uncertainty of available estimates. Measured rates of CO_2 emissions from drained peatlands vary widely, with depth of water table, climate, peat temperature (Marwanto and Agus 2014), and farming practices recognized as sources of variation (Hooijer et al., 2012; Maswar 2011; Carlson et al., 2015). Variation in the fraction of fresh wood debris in the peat, according to Paramananthan (2010a, b) and Veloo et al. (2015), may well have to be added to the commonly used fibric/hemic/sapric classification of 'peat maturity' and stage of decomposition. Bulk density and ash content are partially correlated with peat maturity. Existing published estimates, derived with some variation in methods, range widely: 20 Mg CO_2 ha^{-1} yr^{-1} (Carlson et al., 2015); 2.4–48 Mg CO_2 ha^{-1} yr^{-1} (Maswar 2011); 44.0–58.7 Mg CO_2 ha^{-1} yr^{-1} (DID and LAWOO 1996); 58.4–74.5 Mg CO_2 ha^{-1} yr^{-1} (Couwenberg and Hooijer 2013); 72.7 (Othman et al., 2011) to 100 Mg CO_2 ha^{-1} yr^{-1} (Hooijer et al., 2012). Part of this variation may reflect genuine differences in local contexts but variations in methods and associated biases cannot be excluded. While chamber-based estimates (Wakhid et al., 2017) require scaling up from measurement periods to an annual basis and face challenges in the day-night rhythms of respiration and in separating root from peat-based respiration as described by Marwanto and Agus (2014), the subsidence measurements suffer from uncertainties in the dynamics of microtopography of the peat surface as common measurement protocols for subsidence suggest a single reading of height relative to a rod that is fixed below the peat layers (Couwenberg and Hooijer 2013).

The underlying mineral soil as well as the surface have more relief than in standard diagrammatic representations (Figure 4.1) and spatial variation in peat depth at the scale of annual subsidence rates is considerable. Dynamics of microtopography around the measurement point may thus be confounded with overall subsidence (Maswar 2011). Rather than using a single depth measurement, local mapping of topography around the measurement points might give more certain results. Page et al. (2009) commented that "at the local scale the peat surface microtopography of hummocks, comprising tree bases, and hollows, which are interspersed with tree breathing roots, reduce the water flow rate and help maintain the water table close to or above the surface throughout the year". It is not clear at what temporal scale this microtopography is changing. Beyond variation in water-table depth throughout the year, differences in nutrient supply might also influence results with the specific effects of fertilizer application largely untested. An alternative method for estimating cumulative CO_2 emissions since the start of drainage is based on the assumption that ash components are conservative, and that increasing ash concentration indicates C loss (Grønlund et al., 2008; Maswar 2011). This method relies on estimates of pre-drainage ash content, for example, derived from the ash content in deeper layers of the same profile. The advantage of this method is that single point measurements suffice but it has not been adequately compared with data from actual change monitoring.

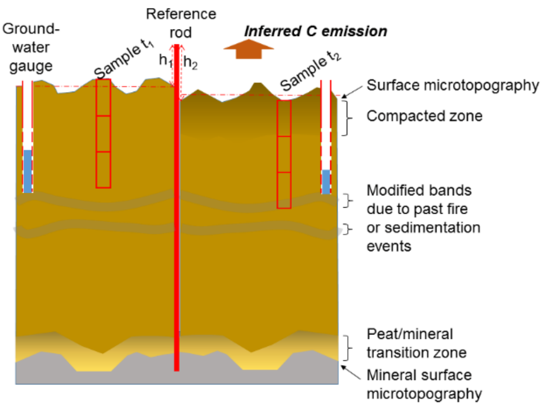

Figure. 4.1. Schematic representation of the challenge to infer C emissions from measured height change with at least two-time intervals (here mirrored around the rod) in the face of compaction, dynamics of surface microtopography and presence of bands of modified peat from past disturbances

Of the total area of Tanjung Jabung Barat District, Jambi Province, Sumatra, Indonesia, approximately 40% (200,000 ha) is peatland (Wahyunto et al., 2003) and 8% (16,065 ha) of that is hutan lindung gambut (HLG) or peat protection forest. In the 1970s, over-exploitation of logging concessions converted primary peat forest to logged-over forest (Widayati et al., 2012), which was later claimed by smallholders, drained and cultivated with coconut (*Cocos nucifera*), rubber (*Hevea brasiliensis*) and coffee (*Coffea liberica*) systems. Recently, large-scale plantations of oil palm and fast-growing pulpwood (*Acacia mangium* and *Acacia crassicarpa*) were established. Conflicts over the land rights assigned to them by the central government became violent (Galudra et al., 2014). CO_2 emissions from drained peat is a major issue in the area. The objective of this study was to estimate CO_2 emissions (Mg CO_2 ha^{-1} yr^{-1}) of different land-use types. We quantified peat subsidence and characteristics under smallholder management in relation to the length of time after drainage and fertilizer application. Specific questions for the measurement and data analysis of smallholder land-use systems on peat were four-fold:

1. is there any variation of subsidence and emissions between land-use types and time after drainage (earlier compared to recent drainage)?
2. does the average of multiple readings of subsidence by taking into account dynamics of microtopography reduce uncertainty relative to a single reading of subsidence?
3. do changes in ash content reflect the rate of emissions?
4. does fertilisation (nitrogen, phosphorus) affect subsidence and/or emissions?

4.2. Methods

4.2.1. Study site

The study was conducted in Tanjung Jabung Barat District on the east coast of Jambi Province, Sumatra, Indonesia. Conditions here represented the eastern coastal peat swamp zone of Sumatra, which constitutes roughly one-third of the peat area in Indonesia. It is one of the peat areas most intensively used for smallholder land-use systems. Based on the Köppen climate classification, the study area is classified as Af with minimum, mean and maximum annual air temperatures of 21°C, 30°C, 32°C, respectively; and mean annual rainfall 2324–2373 mm yr^{-1}. During the study period, November 2012–May 2015, rainfall in 2013 was above average (3208 mm yr^{-1}) (Badan Pusat Statistik Kabupaten Tanjung Jabung Barat 2014).

4.2.2. Measurement locations and experimental design

We measured the rate of CO_2 emissions based on measurement of peat subsidence and analysis of peat characteristics in four dominant land-use types managed by smallholders in the region with 2–3 replications for each land-use type: 1. simple rubber (*Hevea brasiliensis*) agroforest; 2. mixed coconut (*Cocos nucifera*) and coffee (*Coffea liberica*); 3. mixed betel nut (*Areca catechu*) and coffee; and 4. oil palm (*Elaeis guinensis*) plantation. The period after drainage varied 20–40 years (>20 years for mixed betel nut and coffee, >30 years for simple rubber agroforest, and >40 years for mixed coconut and coffee), except for oil-palm plantation, at 1 year after drainage, but it had been previously logged many years ago. All sites had fibric peat with depths of 50–>100 cm. The four-dominant land-use types reflected different stages in the local land-use change trajectory. We could not apply a full factorial design of land-use types and time after drainage, specifically, smallholder oil palm could only be sampled in the early stages of its life cycle. As a reference, we also measured the rate of CO_2 emissions in logged-over forest with natural drainage rather than canals. As peat thickness and depth of water table of drained peatland varies, depending on distance to drainage canals (Maswar 2011; Hooijer et al., 2012), in each replication we used four measurement points (Figure 4.2A) in transects perpendicular to the main drainage canal, covering a wide range of peat thickness and depth of water table.

To test the local effects of increased nitrogen and phosphorus nutrition on peat decomposition and subsidence under the prevailing water management regime, we designed fertilizer application treatment with three levels (0N, 1N, and 2N) based on the doses recommended for oil palm (Table 4.1), following a six-monthly schedule. As illustrated in Figure 4.2C, fertilizer subplots were 2 x 2 m2, with subsidence measurements focussed on their centre. Fertilizer application was tested in three different land-use types: 1. simple rubber agroforest; 2. oil-palm plantation; and 3. logged-over forest, and at measurement point 1 and 4 in Figure 4.2A, to test contrasting conditions of peat and water-table depth.

Table 4.1. Doses of fertilizer (N and P) application for each treatment and age of palm per measurement point and application

Treat-ment	Age of palm (year)	# of applica-tion	Urea (kg/tree/application)[1)]	TSP	Urea (kg/m²/application)	TSP
0N	-	-	-	-	-	-
1N	1	2	0.63	0.63	0.28	0.28
	2	2	0.75	0.75	0.33	0.33
	3	2	0.75	0.75	0.33	0.33
2N	1	2	1.25	1.25	0.55	0.55
	2	2	1.50	1.50	0.66	0.66
	3	2	1.50	1.50	0.66	0.66

Assuming the rates are applied over 2.27 m^2 (1.7 m radius circle around the tree). Source: Mutert et al. (1999b)

4.2.3. Peat subsidence measurements

In November 2012 at each replication at each measurement point (Figure 4.2A), monitoring of peat subsidence began with installing metal rods. At each measurement point, a permanent mark (h_{t1}) was made on the metal rod to indicate the initial point of measurement. Peat subsidence (h_{t2}...h_{tn}) was monitored every six months for 2.5 years (November 2012–May 2015) (Figure 4.2B). To quantify heterogeneity of subsidence and dynamics of microtopography around the metal rods, relative heights in eight cardinal directions were also mapped surrounding the central points of the metal rods, at 2–4 m length with 10 cm intervals (Figure 4.2C). For 0N fertilizer application treatment, we used

484 microtopography points in each replication of oil palm, logged-over forest and rubber; and 324 microtopography points in each replication of mixed betel nut and coffee and mixed coconut and coffee. For 1N and 2N fertilizer application treatment, we used 82 microtopography points in each replication and treatment. For each measurement point, the rate of subsidence (cm yr^{-1}) was then calculated separately, with negative subsidence accepted for points that appeared to rise.

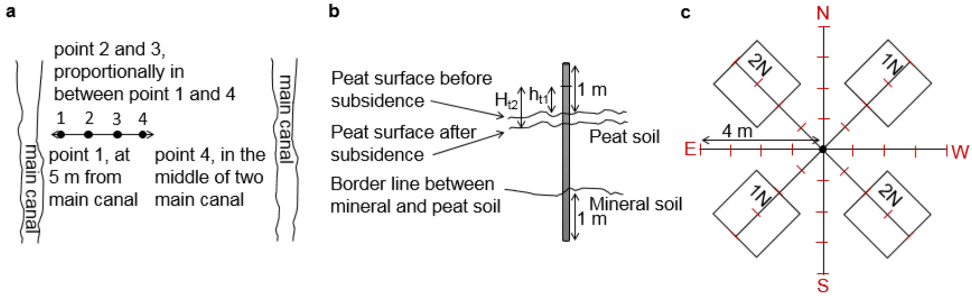

Figure. 4.2. Design of peat subsidence measurement. Four positions of metal rods in transects perpendicular to the main drainage canal to measure peat subsidence (A); illustration of peat subsidence measurement at each metal rod (B); and design of fertilizer application treatment (1N and 2N refer to the amount of fertilizer in Table 4.1)

4.2.4. Peat-characteristics analysis

Every six months at each measurement point and fertilizer application treatment, peat samples to 30 cm depth at 10 cm intervals were taken 0.5–1 m from the metal rod using the Eijkelkamp peat auger (the sample was easily contained in the auger) following Agus et al. (2011). During measurement of microtopography, site compaction by access to the plot could not be fully avoided. The peat samples were taken to the laboratory for bulk density, ash and organic C content analysis. Bulk density was analysed by drying the sample at 105°C for 48 hours or until the sample reached stable dry weight; ash and organic C content was analysed based on the loss on ignition (LOI) method (Agus et al. 2011).

4.2.5. Water-table measurement

The depth of water table at 2 m away from the subsidence measurement point was monitored every month using perforated PVC tubes. At each replication, the depth of water table was calculated over four different measurement points and dates.

4.2.6. Estimation of the rate of CO_2 emission

The rate of CO_2 emission was then estimated from surface height loss (subsidence) and characteristic of peat (bulk density and C organic content) after period of loss (equation

1). The assumption is, after the end of the consolidation phase that follows immediately after drainage, compaction and oxidation are the only causes of surface height loss.

$$C = S_t \times BD_t \times C_t \times 3.67 \qquad [1]$$

where C is annual CO_2 emissions (Mg CO_2 ha^{-1} yr^{-1}), St is annual surface height loss (cm yr^{-1}), Ct is organic C content (%) after loss, BDt is bulk density (g cm-3) after loss, and 3.67 is a conversion from C to CO_2. The relative weight loss on ignition is the complement of relative ash content provided the organic matter content, with estimates of the C concentration in organic matter (which depends essentially on the C:O ratio of the latter) derived from literature.

We also compared the rate of emission based on subsidence to ash content differences (before and after period of loss), modified from Grønlund et al. (2008), which can be used to estimate cumulative emissions since drainage based in a single measurement:

$$C = \left(\left((A_2 \times BD_2 \times T) \times \left({}^{1}/_{A_1} - 1\right) - \left((1 - A_2) \times BD_2 \times T\right)\right)/1.922\right) \times 100 \times 3.67/t \qquad [2]$$

where A_2 is ash concentration measured after t years of change; A_1 is (inferred) ash concentration before loss; BD_2 is bulk density (g cm^{-3}) at measurement time; T is thickness of soil sample; and 1.922, 3.67, and 100 are conversion factors from mass of soil to C, from C to CO_2, and from g cm^{-2} to Mg ha^{-1}, respectively.

A similar calculation (eq. 1 and eq. 2) was also applied to estimate the rate of CO_2 emissions because of fertilizer application.

4.2.7. Statistical data analysis

Characteristics of peat (bulk density, ash and organic C content) were analysed for effect of the single factor of date of measurement, leaving replication, fertilizer application, depth of sampling, and measurement points as co-variates, using SYSTAT 11. In the statistical analysis, a 5% probability of type I errors was accepted in rejecting null-hypotheses of no difference.

4.3. Results

4.3.1. Dynamics of microtopography

Figure 4.3 presents deviation (difference between value at certain point of measurement and average value at first measurement) of microtopography levels of different land-use types, distance to canal, and time of measurement. In general, it shows that in all measured land-use types and distance to canals, the deviation has shifting trends from time to time. It indicates that the level of subsidence is not homogenous over the soil surface. Homogenous subsidence occurs if the trend has 45 degrees of slope. Further analyses of confidence intervals of single and multiple readings (Figure 4.4) found that the confidence interval of multiple readings is not always narrower than a single reading. The rate of subsidence based on multiple readings was slightly higher than that based on a single reading.

4.3.2. Peat characteristics

The bulk density and ash content of different land-use types is presented in Figure 4.5. The bulk density and ash content are the average of replication and distance to canal. Overall, ash content and bulk density of each land-use type did not show differences ($p < 0.05$) among distance to canal and fertilizer application, except for ash content in oil palm (*Elaeis guinensis*) and simple rubber (*Hevea brasiliensis*) agroforest (differences among distance to canal) and bulk density in simple rubber agroforest (differences among fertilizer application). In terms of date of sampling, ash content of each land-use type tended to increase by time and show differences ($p < 0.05$) among date of measurement. By contrast, bulk density of each land-use type did not show differences ($p < 0.05$) among date of measurement, except for oil palm. Oil palm was the only site examined that was one year after drainage. Among the land-use types, the highest and the lowest bulk densities were found in simple rubber agroforest and logged-over forest, respectively, while the highest and lowest ash content were found in simple rubber agroforest and oil palm, respectively.

4.3.3. Peat subsidence and emissions

The pattern of peat characteristics that show differences among date of measurement (Figure 4.5) but not among distance to canal allowed us to estimate the rates of emission (Mg CO_2 ha^{-1} yr^{-1}) of different land-use types and fertilizer application based on peat subsidence and bulk density and organic C content of each measurement date. However, unclear patterns of emissions led us to use average value of bulk density and organic C content over all dates of measurement and present the rates as the weighted average of distance to canal.

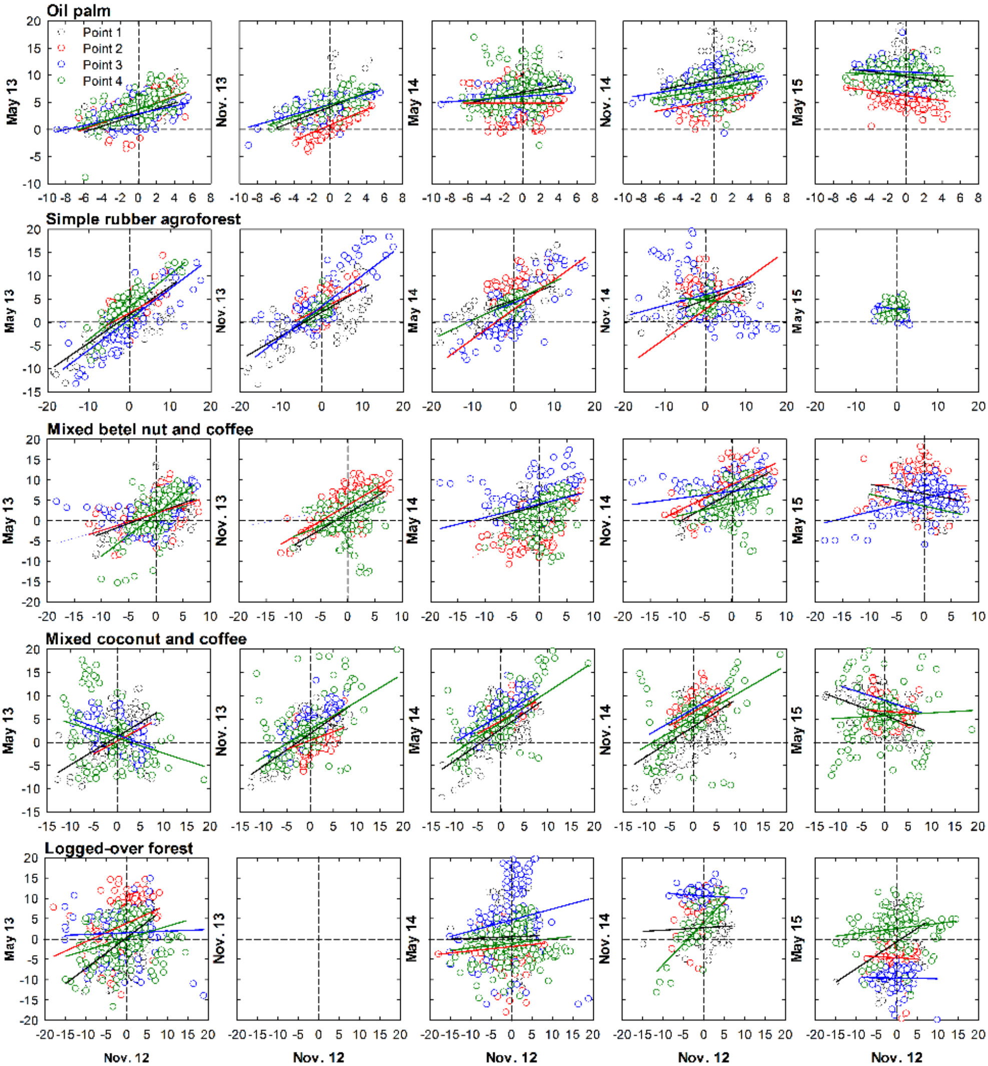

Figure. 4.3. Deviation (difference between values at certain points of measurement and average value at first measurement) of microtopography levels of different land-use types, distance to canal, and time of measurement. X axis is deviation at t and Y axis is deviation at t+1

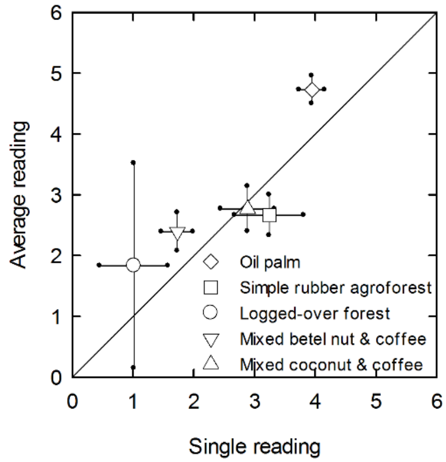

Figure. 4.4. The inferred rate of peat subsidence (cm yr^{-1}) based on a single reading at the central metal rod compared to the average of multiple readings for all microtopography sites

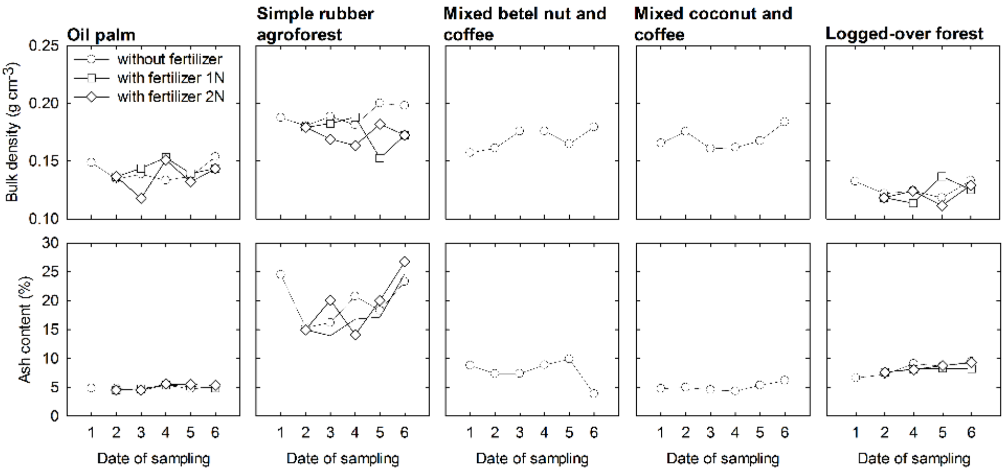

Figure. 4.5. Mean of bulk density (g cm^{-3}) and ash content (%) for different land-use types. Date of sampling: 1. Nov 2012; 2. May 2013; 3. Nov 2013; 4. May 2014; 5. Nov 2014; 6. May 2015.

4.3.3.1. Emissions based on peat subsidence and peat characteristics compared to ash content differences

Figure 4.6 presents the comparison of the rate of emission based on subsidence and peat characteristics (Eq.1) with the rate of emission based on ash content differences (Eq.2). The latter provided extremely high emission estimates, negatively correlated with results of subsidence measurement. For subsequent analysis, we relied on the subsidence measurements.

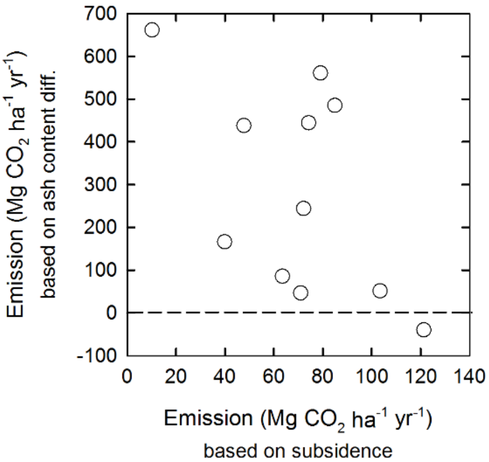

Figure. 4.6. Emissions (Mg CO_2 ha^{-1} yr^{-1}) based on subsidence and peat characteristics (C_{org} and bulk density) compared to ash content differences

4.3.3.2. Emissions of different fertilizer application and land-use types

Table 4.2 shows that fertilizer application did not have a consistent effect on the rates of peat subsidence and emission. The highest rates of peat subsidence and emission were found in the recently established oil palm (4.7 cm yr^{-1} or 121 Mg CO_2 ha^{-1} yr^{-1}) and the lowest in the reference plot with natural canals and logged-over forest (0.5 cm yr^{-1} or 10.2 Mg CO_2 ha^{-1} yr^{-1}). Other land-use types that had drained more than 20 years had 2–3 cm yr^{-1} of subsidence or 70–85 Mg CO_2 ha^{-1} yr^{-1}.

Further analysis by plotting the average of water-table depth and the rate of subsidence showed that the deeper the water table the higher the rate of subsidence (Figure 4.7) but this only occurred at sites drained more than 20 years ago (simple rubber agroforest, mixed coconut and coffee, and mixed betel nut and coffee) or reference site with natural canals and logged-over forest. At the recently established site with oil palm, although the water-table depth was less than those sites with longer periods after drainage, the rate of subsidence was high.

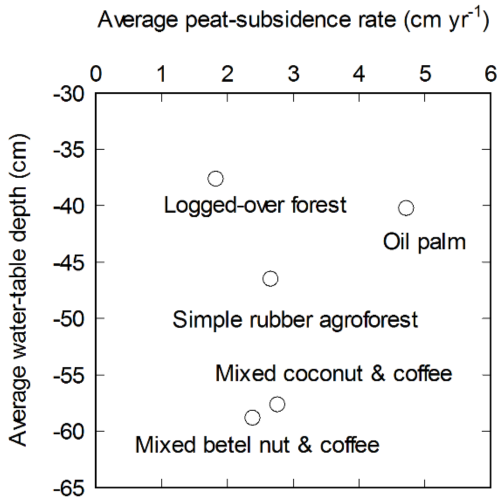

Figure. 4.7. Average of water-table depth (cm) and peat-subsidence rate (cm yr^{-1}) of different land uses at no fertilizer application

4.4. Discussion

We estimated the annual rates of peat subsidence (cm yr^{-1}) and CO_2 emissions (Mg CO_2 ha^{-1} yr^{-1}) of different land-use types under smallholder management. Most studies quantifying CO_2 emissions from tropical peatlands have been focused on large-scale plantations of commodities, such as oil palm (*Elaeis guinensis*) and pulpwood (Page et al., 2011a; Jauhiainen et al., 2012; Hooijer et al., 2012). The CO_2 emissions from smallholder peat land-use systems with less intensive drainage systems have not received enough attention. The study was designed to answer four questions. In response to the first question regarding variation of subsidence and emission between land-use types and time after drainage (earlier compared to recent drainage), our study confirmed that early stages of drainage lead to rapid collapse, even with fairly high groundwater tables.

The recently established oil palm subsided 4.7 cm yr^{-1}, emitting 121 Mg CO_2 ha^{-1} yr^{-1}. However, this value is significantly lower than what was reported in a review on peat CO_2 emissions from oil palm and pulpwood large plantations. Peat emissions in the early stages of plantation drainage are about 178 Mg CO_2 ha^{-1} yr^{-1} (Page et al., 2011a). Other land-use types more than 20 years after drainage subsided by 2–3 cm yr^{-1}, emitting 70–85 Mg CO_2 ha^{-1} yr^{-1}. This value is slightly lower than what was reported in the same review (86 Mg CO_2 ha^{-1} yr^{-1}, annualized over 50 years).

Our estimates were higher than the recent peat-oxidation emission values for tropical peatland set by the Intergovernmental Panel on Climate Change (IPCC 2014), which suggested default values of 51 Mg CO_2 ha^{-1} yr^{-1} for smallholder systems, 55 Mg CO_2 ha^{-1} yr^{-1} for commercial plantations (oil palm, industrial timber) and 10 Mg CO_2 ha^{-1} yr^{-1} for disturbed secondary forest. Estimates by Miettinen et al. (2017) of cumulative carbon emissions estimates since 1990 from peat oxidation in Peninsular Malaysia, Sumatra and Borneo, based on the IPCC defaults, may thus be on the low side. Their estimate that 34% of emissions so far have occurred in smallholder areas and 44% in industrial plantations (mostly oil palm and industrial timber), and the remaining 22% from disturbed forests, would not be much different if our results were added to the emission-factor database, as emission factors would increase for all land uses. Ishikura et al. (2018) reported subsidence of 1.55–1.62 cm yr^{-1} for oil palm in Sarawak (Malaysia), with corresponding CO_2 emissions, measured in chambers and after correction for root respiration, of around 40 Mg CO_2 ha^{-1} yr^{-1}. A further analysis of the differences in substrate (peat type) and details of groundwater dynamics will be needed to reduce uncertainty in the estimates.

In relation to the second question, several studies on microtopography of peatland reported that formation of the microtopography of the peat surface is a product of an interaction of autogenic and allogenic processes (Nungesser 2003), with others noting the effects of water-table fluctuation, tree diversity (Shi et al., 2015; Lampela et al., 2016) and wildfire (Benscoter et al., 2005; Benscoter et al., 2015), though those processes might be random (Lampela et al., 2016). Our subsidence measurement confirmed that the level of subsidence over the soil surface was heterogenous and consequently multiple readings by considering the micro topographical dynamics of subsidence would be more accurate.

Regarding the third question (use of the Grønlund et al. (2008) equation), the results in Figure 4.6 showed that for our 0.5–1 m peat depth setting, estimation of emissions based on one-off (without subsidence recording) measurement of peat characteristics (bulk density and organic C content), with inferred ash content differences to a pre-drainage control, provided high and unstable values compared to the commonly used subsidence method. Although the method may give some early indications in a soil-survey context, close scrutiny of the validity of the underlying assumptions would be needed before it could be used in confidence. Warren et al. (2012) found within a specific data set that the relationship between bulk density and ash content was sufficiently tight to estimate the second from the first. Farmer et al. (2014) found this assumption to be unreliable where multiple land-use histories were involved. The dynamic of C organic content and approximately stable bulk density indicated that the main contribution of peat subsidence is oxidation, or the decomposition process, and a small effect of compaction during measurement, though the plots had been drained 20–40 years ago. In line with this result, Hooijer et al. (2012) reported that oxidation or decomposition was not only the main contribution of peat subsidence at the early stage of peat drainage but can also contribute at the later stages.

Table 4.2. Average of peat subsidence rate (cm yr^{-1}), bulk density (g cm^{-3}), C_{org} (%) and peat emission rate (Mg CO_2 ha^{-1} yr^{-1}) of different land-use types and fertilizer application

Land-use types	Fertilizer application	Years after drainage (yr)	Subsidence rate (cm yr^{-1})	Bulk density (g cm^{-3})	C_{org} (%)	Emissions (Mg CO_2 ha^{-1} yr^{-1})
Oil palm	0	1	4.7	0.14	49.4	121.4
	1		4.2	0.14	49.3	103.5
	2		2.6	0.13	49.3	63.5
Simple rubber agroforest	0	>30	2.7	0.20	41.4	79.1
	1		2.7	0.18	42.4	74.2
	2		2.5	0.18	42.9	72.2
Logged-over forest	0	-	1.8	0.12	47.6	39.9
	1		2.2	0.12	47.7	47.8
	2		0.5	0.11	47.5	10.2
Mixed betel nut & coffee	0	>20	2.4	0.17	48.1	71.0
Mixed coconut & coffee	0	>40	2.8	0.17	49.4	85.0

For the last question, emission effects of fertilizer application on peat subsidence were small relative to effects of water-table depth. This result is in line with findings reported by Oktarita et al. (2017), where the impact of fertilized-induced emissions was minimal, though under fully controlled experimental conditions fertilizer application has been shown to increase the decomposition rate (Reeza et al., 2014). The response of tree-root systems to local nutrient enrichment may contribute to differences between field results and those obtained in conditions where microbial processes dominate.

Overall, our data with long-term emission rates for smallholder land uses in the range of 70–85 Mg CO_2 ha^{-1} yr^{-1}, along with the spatial analysis by Miettinen et al. (2017), support specific attention to emissions from peatland under smallholder management. As shown by Miettinen et al. (2017) and Warren et al. (2017), emissions during land-clearing fires, which have received considerable public attention, are less than half of the total emissions caused by disturbing and converting the remaining peat forests. From a global emissions perspective, the recurrent emissions need to be controlled, with the fine-tuning of water management in already converted peat landscapes a high priority. Current water management depends primarily on uncontrolled drainage in open canals and affects adjacent forests, shifting them from carbon sinks to carbon sources (Miettinen et al., 2017). Effective solutions will require peat hydrological units to be reconciled with the scale at which land-use decisions are made in practice (Ritzema et al., 2014; Evers et al., 2017; Suwarno et al., 2018b).

4.5. Conclusion

Our research found that emission estimates based on peat subsidence can be improved by taking microtopography into account, using multiple readings around measurement rods. The partial independence of local surface dynamics relates to the dynamics of water-table depth, root activity and accumulation of litter on the soil surface may need to be included in estimates of the rate of peat CO_2 emissions of drained peatlands. The rate of peat CO_2 emissions based on the subsidence rate between two different measuring times in combination with peat characteristics (bulk density and C organic content) provided a better estimation than an ash-based ‘internal tracer’ method. Long-term drainage can be expected to decrease the rate of CO_2 emissions at a given groundwater depth, with additional emissions in early stages of the same order as decayed root biomass of the preceding vegetation, while fertilizer application did not show a strong effect on the rates of peat subsidence and emissions.

Chapter 5

Can intensification reduce emission intensity of biofuel through optimized fertilizer use?

Theory and the case of oil palm in Indonesia[8]

[8] *This chapter was published as*
van Noordwijk M, Khasanah N, Dewi S. 2016. Can intensification reduce emission intensity of biofuel through optimized fertilizer use? Theory and the case of oil palm in Indonesia. Global Change Biology Bioenergy: 1-13. DOI: 10.1111/gcbb.12398.

Abstract

Closing yield gaps through higher fertilizer use increases direct greenhouse gas emissions but shares the burden over a larger production volume. Net greenhouse gas (GHG) footprints per unit product under agricultural intensification vary depending on the context, scale, and accounting method. Life cycle analysis of footprints includes attributable emissions due to: I) land conversion ('fixed cost'), II) external inputs used ('variable cost'), III) crop production ('agronomic efficiency'), and IV) post-harvest transport and processing ('proportional' cost). The interplay between fixed and variable costs results in a nuanced opportunity for intermediate levels of intensification to minimize footprints. The fertilizer level that minimizes the footprint may differ from the economic optimum. The optimization problem can be solved algebraically for quadratic crop fertilizer response equations. We applied this theory to data of palm oil production and fertilizer use from 23 plantations across the Indonesian production range. The current EU threshold requiring at least 35% emission saving for biofuel use can never be achieved by palm oil if produced: (i) on peat soils, or (ii) on mineral soils where the C-debt due to conversion is larger than 20 Mg C ha^{-1}, if the footprint is calculated using an emission ratio of N_2O-N/N-fertilizer of 4%. At current fertilizer price levels in Indonesia the economically optimized N fertilizer rate is 344-394 kg N ha^{-1}, while the reported mean N fertilizer rate is 141 kg N ha^{-1} yr^{-1} and rates of 74-277 kg N ha^{-1} would minimize footprints, for a N_2O-N/N-fertilizer ratio of 4-1%, respectively. At a C-debt of 30 Mg C ha^{-1} these values are 200-310 kg N ha^{-1}. Sustainable weighting of ecology and economics would require a higher fertilizer/yield price ratio, depending on C-debt. Increasing production by higher fertilizer use from current 67 to 80% of attainable yields would not decrease footprints in current production conditions.

Keywords: carbon emission, intensification, net emission saving, palm oil, land sparing/sharing, biofuel policy, fertilizer price

5.1. Introduction

The Borlaug or 'land sparing' hypothesis (Sanchez, 1994; Rudel et al., 2009) states that intensifying agriculture will have net positive effects on the environment, regardless of any directly negative environmental impacts of 'green revolution' production technology, as it reduces the land base needed to meet world market demand for agricultural products (food, fibre and fuel) and thus reduces biodiversity loss (Green et al., 2005) as well as emissions from deforestation and forest degradation. The 'land sharing' or ecological agriculture hypothesis that forms its counterpart, suggests that a careful balancing of productivity and environmental services in integrated production systems can contribute to a multifunctionality of integrated landscapes that is superior to the 'segregated' agriculture *plus* forest perspective of the Borlaug hypothesis (van Noordwijk et al., 1995; Tomich et al., 1998; Angelsen and Kaimowitz, 2001; Lee and Barrett, 2001). Choices for an optimal level of intensification may depend on location ('theory of place') (van Noordwijk et al., 2015b), type of environmental services considered (Grau et al., 2013) and scale (Minang et al., 2015). As currently framed (Minang and van Noordwijk, 2013), the sparing *plus* sharing debate considers the wider policy context that is needed to turn a 'necessary' to a 'sufficient' condition: environmental issues and deforestation cannot be resolved without an increase in yield levels that exceeds the growth in global demand for food, fibre and energy. However, it is naive to expect markets to directly effectuate environmental benefits through a pathway of reducing the profitability of less-efficient production modes. Both 'sparing' and 'sharing' approaches will only achieve environmental benefits if the opportunity for such benefits is utilized in active 'caring' approaches (Jackson et al., 2011). As earlier assumptions about direct links between yield and efficiency gap are not supported by evidence (van Noordwijk and Cadisch, 2002; van Noordwijk and Brussaard, 2014c) there is space for intermediate intensity solutions to be optimal from a societal perspective. Regulation of land use, however, cannot easily incorporate the fine-tuning needed to minimize environmental effects of land use change (Lambin et al., 2014). Pricing of input costs deserves further analysis as possible fine-tuning method. We here provide a quantitative analysis of intermediate, optimum intensification levels, applicable to biofuels as costs and benefits can both be expressed in terms of net greenhouse gas emissions. For non-biofuel crops a similar analysis will require further steps to bring alternative options onto a single denominator.

In the biofuel debate the interest has shifted from single characteristics of feedstock types (e.g. comparing soybean, oil palm and *Jatropha* oil), to recognition of the management swing potential (Davis et al., 2013; Creutzig et al., 2015) where the footprint of any feedstock depends on where and how it is produced, as much as on what crop it is. The widest swing potential, according to current data, exists for palm oil, with both the best and worst emission intensities per unit product. Oil palm (*Elaeis guineensis* Jacq.) (Corley and Tinker, 2016) expansion is a 'Pandora box' example (Tomich et al., 1998) of intensified tree crop production that attracts new activities in the tropical forest margins and increases forest conversion rather than reducing it. In public debate, oil palm expansion is held responsible for much of the loss of biodiversity and flagship species, but also as a cause of increased greenhouse gas emissions (Sheil et al., 2009). The yield gap in oil palm production is considerable for large-scale plantations and even larger for smallholder production systems (Woittiez et al., 2016), indicating a Land Equivalent Ratio of below 1.0. Existing self-regulation in the industry is based on recommended 'good agricultural practice' without quantification of existing yield and efficiency gaps (von Greibler, 2013). There is little clarity on the level of fertilizer use that is considered good practice, from both a farm-level profitability and an environmental perspective.

The irony of biofuel use increasing rather than decreasing net anthropogenic greenhouse gas emissions in the 'biofuel boom' of the 2000's has led to a rapid regulatory response. A review of recent life-cycle assessment (LCA) studies in support biofuel policy making (van der Voet et al., 2010) showed considerable variation in outcomes, due to real-world differences, data uncertainties and methodological choices. If fossil fuel is partially substituted by 'biofuel' there are costs as well as benefits in terms of greenhouse gas emissions (Wicke et al., 2008). European regulation of the minimum emission reduction factors compared to the use of fossil fuel (emission saving) due to biofuel use in the Renewable Energy Directive of 2008 (European Communities Commission, 2008) has drawn attention to three types of emission costs (Hoefnagels et al., 2010): 1) the carbon debt due to land conversion from higher to lower time-averaged C stock, 2) emissions associated with the production phase of the biofuel, part of which are on-site and part in the industry producing the inputs used, and 3) emissions due to processing and transport. For emissions associated with the production phase the issue of 'optimum intensification' levels is relevant (Jackson et al., 2011): is there any merit in not fully utilizing the biophysical production opportunity of land that is already in agricultural use by moderating the use of fertilizer and similar inputs? Are current costs of fertilizer and other inputs sufficient to induce their wise and efficient use, and low enough to allow 'environmentally optimum' levels of intensification?

The relationship between agricultural yields, environmental impacts of production and optimized use of inputs has been debated since at least the 1980's (van Noordwijk and de Willigen, 1986; de Wit, 1992; Zoebl, 1996). Increased yields increase the denominator of an efficiency (output/input) metric, but increased input levels increase the numerator, and the outcome depends on the shape of the yield and environmental impact response curves. The shape of these response curves themselves depends on factors such as the within-field spatial variability (van Noordwijk and Wadman, 1992; Cassman and Plant, 1992) and the degree of 'precision farming' adjustment of input levels to patch-level production conditions (Heege, 2015). De Wit (1992) showed that in the presence of multiple yield limiting factors, the overall response of yield to aggregated input levels (or their associated environmental consequences) can be multi-phasic. Neither of the extreme positions in the agriculture-environment debate ('Optimize yields economically and environmental impacts per unit product will be minimal' or 'Minimize inputs to maximize efficiency and minimize environmental impacts per unit product') are tenable as generalizations (Wicke et al., 2008). High yield levels can be achieved in combination with low and high efficiency, high efficiency can be coupled to low and high yields (van Noordwijk and de Willigen, 1987). The relationship between efficiency and yield depends on the finer details of the yield and environmental impact responses to input use, requiring empirical study for each crop and its specific physiology and agronomy (Corley et al., 1971).

Fertilizer subsidies have a long history in developing countries as part of policies to stimulate intensification of agriculture and maintain affordable staple food provisioning to urban people. Attempt to segment the markets and subsidize fertilizer only for certain crops or types of farmers are hard to implement, as regional or local fertilizer markets function well. If fertilizer prices are (too) low, efficiency enhancement is not economical (van Noordwijk and Scholten, 1994), if they are (too) high the economical optimum solution may well be the near-complete mining of the soil (van Noordwijk, 1999). The relevance of shifting net fertilizer subsidies towards net taxation has been debated as a measure to reduce negative environmental effects of agricultural production through ground- and surface water pollution or emission of N_2O, a powerful greenhouse gas. Van Noordwijk and Wadman (1992) defined an environmentally optimum fertilizer level by reference to tolerated levels of nitrate enrichment of ground and surface water in the Netherlands; for potential biofuels this target can be replaced by minimization of the emission footprint.

We will here focus on the relationships between N fertilizer use and the greenhouse gas emissions per unit biofuel use relative to the fossil fuel use it can substitute for, using oil palm production in Indonesia as case study. Data from 23 plantations across the Indonesian production conditions (Khasanah et al., 2012, 2015a,b) provided insights into what is currently considered good agronomic practice, as participation in the survey was voluntary. We will provide an algebraic analysis of the problem in generic terms and then review the available quantitative data. Key policy-relevant questions are:

1. is there an 'environmental optimum' production level at which net emission savings per unit biofuel use are maximized?
2. at what fertilizer/product price ratio is the 'economic optimum' fertilization rate equal to the 'environmental optimum' one that minimizes attributable emissions?
3. how do the answers to questions 1 and 2 depend on the overall emissions from the Life Cycle Analysis: (i) C-debt dues to initial land conversion, (ii) CO_2 emissions due to fertilizer production, (iii) the N_2O emission factor per unit fertilizer use, and (vi) the technical coefficients for emissions due to transport and processing?
4. are current policies for fertilizer subsidies and taxation aligned with environmental efficiency?

5.2. Theory

Four production phases contribute to emission estimates of biofuel production in a life cycle analysis (Figure 5.1): I) carbon debt (positive in all cases where the preceding vegetation had a higher C stock than oil palm plantations themselves) and additional emissions due to conversion (e.g. use of fire on peat soils), II) production of external inputs, such as inorganic fertilizer, III) feedstock production that determines the yield per ha that relates area-based terms to product-based accounting, but that may also lead to change in belowground C stocks, recurrent GHG emissions related to drainage and/or N_2O emissions due to fertilizer use, and IV) transport and processing stages before the product reach the end users. A detailed scheme to estimate net emission of biofuel production and emission saving is provided in the supporting information (The Biofuel Emission Reduction Estimator Scheme (BERES)), with some key parameter values that are considered 'defaults' based on measurement and literature review.

The shape of the response curve describing yield as function of fertilizer input has been much debated in the literature, with many empirical results converging on a Mitscherlich curve with asymptotic approach of a maximum yield. De Wit (1992) posed that the diminishing returns interpretation of Mitscherlich curves disappears when multiple constraints are addressed simultaneously. Van Noordwijk and Wadman (1992) explored how empirical Mitscherlich-type curves can be interpreted as the result of spatial variability at field level and patch-level responses by the crop that can be described by a quadratic equation, with a maximum that can be obtained or exceeded in practice. Quadratic models represent the most optimistic perspective on nutrient use efficiency at crop level with minimum field-scale variability. We use them here, and will revert to the validity of this assumption in the discussion section.

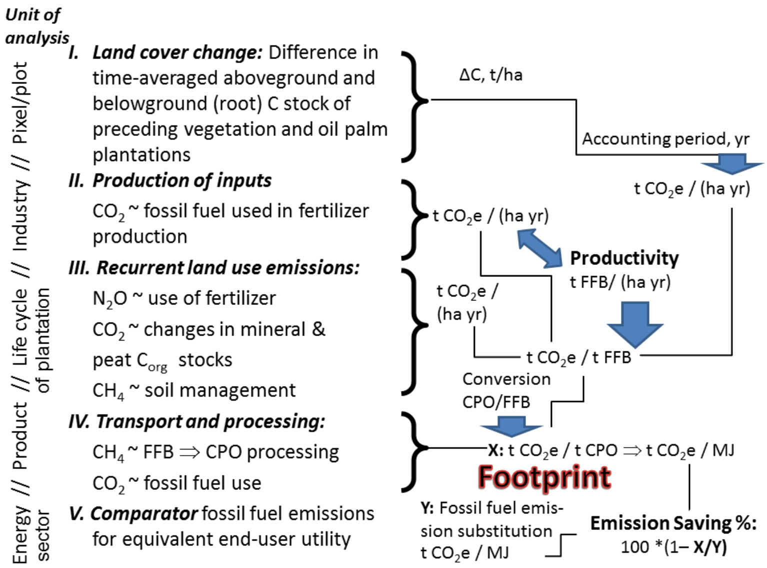

Figure 5.1. Information flow in an assessment of the emission footprint per unit palm oil, and subsequent step to estimate the percentage emission saving in biofuel use.

A quadratic fertilizer (N) yield (Y) response curve ($Y = Y_0 + f N + c N^2$) has 3 parameters (Y_0, f and c), corresponding to the yield without fertilizer use, the initial efficiency of fertilizer use, and a parameter that combines f and the maximum attainable yield, respectively. Net annual emissions per unit crop yield are $E_0 + e_0 + e_f N + \varepsilon Y$ with the parameter E_0 or annualized attribution of the C-debt representing phase I, e_0 (emissions independent of fertilizer use) phase III, e_f (proportional to fertilizer use) phase II and III, and ε (proportional to yield) phase IV.

The emissions per unit production have a local minimum (and hence the emission savings compared to fossil fuel use a local maximum in case of a biofuel crop) when the N-fertilizer rate equals (as derived in supplement S1):

$$N_{minem} = R(\{1 + (1- Y_0 /(f R))/B\}^{0.5}-1)$$

$$R = (E_0+ e_0)/e_f$$

$$B = f R /(Y_{max}-Y_0) = (E_0+ e_0) /\{(e_f /f) (Y_{max}-Y_0)\}$$

where R and B are intermediate terms, f is initial marginal yield increment per unit fertilizer use, E_0 is attributable CO_2eq emissions per ha per year due to initial land conversion, e_0 is attributable CO_2eq emissions per ha per year in the production stage at zero fertilizer use, e_f is attributable CO_2eq emissions per ha per year per unit fertilizer use in the production stage, Y_0 is the yield level in the absence of fertilizer use and Y_{max} is the maximum attainable yield under current circumstances beyond fertilizer use. The dimensionless B grouping is the ratio of the 'fixed cost' emissions E_0+ e_0 and the maximum of fertilizer related emissions, (Y_{max} - Y_0) (e_f /f). If p is the price ratio of yield products and fertilizer inputs, the economic optimum N fertilizer rate equals the fertilizer rate that minimizes emissions per unit yield, if p = p_{SWEET} (SWEET = 'Sustainable Weighting of Ecology Economics Tradeoffs') (see supplementary information for the derivation, S1):

$$p_{SWEET} = f\,(1 - 0.5\,B\,(\{1 + (1- Y_0\,/(f\,R))/B\}^{0.5}-1))$$

While this provides a generic answer to question 2, questions 1, 3 and 4 require parametrization for specific combinations of crop, attributable emissions from C-debt and fertilizer use. Please note that the post-harvest emissions (Phase IV) represented in the term ε are not influencing the fertilizer rate that minimizes net attributable emissions and the outcome of the sparing *versus* sharing debate. Phase IV emissions, however, can be an important determinant of the absolute level of emission attribution per unit final product and whether or not the overall footprint meets standards set.

5.3. Materials and Methods

5.3.1. Sampling design

The IPOC/ICRAF survey of Indonesian palm oil production in 2010 was designed to estimate greenhouse gas emissions due to palm oil production across the major stratifying production factors in Indonesia (Khasanah et al., 2015a,b). The three primary stratifiers of the survey were defined at national level as mineral *versus* peat soils, plantations directly derived from forest or from other land cover types, and three levels of the prevalence of oil palm at provincial level (<1%, 1-5%, >5%), as indicator of the areas that first developed oil palm, are probably most suited to it climatically, and have the most advanced input and output markets. Not all 12 factorial combinations are important in practice, as oil palm on peat has mostly been directly derived from forest. The sampling design followed a stepwise cluster approach, soliciting self-nomination of companies to involve in learning the method while involving in data collection (Khasanah et al., 2012; Khasanah et al., 2015a,b). Candidate companies were asked to describe land history, soil type and the scale of management (plantations, outgrowers, independent smallholders). A total of 23 plantations was selected, for study, representing 9 of the 12 clusters (Table 5.1). Figure 5.2 presents the spatial distribution of the selected samples by relative oil palm density in a province.

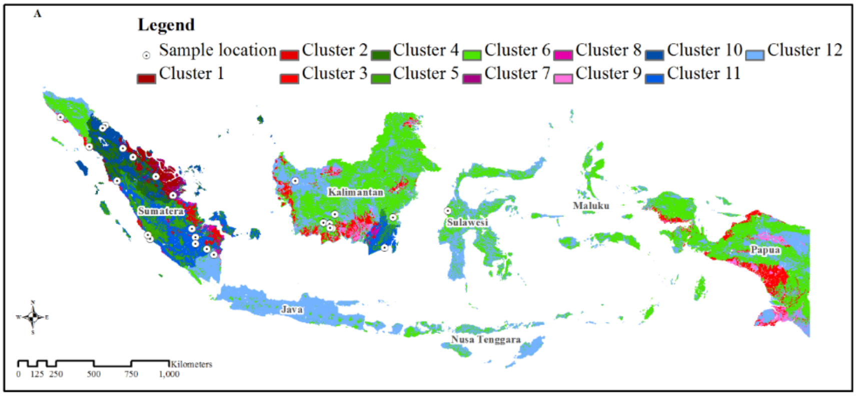

Figure 5.2. Sample distribution of oil palm plantations in the IPOC/ICRAF survey.

5.3.2. Data collection and analysis

In the 23 selected oil palm plantations, we collected the main parameters needed for the Biofuel Emission Reduction Estimator Scheme (BERES) (van Noordwijk et al., 2013; see supporting material S2) to calculate net emission of biofuel production and emission saving using a life cycle approach. The scheme is aligned with the way the EU RED policy requires life-cycle data on the biofuel value chain. In the application, however, we did not use the 2008 'grandfather' rule that ignores C debts for land converted before the rules were made. It requires data for: (i) C-stock (Mg C ha^{-1}) of land cover preceding oil palm plantation (with the concept of time-averaged C-stock applicable to rotations, and the current one to land cover types that are supposed to be in equilibrium), (ii) time-averaged C-stock of the oil palm plantation, Mg C ha^{-1}, (iii) Nitrogen (N) fertilizer level, kg N ha^{-1} and production level of Fresh Fruit Bunches (FFB), Mg ha^{-1} yr^{-1}, (iv) oil extraction rate (OER) of Crude Palm Oil (CPO) and kernel extraction rate, (v) soil CO_2 loss, (vi) emission factors due to fertilizer production, application and (v) emissions due to post-harvest commodity transport and processing before the product reaches the end-user (Germer and Sauerborn, 2008; Wicke et al., 2008; Alkabbashi et al., 2009; Kamahara et al., 2010).

5.3.2.1. Biomass C-stock of land cover preceding oil palm plantation and oil palm plantation

The 'time-averaged aboveground C stock' is the sum of the average over a production cycle of C pools (aboveground tree biomass, understorey vegetation, and surface necromass). The belowground part of biomass is usually considered to be a proportion of aboveground biomass, with land-cover specific data hard to obtain. Data from the survey were used to establish estimates of the time-averaged aboveground C stock of oil palm plantation of around 40 Mg C ha^{-1}, as described in Khasanah et al. (2015b). The time-averaged aboveground C stock of forests and other preceding land cover types were assessed following the rapid carbon stock assessment (RaCSA) methodology and technical manuals (Hairiah et al., 2011). Root biomass was estimated as 25% of aboveground biomass for all land cover types. Identification of land cover type preceding oil palm used the Analysis of land–use and –cover trajectory (ALUCT) protocols (Dewi and Ekadinata, 2013). Changes in time-averaged soil carbon stock when forest or other land cover types were converted into oil palm were analysed by Khasanah et al. (2015a). Khasanah et al 2015a,b discussed how life-cycle inferences could be made for soil C_{org} and the oil palm biomass respectively, despite the incomplete data for certain age classes in the various clusters (Table 5.1).

5.3.2.2. FFB and CPO production in relation to N Fertilizer level

The companies participating in the study provided time series data of their fertilizer use and production level of FFB across the age range of plantations under their management control. For each company, we developed a quadratic equation of FFB production (Y, Mg ha^{-1} yr^{-1}) as a function of age (years after planting; T, yr) to estimate (by integration) the time-averaged FFB production level over the life cycle: $Y = a + b\,T + c\,T^2$. Total N input was calculated across the various fertilizer types reported. The data of N fertilizer application did not show a clear trend with the age of oil palm. Therefore, an average rate of N fertilizer application over the whole life cycle was calculated and used. Time-averaged yield (Y) was related to this average fertilizer rate by regression analysis for a quadratic response model ($Y = Y_0 + f\,N + c\,N^2$, with $c = -f^2/(4\,(Y_{max} - Y_0))$; see equation [5] in S1). While a range of fertilizer types was reported, we focussed on the N content as basis for expected yield response, but used the most commonly used compound fertilizer (15-15-15) as basis for fertilizer costs.

The companies also provided data on their CPO and kernel extraction rate. As variation in these two parameters was limited, an average value of CPO and kernel extraction rate extraction rates was calculated and used in the subsequent analysis.

5.3.2.3. Emission factors due to post-harvest transport and processing

Emission factors due to post-harvest transport and processing were based on fossil fuel use and technical design of the mills and processing steps before the product reaches the end-user (Demirbas, 2007; Wicke et al., 2008; Alkabbashi et al., 2009; Kamahara et al., 2010).

Table 5.1. Sample distribution of oil palm plantations in the IPOC/ICRAF survey across preceding vegetation, soil type, oil palm prevalence in the surrounding province, and plantation management (Khasanah et al., 2015b)

Plantation parameters			Cluster	Number of plantation or landscape	Plantation management[1)]	Number of sampled plots per age category (year)			
Preceding land cover	Soil	Prevalence of oil palm (% of area in province)				0-8	9-16	17-25	Total
Forest	Peat	5–15	1	2	N	2	2	4	8
					P	1	-	-	1
					I	1	-	-	1
		1–5%	2	2	N	4	-	-	4
					P	-	-	-	-
					I	-	-	-	-
		<1%	3	1	N	5	4	1	10
					P	-	1	-	1
					I	-	-	-	-
	Mineral	5–15	4	3	N	2	5	10	17
					P	-	2	2	4
					I	-	-	-	-
		1–5%	5	3	N	6	8	7	21
					P	1	2	-	3
					I	2	1	-	3
		<1%	6	9	N	16	20	7	43
					P	4	4	1	9
					I	10	2	-	12
Non-forest	Peat	5–15	7	-	-	-	-	-	-
		1–5%	8	-	-	-	-	-	-
		<1%	9	-	-	-	-	-	-
	Mineral	5–15	10	2	N	4	5	2	11
					P	-	-	-	-

Plantation parameters			Cluster	Number of plantation or landscape	Plantation management[1)]	Number of sampled plots per age category (year)			
Prece-ding land cover	Soil	Prevalence of oil palm (% of area in province)				0-8	9-16	17-25	Total
					I	-	-	-	-
		1–5%	11	3	N	2	8	6	16
					P	4	6	3	13
					I	2	1	-	3
		<1%	12	-	-	-	-	-	-
		Total		25		66	71	43	180

1. (N = nucleus, P = plasma, I = independent)

5.3.2.4. Sensitivity analysis

To understand the responses of emission saving to changes of carbon debt, N fertilizer application, and ratio of N_2O-N/N-fertilizer a sensitivity analysis was carried out. Five carbon debts: 0, 20, 30, 40, and 60 Mg C ha^{-1} were combined with N fertilizer applications in the range 0 – 550 kg N ha^{-1}, with an interval of 5 kg N ha^{-1}. The Intergovernmental Panel on Climate Change's National Greenhouse Gas Inventory Guidelines suggest that ratio of N_2O-N/N-fertilizer is 1% (IPCC, 2006). Other literature suggests this can be 4% (Crutzen et al., 2008). In the absence of site-specific measurements, both assumptions were compared for impact on the end result. The IPCC national greenhouse gas inventory framework (IPCC 2007 *in* Bentrup F and Pallière C. 2008) includes the CO_2 emissions involved in fertilizer production under industrial processes, rather than land use sections. With a default value of 3.5 kg CO_{2eq} per kg N fertilizer, the net effect of these CO_2 costs of fertilizer production on greenhouse gas emissions is less than the 4.65 kg CO_{2eq} per kg due to the associated N_2O emissions in land use for an N_2O-N/N fertilizer ratio of 0.01, with global warming effect of a molecule of N_2O calculated as 296 times that of a molecule of CO_2.

5.4. Results

5.4.1. Time-averaged aboveground C-stock of land cover preceding oil palm

We found 21 types of land-use systems surrounding the 23 oil palm plantations, which were further classified into three larger categories of 'forest', 'tree-based systems' and 'non-tree-based systems' (Khasanah et al., 2012). The range of time-averaged aboveground C stock values was 150–250 Mg C ha^{-1} for 'forest', 50–150 Mg C ha^{-1} for 'tree-based systems' and less than 50 Mg C ha^{-1} for non-tree- based systems (Figure 5.3). These figures were derived from 924 measured plots, 800 of which came from the ICRAF database of earlier studies in Indonesia.

5.4.2. Level of N Fertilizer and production of FFB and CPO

Based on a survey of 23 plantations throughout the oil palm production domain in Indonesia (Khasanah et al., 2012), we found an average Fresh Fruit Bunch (FFB) yield of 18.8 Mg ha^{-1} yr^{-1} and an average fertilizer use of 141 kg N ha^{-1} yr^{-1} (Figure 5.4 and Table 5.2). FFB-yield and N fertilizer use were closely associated, with an apparent fertilizer response curve of $Y(FFB) = 8.23 + 0.0889N - 0.0001N^2$, with 74.2% of variance accounted for (Figure 5.5a), suggesting $Y_0 = 8.23$ and $Y_{max} = 27.98$ Mg ha^{-1} yr^{-1}. This apparent fertilizer response is derived from survey data, rather than randomized experiments. While we used the N fertilizer rate as basis for the regression, we can assume that other plant nutrients were provided in proportion and/or that residual variation in Figure 5.4a is due to such factors. For oil yield (CPO) per ha the relation was Y(oil) = 1.47 + 0.0298N -5E-05N^2, with 70.2% of variance accounted for (Figure 5.5b). With the average N fertilizer level reported, the yield is expected to be 67% of the maximum FFB yield that can, apparently, be obtained with existing germplasm and plantation management represented in the data set.

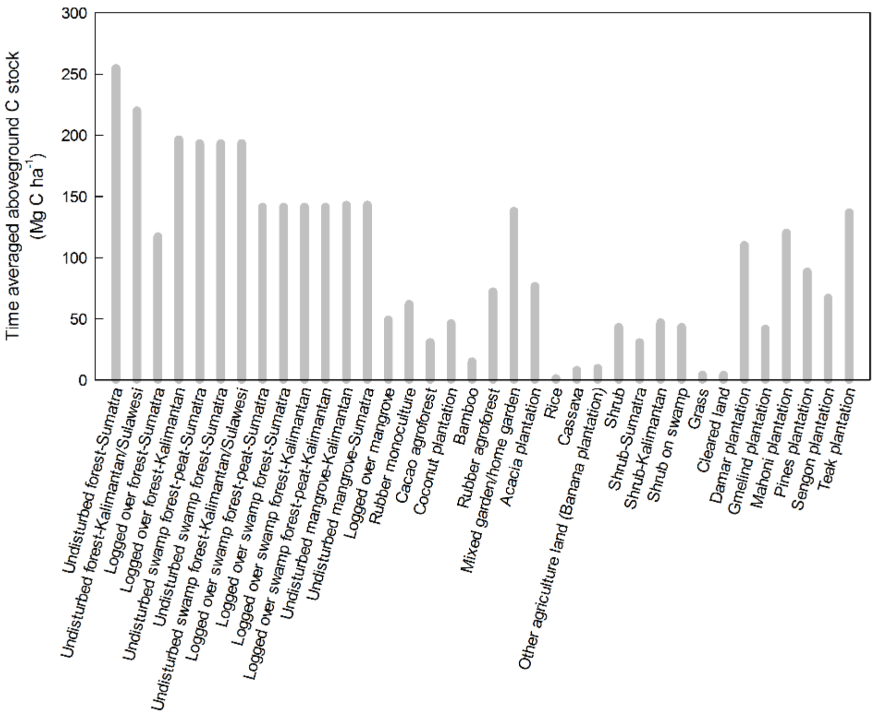

Figure 5.3. Time-averaged aboveground C stock of other land uses involved in the plantations that were part of the IPOC/ICRAF survey.

5.4.3. Emission saving and sensitivity analysis

A default estimate of 40 Mg C ha^{-1}(Khasanah et al., 2015b) of aboveground C stock and no mineral soil loss (Khasanah et al., 2015a) was used to estimate emission saving. When the preceding vegetation had a higher C stock (and conversion took place after the cut-off date of applicable standards, e.g. 2008 for the EU RED), the plantation started with a 'carbon debt'. If preceding C stock was less, the calculation can reflect a net emission saving for the first production cycle. Rather than a single 'typical' value the IPOC/ICRAF data set shows wide variation in C-debt (phase I), yield levels and N-fertilizer use (Phase II and III). Our data support the conclusion that peatland emissions are off the scale and preclude attainment of the emission saving standards (Figure 5.6) (Couwenberg et al., 2010).

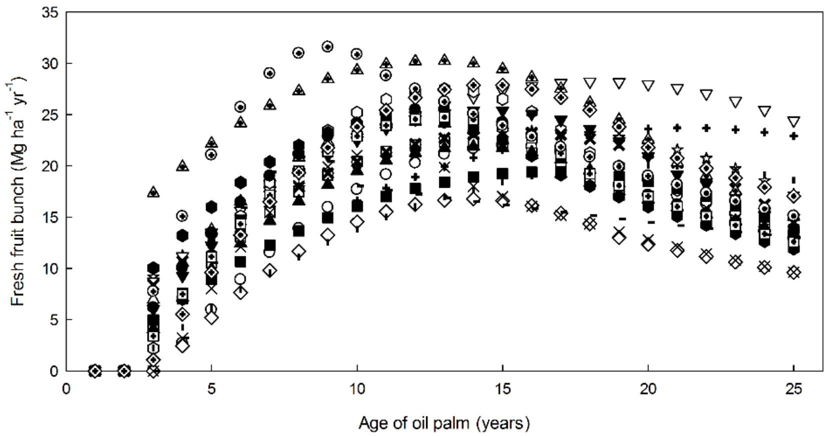

Figure 5.4. Relationship between the age of the oil palm and fresh fruit bunch (FFB) production level as derived for the plantations that were part of the IPOC/ICRAF survey.

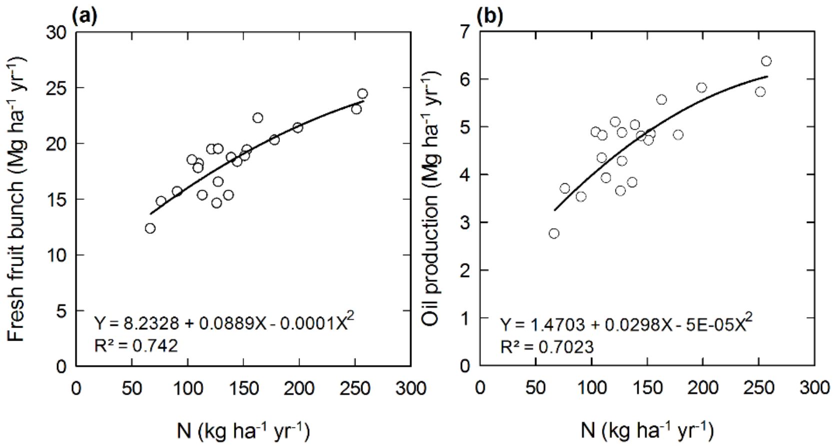

Figure 5.5. Correlation between two properties assessed at life cycle level: the average yearly N fertilizer application and average yearly fresh fruit bunch (FFB) (a), the average yearly N fertilizer application and oil production (b).

The curvature of relationship of level of N Fertilizer and production of FFB plus the effect of a 'fixed cost' of C debt leads to an interesting shift in the shape and positions of the curves that relate the emission savings to the N fertilizer level in the production stage (Figure 5.7). A net emission saving target of 35% cannot be achieved if C debt is more than

20 Mg C ha^{-1} for a N_2O/N-fertilizer loss rate 4% and when C debt is more than 40 Mg C ha^{-1} for a N_2O/N-fertilizer loss rate of 1%.

For many parameter combinations cases there is a weakly defined 'optimum' N fertilizer level that maximizes the emission savings, within a rather broad range where emission savings vary less than 5% (differences that may be below experimental error); in some cases, the optimum is outside the 0 – 500 kg N ha^{-1} yr^{-1}, and zero fertilizer use would give the highest emission reduction rate per unit biofuel derived from the production system (Table 5.3).

Table 5.2. Time-averaged of N fertilizer application, yield level and oil extraction rate per plantation; plantation identity (ID) with 'a' refers to nucleus (plantation), 'b' to plasma (smallholders)

Plantation ID	N fertilizer[1], kg N ha^{-1} yr^{-1}	FFB[2], Mg ha^{-1} yr^{-1}	Kernel[3], %	OER of CPO[3], %	PKO[4], %
001	144.96	18.30	5.16	23.63	0.5
002	121.87	19.43	4.24	24.07	0.5
005	110.49	18.16	4.97	23.97	0.5
006	91.09	15.64	4.29	20.36	0.5
007	251.87	23.01	4.75	22.48	0.5
008	124.31	16.71	4.75	20.54	0.5
010	66.98	11.77	4.87	19.92	0.5
011a	153.61	19.38	5.31	22.31	0.5
011b	151.76	18.84			0.5
013	127.83	16.51	5.73	23.02	0.5
014	139.55	18.70	5.74	24.01	0.5
015	127.91	19.47			0.5
016	113.65	15.44	4.86	23.15	0.5
017	104.39	18.49	4.80	23.99	0.5
018	257.38	24.41	4.90	23.62	0.5
019	109.84	17.76	3.87	22.49	0.5
020	163.52	22.22			0.5
021a	126.52	13.96			0.5
021b	137.07	14.46			0.5
022	76.75	14.76	4.35	22.86	0.5
023	178.45	20.25	4.24	21.68	0.5

1) Time-averaged N fertilizer rates (over the life cycle, no available data for plantation ID 003, 004, 009 and 012, within emission saving estimation, default data then used (141 kg N ha^{-1} yr^{-1}).
2) Time-averaged production rates (over the life cycle), no available data for plantation ID 003, 004, 009 and 012, within carbon footprint estimation, default data then used (18.8 Mg ha^{-1} yr^{-1}).
3) No available data for plantation ID 003, 004, 009, 012, 015, 020 and 021, within emission saving estimation, default data then used (23% for OER and 5% for kernel;
4) PKO palm kernel oil; estimate based on Corley & Tinker, 2016.

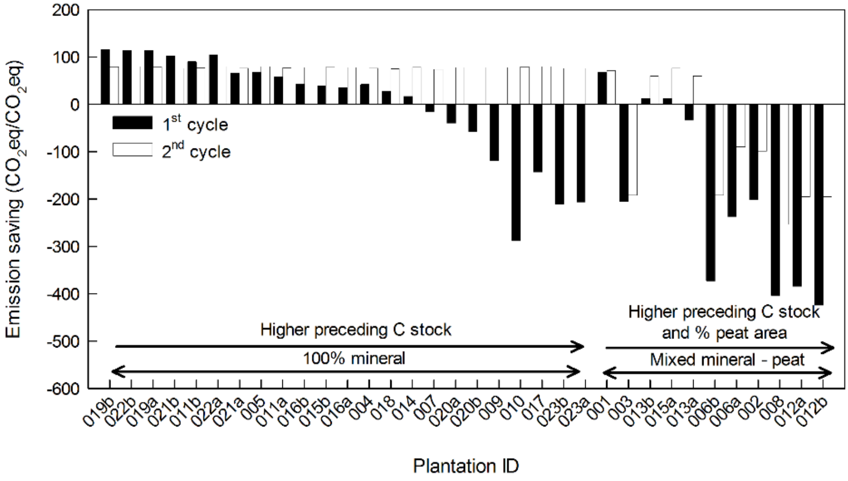

Figure 5.6. Attributable emission savings in relation to preceding carbon stock and N fertilizer application; plantation identity (ID) with a refers to nucleus (company), b plasma (smallholders); C debts before 2008 are included in the calculations and N2O/N is 1%.

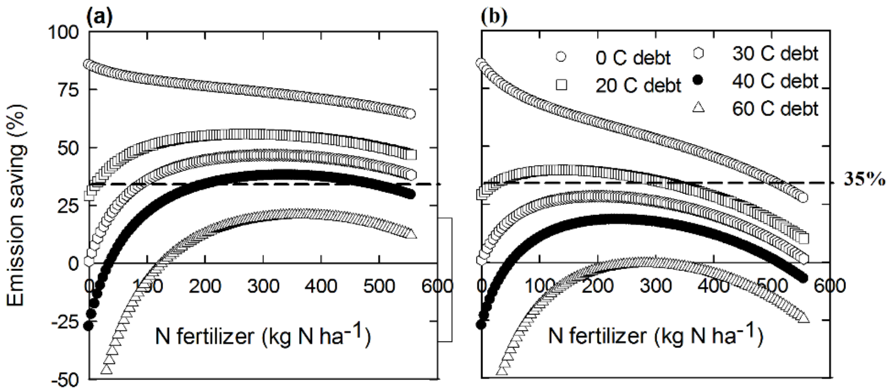

Figure 5.7. Relationship between N fertilizer level and the net emission reduction if Indonesian palm oil is used as feedstock for biodiesel at default parameter conditions, for two levels of the assumed N_2O–N/N fertilizer emission ratio and five levels of carbon debt (preceding time-averaged C stock of oil palm plantations): (a) 1% N loss as N_2O, (b) 4% N loss as N_2O.

5.5. Discussion

Our analysis showed that under parameter conditions that apply to relevant subsets of palm oil production on mineral soil in Indonesia, there is an 'environmental optimum' production level at which net emission savings per unit biofuel use are maximized. The net emission savings decrease strongly with increasing C debt, but the N fertilizer rate that maximizes emission savings increases with C debt. For the production systems represented in the survey (which may not represent the real average of Indonesian palm oil production across all production conditions as the sampling design included self-nomination of companies), the reported N fertilizer rate of 141 kg N ha^{-1} yr^{-1} was substantially below the 'economic optimum' rate and likely achieving only 67% of attainable yield (as defined by the empirical Y_{max} parameter), but using much less fertilizer than would be needed to achieve the maximum (444 kg N ha^{-1}). However, the economic optimum estimate will be lowered if further risks (physical production, prices) are included in the model. A safety margin of a factor 6 on p has to be inferred to explain the average fertilizer level observed. The N fertilizer level used at each of the plantations might reflect the actual economic optimum for the type of planting material and local circumstances, which may not be the same across all plantations in the data set. Figure 5.5 is not the result of a controlled fertilizer experiment, but a summary of current fertilizer use and yields, where assessment of the life-cycle average yield required extrapolation beyond the data (Figure 5.4) and as such has some uncertainty built in. Our assumption of a quadratic response model represents the most efficient side of the spectrum, with field-scale variability likely shifting towards Mitscherlich-type response curves with higher economic optimum fertilizer rates, and lower environmentally acceptable ones (van Noordwijk and Wadman, 1992). Figure 5.8 shows the effects of spatial variability in the three parameters of the fertilizer-yield response. Variability in Y_{max} (e.g. through variability in plant characteristics) has a stronger depressing effect on the response curve than variation in Y_0 or f, but when all three are variable effects are strongest. Interestingly, effects become noticeable at fertilizer rates above 200 kg N ha^{-1} and relative yield levels of 80% of Y_{max}. There may be space to increase yields from 67 to 80% of Y_{max} before negative effects on the emissions footprint emerge. The recorded fertilizer rate is in the environmental optimum range that maximizes emission savings per unit biofuel use if a 4% N_2O-N/N-fertilizer ratio is used, and below this level if a 1% N_2O emission factor applies.

The C debt (Phase I) and N_2O emission per unit N fertilizer use (Phase III) are the two dominant parameters in the calculation. The first factor had been recognized before (Agus et al., 2013a), the second not yet explicitly. Under the EU RED policy conversion to oil palm before 2008 is not considered, so older plantations have a zero C debt. This grandfathering rule was not included in the construction of Figure 5.5. Details of soil and crop management in Phase III may influence results for N_2O emissions. The realistic value of N_2O-N/N-fertilizer ratio may well be between the 1% estimate of IPCC (IPCC, 2006) and the 4% value proposed by Crutzen et al. (2008). Uncertainty about the true value of this parameter needs to be considered in the application of biofuel standards, but may apply across all crops. Further measurements of this ratio are a priority for research (Reijnders, 2011). Richards et al. (2016) compared a number of existing models and calculation schemes for N_2O fluxes from tropical agricultural soils, and found that the substantial variation in both space and time in measured fluxes is not adequately accounted for by any current model. The IPCC emission factors are at least calibrated to global average emission data, but there is opportunity to improve on both practice and accounting method.

Table 5.3. Key characteristics of the relationship between N fertilizer and net emission reduction in Figure 5.7

N_2O-N/N-fertilizer	C debt, ton C ha^{-1}	Max. emission savings (%)	Optimum fertilizer, kg N ha^{-1}	Meeting 35% target[1)]	
				Min	Max
0.01	0	85.5	0	0	>500
0.01	20	55.8	270	15	>500
0.01	30	46.7	310	95	>500
0.01	40	38.0	335	210	475
0.01	60	20.8	365	-	-
0.04	0	85.5	0	0	500
0.04	20	39.8	140	30	395
0.04	30	28.5	200	-	-
0.04	40	18.3	235	-	-
0.04	60	-0.6	280	-	-

1) Acceptable fertilizer range to achieve at least 35% emission savings

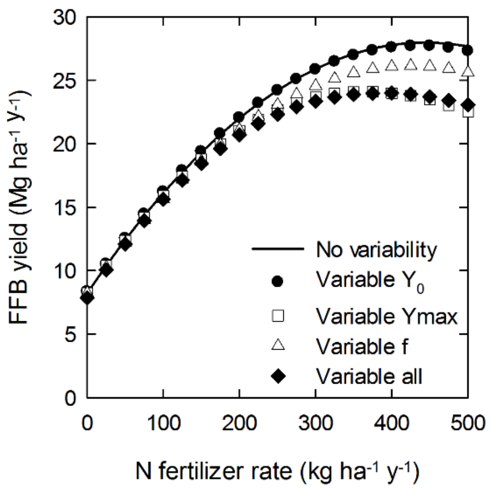

Figure 5.8. Effect of spatial variability on any or all three parameters of the fertilizer response curve of Figure 5.5a; average over 100 independent draws from uniform distributions in the range of 50–150% of original value.

Phase IV of the life cycle, transport and processing can have a strong impact on the absolute levels of emission saving (Choo et al., 2011), but does not influence the environmentally optimum N fertilizer rate in Phase II, as phase III is expressed per unit product. Full utilization of biomass residues and by-products for static energy production, rather than focus on biofuel, can increase emission savings (Kamahara et al., 2010), but may interfere with recycling of organic residues to the plantations, affecting the maintenance of soil organic matter. Further analysis of the IPOC/ICRAF data will clarify which current management practices are at risk of declining C_{org} content, while overall levels can be just about maintained (Khasanah et al., 2015a). Maintaining C_{org} content of forest-derived mineral soils is probably possible (Powers et al., 2011).

In the 100-400 kg N ha^{-1} yr^{-1} range that includes virtually all data points, the emission savings per unit biofuel respond weakly positive or weakly negative to the N fertilizer level. Given the uncertainties around the data, there is no strong argument for modifying fertilizer price policies as a measure to reduce emissions. The N fertilizer rates currently used are slightly below what would be 'environmental' optimum in most conditions. Overall, the data indicate that intensification through increases of fertilizer rates above current practice could increase yields from the current 67 to 80% of attainable yields without negative effects on the footprint of Indonesian palm oil. Our analysis showed that there is an intermediate level of intensification of palm oil production system, achieving between 67 and 80% of its potential that maximizes the possible net emission savings when palm oil is used as biofuel. The C debt (phase I) and processing/transport parameters (phase IV) have an overriding impact on the net emission savings attributed to palm oil use, but phase III does not influence the level of intensification that minimizes emissions. Behavioural studies on fine-tuning management decisions matter for achieving sustainability goals in the oil palm industry (Choong and McKay, 2014), as well as elsewhere. In between Borlaug hypothesis and ecological agriculture, intermediate levels of intensification need to be fine-tuned to match the emerging public policy standards. Fertilizer price instruments cannot, in this situation, be expected to secure environmental policy outcomes beyond what land use policies and market-based accountability for footprints can achieve.

Chapter 6

Diversification as Strategy for Smallholder Oil Palm Production: bioeconomic evaluation of options[9]

[9] Khasanah N, van Noordwijk M, Slingerland M, Sofiyudin M, Stomph D, Migeon AD, Hairiah. Diversification as Strategy for Smallholder Oil Palm Production: bioeconomic evaluation of options. *To be published in Agroforestry System.*

Abstract

Driven by increased global demand of palm oil due to the needs of food and biofuel sectors, oil palm plantations based on a monoculture technology have expanded into lowland tropical forests and replacing diverse rubber-based agroforestry systems. Interest in mixed oil palm systems is increasing as it might be a strategy to diversify oil palm production, increase efficiency of the use of land and other resources, reduce farmer risk and decrease greenhouse gas (GHG) emissions. We used the process-based Water, Nutrient and Light Capture in Agroforestry System (WaNuLCAS) model to explore mixed oil palm + cocoa and oil palm + pepper intercrop systems with modified ('double row') planting patterns for Indonesian contexts and estimated consequences for the carbon footprint using the Biofuel Emission Reduction Estimator Scheme (BERES). The mixed systems were further analysed for multifunctional Land Equivalent Ratio (LERm), economic and environmental performance indicators. The oil palm + cocoa intercrop provided high LER (1.4) and high water percolation to ground water and can still obtain the 60% emission saving target with a 10 Mg ha^{-1} initial carbon debt. Oil palm – cocoa intercropping has closer return to labour to oil palm monoculture and higher benefit cost ratio than the oil palm – pepper combination that maximizes Net Present Value. Oil palm – cocoa systems are also less sensitive to price uncertainty for oil palm, and buffer for oil palm and cocoa production risks, assumed to be independent of each other. Considerable economic and environmental system improvements appear to be feasible through mixed oil palm systems and diversification as a pathway to intensification deserves full attention of research and policy development.

Keywords: agroforestry, carbon footprint, cocoa, ex-ante analysis, land equivalent ratio (LER), mixed oil palm, pepper

6.1. Introduction

A tenfold increase in palm oil export from Indonesia in the period 2000 - 2020 has been forecasted (Directorate general of estate crops, 2016a), matching global demand for low-cost vegetable oil in food and biofuel sectors. The area planted with oil palm has increased to a current 12 Mha (6% of Indonesia's land area). On much larger areas logging rights have been obtained on the basis of planned oil palm expansion. The deforestation observed and the associated greenhouse gas emissions and biodiversity loss have hence been attributed to 'agriculture' as driver, rather than to 'forest management' (Sheil et al. 2007, Koh and Wilcove, 2008; Koh et al., 2011; Carlson et al., 2012; van Noordwijk et al., 2017). Yet, expansion of oil palm and the ease of obtaining the required permits have had major effects, replacing a very diverse natural vegetation, or still diverse rubber-based agroforestry (Joshi et al 2003; Tata et al. 2008; Villamor et al. 2014) with a monoculture of oil palms, leaving only small riparian zones or local hills as 'high conservation value areas'. The multitude of 'ecosystem services' of these diverse landscapes have been replaced by a singular focus on 'provisioning' services for external markets (Tscharntke et al. 2012), providing income from which farmers or plantation labourers will have to buy what they in the past could obtain for free. 'Outsourcing' of staple foods can be justified from a household economy perspective if the terms of trade are favourable, but micronutrient-rich food and dietary diversity are at risk if local food sources disappear (Naylor et al., 2007; van Noordwijk et al., 2014d; Ickowitz et al., 2016). With farmgate prices fluctuating, specialization into a single commodity forms a considerable risk at household level, while companies can diversify at higher scales to buffer their risks. With smallholders increasing in their share of production, plot-level diversification deserves attention.

Expansion of oil palm has occurred mostly in lowland parts of Sumatra and Kalimantan where climate and soil are suitable, with average annual rainfall of at least 2000 mm, evenly distributed over the year without marked dry season, temperature in the 24–28°C range, 5–7 hours of sunshine per day in all months, a slope less than 5%, well drained soils that don't flood in wet periods, soils with clay, sandy clay or clay loam as texture, and no root restricting layers above 100 cm depth (Corley and Thinker, 2015). As the best sites (Northern part of Sumatra and Western part of Kalimantan), were converted first, current expansion (10 % $year^{-1}$ for the last 40 years; Directorate general of estate crops, 2016a), includes climates and soils beyond the optimal range, such as in the eastern part of Kalimantan, southern part of Sumatra and wettest parts of Sulawesi, affecting yield in various ways (Woittiez et al., 2017). In areas with longer dry periods increased soil water buffering is needed, but acid soil conditions restrict root development (Mutert, 1999a) and make the palms more vulnerable to water stress, leading to increase in male and reduction of female inflorescences (Adam et al., 2011; Gawangkar et al., 2003; Breure,

1982) depressing fruit production approximately 12 months after the stress occurrs (Corley and Tinker, 2015; Woittiez et al. 2017). While oil palm was promoted in Malaysia in the 1960's as part of an agricultural diversification program (Simeh and Ahmad, 2001), it replaced rubber in large areas, rather than complementing it. Although intercropping oil palm and cocoa proved to be feasible (Amoah et al., 1995; Corley and Thinker, 2015), it required technical expertise and supply chain engagement beyond what companies were willing to invest in. For smallholders the pro's and con's of diversification may differ from those for companies. Diversification of oil palm plantations with cash crops may not only reduce the social and economic risks of depending on a single cash crop, it could even overcome some of the limiting factors for oil palm production in less suitable climate and soil conditions. Under some conditions the presence of other cash crops that have deeper root systems than oil palm (e.g. due to higher tolerance of acid subsoil conditions) could, through the hydraulic equilibration process (Bayala et al., 2008), maintain soil water content in the topsoil in dry periods, reducing the shift to male flowers in oil palm.

Especially outside of the core oil palm area with the best soils and climates, mixed oil palm systems, as common in the African centre of origin of the species, might thus be a strategy for increasing net income and income stability for farmers. Intercropping oil palm with food crops has been widely studied for several decades not only in its origin countries, but also in Asia. The studies addressed various research topics: local perceptions and strategies on intercropping, production of food crops at early stage of oil palm growth and residual effect of intercropping on the yield and productivity of oil palm at later production stage (Nchanji et al., 2016; Okyere et al., 2014; Putra et al., 2012; Orewa, 2008; Salako et al., 1995). Interest in intercropping oil palm with cash crops received renewed attention recently. Gérard et al (2017), Stomph (2017) and Migeon (2018) initiated studies on oil-palm yields in diversified plantations and reported that considerable economic and environmental system improvements appear to be feasible through mixed oil palm systems in sub-optimal climates.

As part of the 'land sparing' versus 'land sharing' debate (Renwick and Schellhorn, 2016; Mertz and Mertens, 2017; Phalan, 2018) the merits of intensified monoculture production (high yields, but also direct environmental impacts of high input use) have been compared with those of diversified, 'ecologically intensified' production systems (lower yields, but better in terms of environmental services). As it refers to the amount of land needed to achieve the production of a range of products, the Land Equivalent Ratio (LER) is directly relevant for the 'land sparing' debate (Martin-Guay et al., 2018). Interestingly, the common finding that LER values above 1 are feasible in intercropping (Szumigalski et al., 2008; Yu et al., 2015), suggest that 'land sharing' may be the best way to achieve 'land sparing' as a goal of efficient use of land. Khasanah et al. (2015c) found that LER values up to 1.8 are feasible for teak-maize systems in Central Java. As suggested recently (van Noordwijk et al., 2018), an extended LER_m index that includes all aspects of multifunctionality (beyond commodity production) might take the debate further into the analysis of existing landscape mosaics, that include a range of intensities of land use and monocultures as well as mixed cropping systems. To do so, a better understanding is needed of the rationales and methods for oil palm diversification, especially under smallholder management systems.

In the context of palm oil used as biofuel feedstock, a diversification strategy might also have positive environmental impacts by reducing the carbon footprint and/or increasing N use efficiency through safety net functionality (Rowe et al., 1999; Suprayogo et al. 2002; Cadisch et al. 2004). Davis et al. (2013) introduced the term 'management swing potential' for biofuel crops, comparing the best and worst ways of current production in terms of environmental impacts. There are some management options that might potentially 'swing' the environmental impacts for palm oil as biofuel feedstock that link to aspects of the production systems (van Noordwijk et al., 2017) for example strategic management options such as mixed trees species and associated planting patterns and tactical management options such as increased dose of fertilizer applications and use of methane trapping in oil processing.

This study aims to explore, analyse, and identify best performance of oil palm + cocoa and oil palm + pepper intercropping in the Indonesian context as a strategy to increase (or maintain) oil palm production in lower-risk and more land-efficient production systems. Exploration of feasibility of oil palm mixed systems can be tested directly in the field by establishing long-term experiments addressing strategic and tactical managements options to understand their trade-offs between productivity, economic and environmental performance. However, long-term experiments require a lot of time, labour, funds and persistence. Hence, this study relied on a well-established tree-soil-crop interaction model called Water, Nutrient and Light Capture in Agroforestry System (WaNuLCAS) (van Noordwijk and Lusiana 1999; van Noordwijk et al. 2011) and the Biofuel Emission Reduction Estimator Scheme (BERES) (van Noordwijk et al., 2013). Specific routines were developed to describe growth and fruit production by palms, and validated with existing production data from monoculture plantations. A crop library was made for pepper (*Piper Nigrum L.*) by Migeon (2018) based on e.g. allometric relations and root development when grown in monocultures, while tree library for cacao already existed. The mixed systems were further analysed for the multifunctional land equivalent ratio (LERm), economic performance indicators (as in Khasanah et al. 2015c) and for environmental performance indicators. The current exploration is also informed by experimental plots that test sustainability of diversification of oil palm plantation in Brazil (cocoa) and Malaysia (pepper).

Specific questions for the current study analysis were:

1. To what degree can mixed oil palm cocoa or pepper systems be a strategy to diversify oil palm production, reduce farmer risk and decrease GHG emissions?
2. To what degree can selected mixed oil palm systems be land saving strategies with a land equivalent ratio above 1?
3. How are various farm economic indicators (returns to land, labour and investment) reflecting farmer risk and expected benefits in mixed systems compared to monoculture oil palm?
4. What effect will intercropping have on attributed carbon emissions per unit palm oil, in relation to the existing norms for biofuel emissions saving?

6.2. Methodology

6.2.1. Study area

The exploration of intercropping oil palm using WaNuLCAS model is based on the climate and soil characteristics of an oil palm plantation of PT. Astra Agro Lestari in Kumai sub district (Pangkalan Bun district, Central Kalimantan, Indonesia; 2^{o} 25' 17.68" S, 111^{0} 46' 52.8" E, 20 m asl). The explored site has minimum and maximum annual air temperatures of 23^{o}C, and 32^{o}C, respectively; and an annual rainfall 2200 mm yr^{-1} (Figure 6.1). The soil is an Ultisol with clay soil texture and with pH around 4 (Table 6.1). The soil data needed for the model were the result of laboratory analysis at Brawijaya University (Malang, Indonesia), except for bulk density; bulk density was estimated using a pedotranfer function (Wösten et al. 1995).

6.2.2. Brief description of WaNuLCAS model

The WaNuLCAS 4.3 model is a generic tree – crop growth model for a wide range of agroforestry systems that considers both above (light) and belowground (soil water and nutrient: N and P) resources interaction as factors determining plant growth subjects to complementarity and competition (van Noordwijk and Lusiana 1999; van Noordwijk et al. 2011). The interactions are based on above- and below-ground architecture, physiology and phenology and interpreted in different modules including cropping management options (Figure 6.2A). As oil palm has different characteristics compared to other trees, a specific module was developed representing the physiology and phenology of oil palm flower and fruit development. The oil palm module includes five elements: time keeping of frond emergence (phyllochron time steps), sex determination of flowers, fruit abortion, bookkeeping of fruit stage development, and a possible harvest cycle of a fruit bunch at the end of each phyllochron. Three factors: water availability, nutrient availability, and growth reserves determine the dynamics of phyllochron time, flower determination and fruit development.

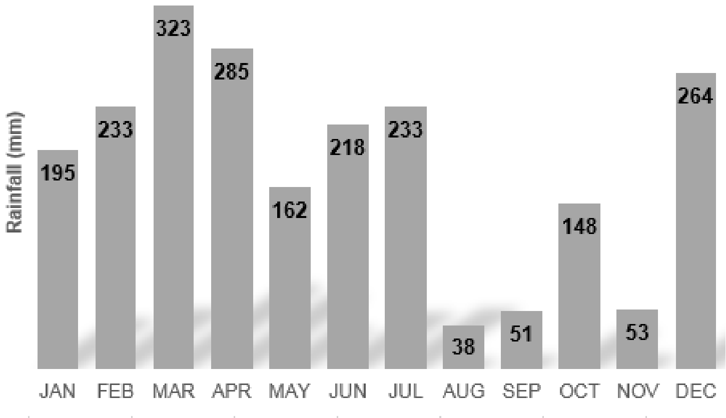

Figure 6.1. Monthly rainfall year 2012 (source: PT. Agro Menara Rachmat)

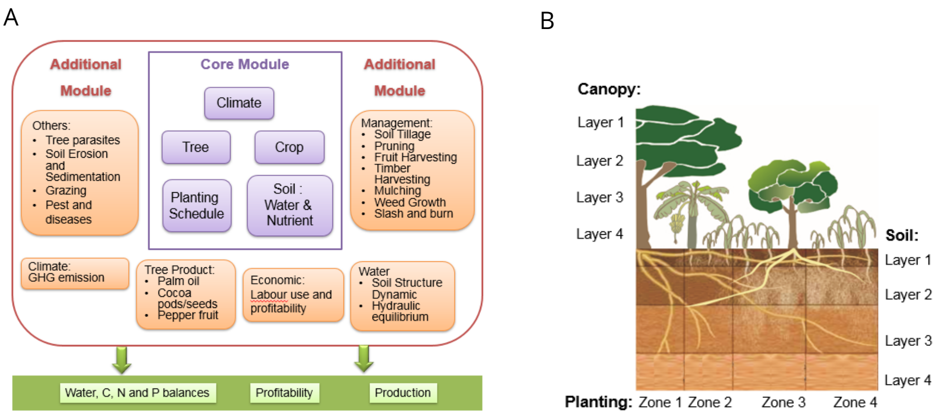

Figure 6.2. Main modules in WaNuLCAS model and its output (A), configuration of the models planting zones, canopy layers and soil layers (B)

Table 6.1. Soil characteristics of clay soil texture used for model parametrization

Layers	Clay	Silt	Sand	C_{org}	Bulk density	CEC	pH	N-mineral	P-mineral
(cm)		(%)			(g cm^{-3})	(cmol kg^{-1})		(mg cm^{-3})	(mg kg^{-1})
0-10	27.85	27.85	44	4.2	1.08	9.52	3.91	0.0041	9.66
10-20	33.18	19.91	47	2.5	1.15	8.33	3.97	0.0038	4.57
20-50	47.54	13.72	39	1.2	1.28	7.95	3.99	0.0034	4.06
50-100	64.63	10.67	25	0.7	1.41	6.61	4.01	0.0012	0.89

The model represents a four-layer soil profile with four-spatial zone where trees and/or crops can be planted and has a daily time step (Figure 6.2B). The model was chosen for this study because it has flexibility to represent tree – crop management options. In this study the model was used to explore growth and production of oil palm, cocoa and pepper when intercropped (see section 6.2.4) and to analyse economic and environmental performance of each system using specific indicators and to assess its land productivity (see section 6.2.5).

6.2.3. WaNuLCAS model calibration and validation

Prior to the use of WaNuLCAS model to explore, analyse, and identify best performance of mixed oil palm systems, a series of model calibration and validation runs to test validity of the model were conducted on the monocultures. Extensive calibration and validation was conducted for oil palm growth and production. For cocoa and pepper growth and production parametrization and calibration have been conducted on smaller data sets by Stomph, 2017 and Migeon, 2018, respectively. Further fine tuning and evaluation consisted of comparisons of simulated data with average cocoa and pepper production as presented in statistik perkebunan Indonesia (tree crop estate statistic of Indonesia) 2015- 2017 (Directorate general of estate crops, 2016b,c).

6.2.3.1. Model parameterization

The main climate and soil data as presented in Figure 6.1 and Table 6.1 were used for model parameterization for all three crops. We used tree and crop growth characteristic input parameters from the model libraries. For pepper Migeon (2018) parametrized the model based on field measurements of pepper monoculture in Konawe district, Southeast Sulawesi, Indonesia. For fertilizer application, nitrogen (N) and phosphorous (P) were applied to the systems with dose and schedule following Pahan, 2015, Salim et al., 2009, Manohara and Wahyuno (2013) for oil palm, cocoa and pepper, respectively (Table 6.2).

Table 6.2. Dose and schedule of fertilizer application

Schedule (Year)	Oil palm (kg ha^{-1})		Cocoa (kg ha^{-1})		Pepper (kg ha^{-1})
	Urea	TSP	N	P	NPK
1	165.6	414	25.3	19.8	320
2	213.9	207	41.4	32.4	640
3	296.7	241.5	147.2	162.0	2560
4 – 5	365.7	310.5	128.8	162.0	2560
> 5 years	552	655.5	128.8	162.0	2560

6.2.3.2. Model performance evaluation

Evaluation of model performance was conducted by comparing simulated and measured data for oil palm monoculture. The oil palm data used for calibration and validation is average data of more than 20 plantation surveyed and published in van Noordwijk et al., 2017. For cocoa and pepper, simulated data was compared to national figures of cocoa and pepper production presented in statistik perkebunan Indonesia (tree crop estate statistic of Indonesia) 2015- 2017 (Directorate general of estate crops, 2016b,c). Statistical indicators proposed by Loague and Green (1991) (Table 6.3) and coefficient regression were used to evaluate the performance of the model for oil palm production.

6.2.4. Diversification scenarios

Mixed oil palm cocoa or pepper were selected as diversification scenarios. Details of planting density and years of intercropping are presented in Table 6.4, while Figure 6.3 presents design and spacing of intercropping oil palm with cocoa or pepper in a double row arrangement adapted from the system developed by Embrapa in Brazil and the Malaysian Oil Palm Board (Suboh et al, 2009), respectively. The selected scenarios considered different species characteristics, management requirements, profitability parameters and environmental impacts. For environmental performance analysis, a long-term mixed natural forest was also simulated as reference for the same soil and climate conditions.

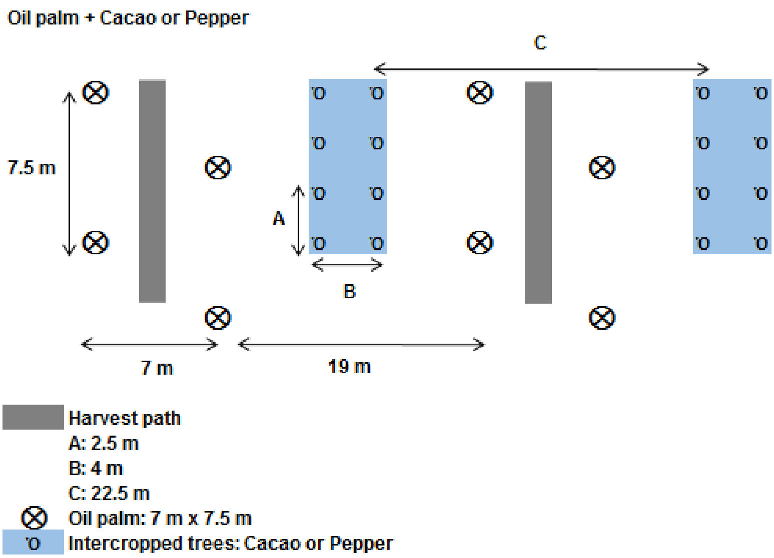

Figure 6.3. Design and spacing of intercropping oil palm with Cocoa or Pepper

Table 6.3. Statistical criteria for model performance evaluation

Criteria	Symbol	Calculation formula	Range	Optimum
Maximum error	ME	$Max\|P_i - O_i\|_{i=1}^{n}$	≥ 0	0
Root mean square	RMSE	$\left(\sum_{i=1}^{n}(P_i - O_i)^2 / n\right)^{\frac{1}{2}} x \frac{100}{O_{mean}}$	≥ 0	0
Coefficient of determination	CD	$\frac{\sum_{i=1}^{n}(O_i - O_{mean})^2}{\sum_{i=1}^{n}(P_i - O_{mean})^2}$	≥ 0	1
Modelling efficiency	EF	$\frac{(\sum_{i=1}^{n}(O_i - O_{mean})^2 - \sum_{i=1}^{n}(P_i - O_i)^2)}{\sum_{i=1}^{n}(O_i - O_{mean})^2}$	≤ 1	1
Coefficient of residual mass	CRM	$\frac{(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i)}{\sum_{i=1}^{n} O_1}$	≤ 1	0

P_i = predicted values, O_i = observed values, n = number of samples and O_{mean} is the mean of the observed data

Table 6.4. The simulated diversification scenarios with details on intercrop species, planting density and years of intercropping.

Scenario	Systems	Mixed species (IS)	Planting distance tree (m) Oil palm | IS	Tree density (trees/ha) Oil palm | IS	Years of intercrop
1.	Oil palm monoculture	-	8.5 x 8.5 | -	138 | -	-
2.	Cocoa monoculture	-	- | 3 x 3	- | 1111	-
3.	Pepper monoculture	-	- | 2.5 x 2.5	- | 1600	-
4.	Mixed Oil plam	Cocoa	7 x 7.5 | 4 x 2.5	100 | 320	- | 25
5.		Pepper	7 x 7.5 | 4 x 2.5	100 | 320	- | 25

6.2.5. Scenario analysis

6.2.5.1. Land Productivity

WaNuLCAS model outputs were used to calculate Land Equivalent Ratio (LER). which is the ratio of the area under monocropping to the area under intercropping needed to give equal amounts of yield at the same management level. When the LER index of an intercropped system is equal to or higher than 1, it indicates that the intercropped system is feasible. For example, LER 1.1 indicates that the area planted to monocultures would need to be 10% greater than the area planted to the intercrop for the two to produce the same production. The LER was calculated as the sum of the fractions of the intercropped yields divided by the monocrop yields:

$$LER = \left({}^{PI_{t1}}/_{PM_{t1}}\right) + \left({}^{PI_{t2}}/_{PM_{t2}}\right) + \cdots + \left({}^{PI_{tn}}/_{PM_{tn}}\right)$$

Where PI_{t1}… PI_{tn} is productivity of mixed system species 1 – species n, PM_{t1}… PM_{tn} is productivity of monoculture system species 1 – species n.

6.2.5.2. Environmental performance indicators

WaNuLCAS model outputs were also used to calculate ratios of carbon stock, water used by plant, deep drainage, surface run off and N losses as fractions of reference condition (protected forest). In both simulated and reference cases the water used by plant, deep drainage and surface run off was presented as a fraction of rainfall.

$$EI = \left({}^{EM}/_{ER}\right)$$

Where EI is ratio of carbon stock, water used by plant, deep drainage, surface run off or N losses of simulated scenario (EM) to carbon stock, deep drainage, surface run off or N losses of simulated reference condition/forest (ER).

6.2.5.3. Economic performance indicators

We used three economic performance indicators, Net Present Value (NPV) or Return to Land, Return to Labour (RtL), and benefit cost ratio (BCR). These indicators are used to determine whether the mixed system is profitable. When the NPV > 0 and RtL is higher than the daily wage rate, it indicates that the mixed system is profitable. Returns to Labour is defined as the labour cost at which the NPV is zero. The NPV is calculated as follow:

$$NPV = \sum_{t=0}^{t=n} \frac{R_t - C_t}{(1+i)^t}$$

where: R_t is revenue at year *t*, C_t is cost at year *t*, *t* is time denoting year and *i* is discount rate.

A farm level assessment was developed for each system. A compilation of farm level input consisting of labour hours and costs, prices of fertilizer, chemical inputs, planting materials and tools required for the analysis was formed based on actual data collected in Sumatra (oil palm), Sulawesi (cocoa) and Kalimantan (pepper), the areas where the majority of the crops were produced. Prices of inputs were incorporated and estimated using local market prices, which included an interest rate of 7 % and Rupiah currency exchange rate (USD 1 = IDR 13.700) A labour wage rate was also included at USD 5 per day. Product prices were based on data presented in statistic perkebunan Indonesia (tree crops estate statistic of Indonesia) 2015- 2017 (Directorate general of estate crops, 2016a,b,c) for FFB (USD 0.1/kg), cocoa (USD 1.7/kg), and pepper (USD 10.2/kg).

6.2.5.4. Carbon footprint and overall performance

WaNuLCAS model input (fertilizer application) - outputs (yield) were also used to estimate carbon footprint of palm oil for biofuel using Biofuel Emission Reduction Estimator Scheme (BERES) (van Noordwijk et al., 2013, 2017) and compare it between scenarios to see which mixed system generates high yields while having a minimum carbon footprint at different amounts of carbon debt.

The BERES is a comprehensive accounting system on carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions of biofuel production of palm oil that includes three phase of crop production processes: land conversion, palm oil production and use of external inputs, and post-harvest transport and processing. It calculates carbon footprint or net emissions of biofuel production that is expressed as CO_2 equivalent and emission saving compared to the use of fossil fuel using a life cycle approach. The scheme was used for this study to estimate one of environmental indicator as it is consistent with the life cycle analysis (LCA) of net emissions for biofuel production systems used by the renewable energy directive (RED) of the EU. We apply two scenarios of carbon footprint: with and without carbon debt sharing with intercropped trees.

6.3. Results

6.3.1. Model performance evaluation

Figure 6.4 and Table 6.5 present comparison of simulated and measured fresh fruit bunch and evaluation of model performance of monoculture system. Overall evaluation of fresh fruit bunch indicated a moderately good fit between simulated and measured data with a coefficient determination and a coefficient regression of 0.6 (optimum value 1) and 1.07 (optimum value 1). The discrepancy is on the early (measured higher than simulated) and late (simulated higher than measured) production stage but both simulated and measured have average fresh fruit bunch over one cycle (of 25 years) of around 19.5 Mg ha-1. Cocoa and pepper monoculture systems has average production over one cycle (of equal length to oil palm) of around 775 kg ha^{-1} and 856 kg ha^{-1}, respectively. This value is close to the figure of cocoa and pepper production described in statistik perkebunan Indonesia (tree crop estate statistic of Indonesia) 2015- 2017 (Directorate general of estate crops, 2016b,c).

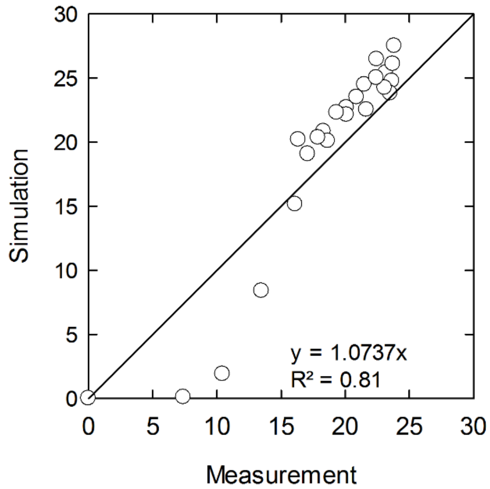

Figure 6.4. A comparison of simulated and measured fresh fruit bunch of oil palm for a full production cycle (Mg ha^{-1})

Table 6.5. Result of model evaluation according to Loague and Green (1991)

Criteria	Value	Range	Optimum
ME	8.6	≥ 0	0
RMSE	18.5	≥ 0	0
CD	0.6	≥ 0	1
EF	-0.8	≤ 1	1
CRM	-0.1	≤ 1	0

6.3.2. Production

Figure 6.5 describes production of fresh fruit bunch (Figure 6.5A), dry weight of cocoa bean (Figure 6.5B) and dry weight of pepper (Figure 6.5C) (Mg ha^{-1}) of different simulated systems. The yield of oil palm response to the changes of design (from single row to double row), tree density (from 138 palms ha^{-1} to 100 palms ha^{-1}), and intercropped tree (cocoa and pepper). Under single row arrangement and density of 138 palms ha^{-1}, average fresh fruit bunch over one cycle around 19.5 Mg ha^{-1}, it decreases to 16 Mg $ha^{-1}$and 14 Mg ha^{-1} when intercropped with cocoa and pepper in double row arrangement, respectively.

Similar trend also shows in yield of cocoa and pepper, under monoculture system, the yield around 775 kg ha^{-1} and 856 kg ha^{-1} for cocoa and pepper, respectively. It reduces to 475 kg ha^{-1} (cocoa) and 240 kg ha^{-1} (pepper) when it mixed with oil palm with tree density around 29% and 20% of monoculture cocoa and pepper, respectively.

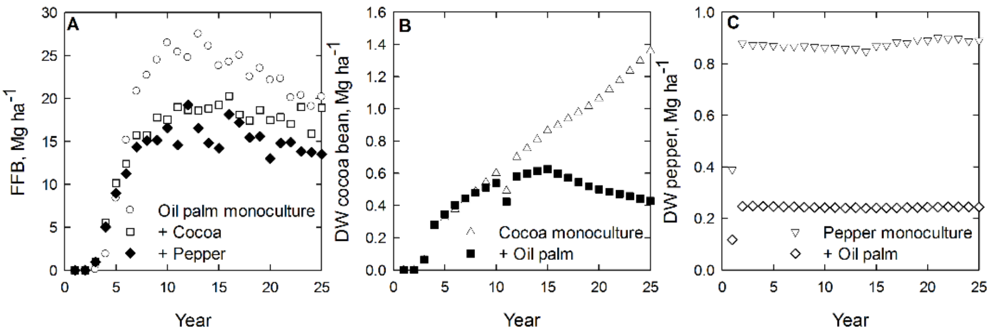

Figure 6.5. Production of fresh fruit bunch (A), dry weight of cocoa bean (B) and dry weight of pepper (C) (Mg ha^{-1}) of different simulated system.

6.3.3. Land productivity and environmental performances indicators

Table 6.6 presents land productivity indicated by land equivalent ratio (LER) value and environmental performance indicators represented by ratio of C stock, water use efficiency, deep drainage, run off and N losses of the systems to reference condition (forest). The LER of oil palm + cocoa intercrop exceeds 1 (1.4), while the LER of oil palm + pepper intercrop is 1. However, in term of environmental performance indicators, oil palm monoculture has higher C stock and water use, and lower run off and N losses than the cocoa-oil palm intercrop. The cocoa-oil palm intercrop has a higher deep drainage water compared to oil palm monoculture. If we compare the environmental performance indicators of oil palm + cacao intercrop and oil palm + pepper intercrop, both oil palm + pepper intercrop and oil palm + cocoa intercrop has considerable advantages over the oil palm monoculture. Furthermore, oil palm monoculture and oil palm + cocoa intercrop had greater groundwater recharge than the forest.

Table 6.6. Land productivity (LER) and environmental performance (C stock, water use efficiency, water yield, run off and N losses) for each simulated scenario

Systems	Relative to respective monocultures	Relative to natural forest				
	LER[1)]	C stock	WUE[1)]	Groundwater recharge[1)]	Run off[2)]	N losses[2)]
Monoculture OP	1.00	0.20	0.85	1.02	1.09	2.19
OP + Cocoa	1.44	0.15	0.69	1.13	1.17	2.59
OP + Pepper	0.99	0.13	0.87	0.87	1.02	3.89

1) Value above 1 means positive impact
2) Value above 1 means negative impact

6.3.4. Economic performance indicators

Table 6.7 presents economic performance indicators represented by NPV, return to labour, benefit and cost ratio (BCR), years to positive cash flow and cost of establishment. Compared to monoculture, and discounting costs and benefits over a 25 year of cycle, oil palm + cocoa and oil palm + pepper provide a 24% and 48% higher NPV, respectively. However, to establish and maintain the intercrops an additional labour input of 7% (oil palm + cocoa) and 72% (oil palm + pepper) was required. This is reflected in the reduction of RtL by 3% for oil palm + cocoa and 141% for oil palm + pepper. Oil palm + cocoa had the highest BCR. Further analysis at reduced FFB price around uncertainty of yield of both oil palm and intercropped trees, showed further advantages of the oil palm + cocoa scenario for all economic indicators. The establishment cost is sum of cost before reaching positive cash flow, hence it varies between yield.

6.3.5. Carbon footprint

Figure 6.6 presents the carbon footprint of palm oil when it is used as biofuel and is produced in various land use systems, with various amount of C debt due to initial conversion. The carbon footprint is presented as emissions saving (%) compared to the use of fossil fuel. Without sharing of the load of carbon debt with intercropped trees and with current target of emission saving (60%), oil palm + cocoa intercrop can meet the target at maximum 10 Mg C ha^{-1} carbon debt, the same situation also provided by oil palm monoculture (Figure 6.6A). The saving can be higher if we apply sharing of the load of the carbon debt with intercropped trees (Figure 6.6B), but the debt cannot be higher than 10 Mg ha^{-1} if one has to meet the target.

Table 6.7. Economic performance indicators Net Present Value (NPV), return to labour (RtL), benefit-cost ratio (BCR), years to positive cash flow and cost of establishment, for each simulated scenario with added uncertainty in physical yield (from 0.8 to 1.2 times the default value for OP, cocoa or pepper) and FFB prices (from 0.1 to 0.07 USD kg^{-1})

Systems	Price of FFB, USD/kg	**NPV** (USD ha^{-1}, *relative to default*)			**RtL** (USD Person day^{-1}, *relative to default*)			**BCR** (ratio, *relative to default*)			**Years to positive cash flow** (#years, *relative to default*)			**Establishment cost** (USD ha^{-1}, *relative to default*)		
		0.8Y	**Y**	**1.2Y**	**0.8Y**	**Y**	**1.2Y**	**0.8Y**	**Y**	**1.2Y**	**0.8Y**	**Y**	**1.2Y**	**0.8Y**	**Y**	**1.2Y**
Y variation in OP																
OP Monoculture	0.1	7988	11062	14137	23.7	30.9	38.1	2.2	2.5	2.8	5	5	5	1838	1910	1981
		0.72	*1.00*	*1.28*	*0.77*	*1.00*	*1.23*	*0.88*	*1.00*	*1.12*	*1.00*	*1.00*	*1.00*	*0.96*	*1.00*	*1.04*
	0.07	3776	5797	7818	13.9	18.6	23.3	1.6	1.8	2	5	5	5	1839	1910	1981
		0.34	*0.52*	*0.71*	*0.45*	*0.60*	*0.75*	*0.64*	*0.72*	*0.80*	*1.00*	*1.00*	*1.00*	*0.96*	*1.00*	*1.04*
OP + Cocoa	0.1	12167	14656	17144	26.1	30.4	34.7	2.9	3.1	3.3	4	4	4	1291	1317	1344
		1.10	*1.32*	*1.55*	*0.84*	*0.98*	*1.12*	*1.16*	*1.24*	*1.32*	*0.80*	*0.80*	*0.80*	*0.68*	*0.69*	*0.70*
	0.07	8816	10467	12118	20.3	23.2	26.0	2.4	2.5	2.6	4	4	4	1291	1317	1344
		0.80	*0.95*	*1.10*	*0.66*	*0.75*	*0.84*	*0.96*	*1.00*	*1.04*	*0.80*	*0.80*	*0.80*	*0.68*	*0.69*	*0.70*
OP + Pepper	0.1	19129	21603	23348	12.1	12.9	13.6	2.0	2.1	2.2	2	2	2	1206	1206	1206
		1.73	*1.95*	*2.11*	*0.39*	*0.42*	*0.44*	*0.80*	*0.84*	*0.88*	*0.40*	*0.40*	*0.40*	*0.63*	*0.63*	*0.63*
	0.07	16212	17592	18972	11.0	11.5	12.0	1.9	1.9	2.0	2	2	2	1206	1206	1206
		1.47	*1.59*	*1.72*	*0.36*	*0.37*	*0.39*	*0.76*	*0.76*	*0.80*	*0.40*	*0.40*	*0.40*	*0.63*	*0.63*	*0.63*
Y variation in cocoa																
OP + Cocoa	0.1	13353	14656	15958	29.5	30.4	31.2	3	3.1	3.2	4	4	4	1306	1317	1329
		1.21	*1.32*	*1.44*	*0.95*	*0.98*	*1.01*	*1.20*	*1.24*	*1.28*	*0.80*	*0.80*	*0.80*	*0.68*	*0.69*	*0.70*
	0.07	9164	10467	11769	21.8	23.2	24.4	2.4	2.5	2.6	4	4	4	1306	1317	1329
		0.83	*0.95*	*1.06*	*0.71*	*0.75*	*0.79*	*0.96*	*1.00*	*1.04*	*0.80*	*0.80*	*0.80*	*0.68*	*0.69*	*0.70*

Systems	Price of FFB, USD/kg	NPV (USD ha^{-1}, *relative to default*)			RtL (USD Person day^{-1}, *relative to default*)			BCR (ratio, *relative to default*)			Years to positive cash flow (#years, *relative to default*)			Establishment cost (USD ha^{-1}, *relative to default*)		
		0.8Y	**Y**	**1.2Y**	**0.8Y**	**Y**	**1.2Y**	**0.8Y**	**Y**	**1.2Y**	**0.8Y**	**Y**	**1.2Y**	**0.8Y**	**Y**	**1.2Y**
Y variation in pepper																
OP + Pepper	0.1	18110	21603	24367	13.1	12.9	12.7	2.1	2.1	2.1	2	2	2	1101	1206	1310
		1.64	*1.95*	*2.20*	*0.42*	*0.42*	*0.41*	*0.84*	*0.84*	*0.84*	*0.40*	*0.40*	*0.40*	*0.58*	*0.63*	*0.69*
	0.07	14463	17592	20721	11.5	11.5	11.5	1.9	1.9	2.0	2	2	2	1101	1206	1310
		1.31	*1.59*	*1.87*	*0.37*	*0.37*	*0.37*	*0.76*	*0.76*	*0.80*	*0.40*	*0.40*	*0.40*	*0.58*	*0.63*	*0.69*
Relative ranges																
OP Monoculture		*0.34 – 1.28*			*0.45 – 1.23*			*0.64 – 1.12*			*1.0*			*0.96 – 1.04*		
OP + Cocoa		*0.80 – 1.55*			*0.66 – 1.12*			*0.96 – 1.32*			*0.8*			*0.68 – 0.70*		
OP + Pepper		*1.31 – 2.20*			*0.37 - 0.44*			*0.76 – 0.88*			*0.4*			*0.58 – 0.69*		

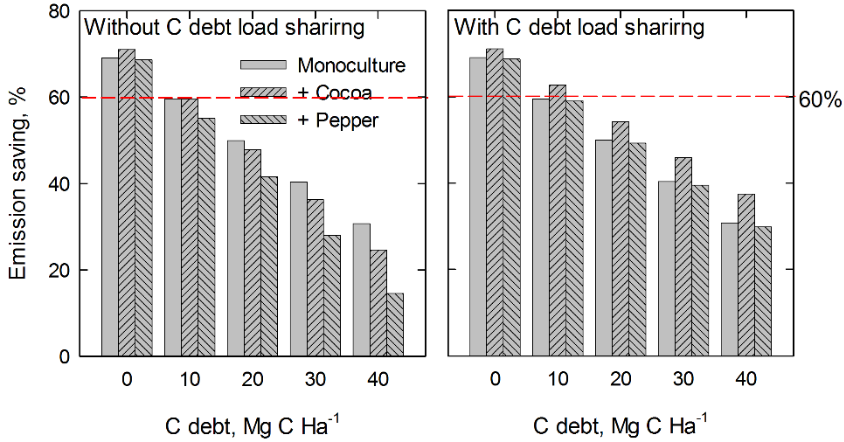

Figure 6.6. Carbon footprint of palm oil when it is used as biofuel under different systems and various amount of C debt, without (left) and with (right) sharing of the C debts over the intercropped trees. The carbon footprint is presented as saving emission (%) compared to the use of fossil fuel

6.4. Discussions

This study aims to explore, analyse, and identify best performance of oil palm – cocoa and oil palm – pepper intercrop within the Indonesian context as a strategy to increase oil palm production and reduce the carbon footprint and hypothesized that selected mixed oil palm systems have land saving with a land equivalent ratio above 1, improve farmer benefits and reduce carbon emissions. The results showed that mixed oil palm achieved the hypotheses.

The land equivalent ratio (LER) of oil palm – cocoa intercrop exceeds 1 (1.44), while for oil palm – pepper it is 0.99. It indicated that there is indeed a benefit in term of production to be obtained by combining oil palm and cocoa compared to monocultures of oil palm and cocoa. Although mixed oil palm required additional labour compared to oil palm monoculture as indicated in lower return to labour, under smallholder management this might not a limitation (Schwarze et al., 2015; Vermeulen & Goad, 2006). The economic performance of oil palm – cocoa intercrop is also more resistant to the uncertainty of price of oil palm and variation in production of oil palm and cocoa. From an environmental perspective, both oil palm + pepper intercrop and oil palm + cocoa intercrop has certain environmental performance benefits: Run-off decreased and WUE increased under oil palm-pepper intercrop, whereas ground water recharge increased under oil palm-cocoa intercrop. However, C stock decreased, and N losses increased under both intercrops compared to oil palm monoculture. Zooming in into the carbon footprint, which is relevant when the palm oil is used for biofuel, palm oil from oil palm – cocoa intercropping, with maximum carbon debt of 10 Mg C ha^{-1} complies to the threshold of 60% savings compared to fossil fuel as set by the European Union. However, to achieve this, smallholders need to follow best management practices which would be an enormous challenge for especially the independent smallholders. Independent smallholders have the most complex cropping systems, and are the most diverse in their management practices, and are often not connected to input suppliers and markets hence the cost to comply to certification for the biofuel market might not be economically feasible (Hutabarat et al., 2018).

The presented examples illustrate the complexity of decision making and defining a farming practice as the most sustainable option from economic and environmental perspectives. For example, if a smallholder seeks an early positive net return, high WUE and low run-off oil palm – pepper is preferred, if a smallholder aims at obtaining higher returns to labour, low establishment cost and enhanced environmental performance in terms of a lower carbon footprint oil palm – cocoa is preferred. When the farmer is only focused on returns to labour, the oil palm monoculture can be chosen.

Multifunctionality perspectives have to reconcile trade-offs that exist between various aspects of environmental and economic performance. The LER_p, or productivity focussed land equivalent ratio, is interpreted here as indicator of 'land sparing': a higher ratio implies that less land is needed to obtain the same amount of commodities (assuming that there is demand for oil palm, cocoa and pepper, and that they can be produced in either mixed systems or monocultures). The LER_p reflects opportunity for biodiversity and C stock conservation outside of the productive parts of the landscape. The $LER_{r,}$ or land equivalent ratio for regulating functions, involves 5 indicators (Table 6.6): the globally relevant C stock, water use efficiency, groundwater recharge, surface runoff and N losses, all scaled by the values that can be expected for forest in the same soil and climate. The latter two are treated as disfunctions, and the inverse of the relative value is added for a LER_r. Stakeholders may attach different levels of importance to these functions. We here considered an equal weighting for the five indicators, and a more locally focussed one where groundwater recharge is valued most and C stock least. Results (Table 6.8) show that for the functions considered the LER_r of oil palm monoculture is (slightly) higher than that for the intercropping systems, but all values are clearly below 1.0 (which uses the natural forest as reference). When comparing the LER_m values (so far with equal weights for LER_p and LER_r), the oil palm + cocoa system is the highest (and only above 1), for both ways of weighing regulating functions.

Table 6.8. Multifunctional land equivalent ratio LER_m on the basis of LER_p and LER_r (for productive and regulating functions, respectively) for three different land use systems

Systems	LER_p	LER_{r1} 1)	LER_{r2} 2)	LER_{m1} 3)	LER_{m2} 4)
Monoculture OP	1.00	0.69	0.79	0.84	0.90
OP + cocoa	1.44	0.64	0.77	1.04	1.10
OP + pepper	0.99	0.62	0.73	0.81	0.86

1) Equal weight for C stock, water use efficiency, groundwater recharge, run off and N losses (1), data in Table 6.6
2) Weight for C stock, water use efficiency, groundwater recharge, run off and N losses is 0.5, 0.5, 1.5, 2 and 1, respectively
3) Combining LER_p and LER_{r1}
4) Combining LER_p and LER_{r2}

Economic performance indicators presented in Table 6.7 are combined with the environmental performance indicators presented in Table 6.8 for an overall evaluation of the trade-offs between negative environmental impacts and positive increase of welfare. All three systems considered have Benefit Cost Ratios substantially above 1.0, so they are 'bankable' at commercial interest rates. When Net Present Value (returns to land) is to be maximized (while paying for labour at the going wage rate), the combination of oil palm and pepper is best; it also has the shortest time to positive cash flow, but one may have to accept higher rates of nitrogen losses. When Returns to Labour is the primary criterion (as it can be in smallholder systems), oil palm + cocoa is equivalent with oil palm monoculture (lower risk, slightly lower average), but oil palm + pepper stays behind.

Where there are multiple opinions on the relative importance of these indicators, and different resource endowments, we can expect a mosaic landscape to emerge with diversity in farming styles. From an aggregate perspective such a mosaic may be more resilient and functional than a landscape where only a single land use system (be it monoculture or mixed system) exists.

The modelling exercise presented here had to leave many options out of consideration, such as inclusion of semi-domesticated trees from the forest with high value such as eaglewood (gaharu). This value can only be captured when new products and markets are developed and when prices stay attractive even when "harvesting" a rare species from the forest is replaced by mainstream cultivation of larger volumes (Soeharto et al., 2017). Oil palm–livestock combinations have also not been included in our exercise as the WaNulCas model is not suitable to assess such systems. Yet they merit attention and assessment as smallholders and companies have been observed to practice livestock grazing in their oil palm plantations, but no studies have been published yet on their economic and environmental performance.

6.5. Conclusion

Mixed oil palm cultivation systems provided considerable economic and environmental system improvements. The performance varied over a set of economic and environmental indicators and weighing factor should be applied to choose the system that provides the desired balance between economic and environmental enhancement. The only indicator at which an oil palm monoculture showed to be superior to any diversification scenario was the high returns to labour as it required lower labour compared to mixed systems. Mixed systems can support oil palm as a biofuel crop by reducing its carbon footprint. From the perspective of the land sharing versus land sparing debate, mixed oil palm can be a way to achieve land sparing through more efficient use of land.

Chapter 7

General Discussion

7.1. Overview

The success of oil palm expansion in response to the rapidly increasing demand for low-cost vegetable oils has made it one of the most controversial crops of the world (Rivai and Levang, 2014; Ntsomboh-Ntsefong et al., 2016). Indonesia as the world's largest producer of palm oil attracts both strongly negative and strongly positive opinions competing for attention (World growth, 2011; Patrenko et al., 2016). Positive perceptions mostly come from the companies involved and from part of the rural communities benefitting from the expansion. The expansion has catalysed rural development in developing infrastructure and providing employment, hence improving living standards and nutrition (but see Oosterveer et al., 2014, Euler et al., 2017 for partly contrasting views and data). It also provided additional land use options for smallholder farmers, mostly complementing the rubber-based livelihoods common in the climate zone where oil palm is an option (Schwarze, 2015). Negative perceptions mostly came from human rights advocates and environmental NGOs and importer countries, calling attention to negative impacts of the expansion in forest frontier zones, where deforestation led to GHG emissions and loss of biodiversity (Koh et al., 2008; Reijnders and Huijbregts, 2008). 'Issue cycle' dynamics of the ensuing debate were reviewed by van Noordwijk et al. (2017), calling attention to the contrast between Kalimantan, where most of the forest frontier expansion with its social and environmental effects took place, and Sumatra, where most of the palm oil is produced and where the shift to smallholder production has advanced furthest (Jelsma et al., 2017).

This thesis focused on a specific subset of the debate on the drivers, consequences and control of oil palm expansion: the effects on the carbon balance in the landscapes where it is produced and its consequences for the total anthropogenic carbon emissions when it is used as partial substitution for fossil fuels.

The overall research objectives of this study were (1) to estimate the carbon footprint of palm oil production in Indonesia when it is used as biofuel and express it as CO_2 equivalent and emissions saving compared to the use of fossil fuel, and (2) to explore mixed oil palm systems as diversification strategy to increase farmer benefit and to reduce carbon footprint. To answer these objectives, five research questions (RQs) were formulated that associate with five research chapters of this thesis:

1. What is the range of aboveground time-averaged C stocks (Mg C ha^{-1}) of various types of oil palm plantations in Indonesia? Are there relevant differences between the three main plantation management conditions found in Indonesia: nucleus, plasma, and independent smallholders, and between soil types (mineral versus peat)?

2. What is the belowground time-averaged C stock (Mg C ha^{-1}) on mineral soil of oil palm plantations in Indonesia and how does temporal variations of soil organic content (C_{org}, %) and soil bulk density (BD, g cm^{-3}) influence the results for the top 30 cm used in C accounting?
3. How does variation in subsidence (cm yr^{-1}) and CO_2 emission (Mg CO_2 ha^{-1} yr^{-1}) rates of smallholder oil palm plantations on peat compare to that for other land-use types, in relation to conversion history (recent or earlier drainage), and fertilizer application?
4. How does intensification level (fertilizer use) influence the carbon footprint of palm oil production in Indonesia and its attributed emission savings when used as substitute for fossil fuel? Do environmentally and economically optimized intensification levels match the current carbon footprint per unit biofuel?
5. Can the development of mixed oil palm systems be a strategy to not only reduce farmer risk and address some of the associated social concerns, but also reduce the footprint of palm oil?

The preceding four empirical chapters and one focused on scenario analysis of intercropping provided answers to each of the five research questions. In this chapter the remaining uncertainty around these answers will be discussed, with specific reflection on the methods used. Section 7.2 will cover weaknesses and strengths of the methods and approaches used in this thesis, section 7.3 will synthesize findings on the carbon footprint of palm oil production, and section 7.4 will discuss intercropping oil palm as diversification strategy, potentially reducing the footprint. Conclusions will be formulated in section 7.5, with recommendations for future research in section 7.6.

Figure 7.1. Harvest time (left) and one of footprint component (right)

7.2. Methods and approaches

7.2.1. Sampling design

Chapters 2, 3 and 5 were based on a single survey, carried out in close cooperation with the Indonesian palm oil committee and many of the major oil palm companies in

Indonesia. This cooperation provided a unique opportunity to collect an unprecedented data set across the industry, using a stratified sampling design, as well as work with researchers within these companies to help them understand the methods and obtain comparisons between the performance of their own plantations relative to the whole data set. As described in chapters 2 and 3, the sampling of plantations used a stratified sampling scheme that resulted 12 clusters. These took into account three of the major factors that can differentiate footprints: 1) recent land use history, comparing plantations deriving from natural forests and non-forest (degraded forests, grasslands or agroforests); 2) mineral soil versus peatlands; 3) the prominence of oil palm in the landscape (0 – 5, 5 – 10, >10%). However, the voluntary nature of participation by the companies involved implied that it would not be a representative sample of Indonesian palm oil production at the time of sampling, but rather represent what the companies proposed as their 'best management practice' examples, representing what they saw as their future. Reality on the ground did not always match the initial assignment of plantations to clusters. Three clusters in the scheme were left empty, as no samples matched the criteria; oil palm on peat not derived from forest is probably indeed scarce.

Further detail on the sampling design at plot level for above and belowground C stock measurement was described in Chapters 2 and 3. The sampling method used was in line with global standards for carbon stock measurement published by IPCC (Eggleston et al., 2006), with some adjustment to reflect the characteristics of oil palm and plantation management, such as the zoning around each palm. As describe in chapter 2, the aboveground C stock sampling represented by 10 palms per plot and included destructive sampling that allowed allometric equations to be verified. Selection of the 10 palms in each plot followed the standardized selection scheme used in establishing Leaf Sampling Units (LSU) for fertilizer recommendation. Therefore, spatial variation in palm growth within each plantation was well represented.

7.2.2. Soil carbon data

As detailed in Chapter 3, the belowground C stock sampling of the topmost 30 cm of soil took four management zones into account (weeded circle, interrow, frond stacks, and harvest paths) that are commonly found in oil palm plantation. In practice, however, the proportion of area in each zone varied and some adjustments were needed to derive appropriately weighted averages for the plot as a whole. In the sampling scheme spatial variation of two key determinants of soil C stock (C_{org} concentration per unit soil dry weight and soil bulk density) were sampled consistently, and were found to vary in opposite directions across management zones and over time, making effects on calculated C stocks (C per unit volume of soil) smaller than those of C_{org} when considered alone. As consistent soil bulk density data are much scarcer in the literature than C_{org} measurements, this may in part account for the difference between our conclusion of 'no discernable effect over a palm's life cycle' and other publications (Guo and Gifford, 2002; Schroth et al., 2002; Don et al., 2011; de Blécourt et al, 2013) that report a decline in the early years after conversion. Two other reasons for this contrast are: our extrapolation to the full life span of a palm (including the recovery in later phases), and a problematic aspect of globally agreed soil carbon accounting: its focus on the 0-30 cm layer. As a consequence of soil compaction, the soil layer that was below 30 cm initially, became part of the 30-cm layer, adding to the C content of this layer. To the degree possible, we corrected our data for changes in effective sampling depth to understand actual changes, beyond what international stock accounting mandates. The global agreement to restrict soil C accounts to the top 30 cm can be seen as a middle ground between full accounting of all changes in this important pool, and the scarcity of reliable data, plus large variability relative to small and delayed land use effects at greater depth. Full accounting to these factors would substantially add to the costs of data collection. adding to costs of knowledge.

7.2.3. Experimental plot for peat subsidence

The experimental plots described in chapter 4 to measure peat subsidence were sustained for more than two years to represent the dynamics of peat and its characteristics. They were, unfortunately in hindsight, completed before the strong dry season of 2015/2016 as strong dry season may increases the subsidence. As common in this type of surveys, the sampling had to deal with the realities of land use change in the area and a factorial scheme of age since conversion by land use could not be implemented. In the interpretation of data, we thus had to accept a confounding of age and land use.

As a step beyond standard procedures we took multiple measurements of microtopography around the central sampling point. Although laborious and increasing the time spent by researchers around the sampling point, and potentially adding to compaction, such data were found to add detail to the observed central point subsidence. Much of the time spent in sampling is used to move between sampling points in a landscape of low accessibility, yet the additional time investment was considered to be worthwhile. Further use of our sampling protocol is recommended as it increases accuracy of subsidence compared to single reading of subsidence.

7.2.4. Life cycle approach

Life-Cycle Analysis (LCA) as used in environmental impact studies was designed to assess all environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition based on land use, via production, conversion, transport and use phases, to waste management (Rebitzer et al., 2004, Finnveden et al., 2009). It is supposed to reach from cradle to grave. A specific challenge for perennial crops is that data need to be integrated over a plantations' life cycle, nested within the assessment of a products' life cycle. In carbon accounting the concept of a time-averaged C stock of a land use system has been developed to ease such comparisons (Hairiah et al., 2001, van Noordwijk et al., 2002, Palm et al., 2004).

The life cycle approach used in chapter 5 is a globally accepted approach for carbon footprint calculations and it is in line with EU RED policy (EU Directive, 2009), as it included three phases of productions: (i) land conversion, (ii) the growth the oil palms and use of input, (iii) post-harvest transport and processing. As the focus of our primary data collection was on the first two phases, the use of reference data for phase 3 and use of standard IPCC standards for a N_2O emission factor on mineral soils and on peat may add uncertainty of the results.

In the assessment of intensification options in chapter 5 we used a relationship between yield and fertilizer use that was based on surveys across plantations, rather than on experiments were the rate of fertilizer was varied, all other factors being equal. Recommended rates of fertilizer use depend on age of the plantation and yield effects over a palms' life cycle involve interactions and thus uncertainty (Woittiez et al., 2017). The empirical correlation that we used cannot be used as prediction of what may happen as immediate response on any individual plantation when fertilizer rates are increased (or decreased), but it may on an aggregate level describe what can be expected for the plantation sector as a whole. The relationships developed in chapter 5 may well indicate the shape of overall response curves, but will require further validation if fertilizer management practices change from the current ones.

7.2.5. Processes based model

In chapter 6, the WaNuLCAS model (van Noordwijk et al., 2011) was chosen to simulate oil palm intercropping. There are several other processes-based models for oil palm monocultures, for example PALMSIM (Hoffmann et al., 2014) and APSIM (Huth et al.,2014). The WaNuLCAS model was chosen as the model can deal with the temporal and spatial consequences of a wide range of agroforestry systems for water, nutrient and light capture as key ecological interactions. It simulates dynamic processes at plot scale with interactions between above and below ground plant growth and has the flexibility to represent tree – crop management options.

As a first step in using the model for intercropping scenarios we had to ensure that its predictions for time patterns of yield in monoculture were in accordance with existing data. Efforts were made to not 'over- tune' the model, accepting a considerable amount of unexplained variability. Our primary use of the model was for comparisons between monoculture and intercropping, given specific architectural and functional properties of each crop. As such the level of 'validation' shown may have been sufficient, but for other uses of the model (e.g. exploring responses of yield to site properties and climate variability) further validation sets will be needed.

7.3. Carbon footprint of palm oil production

Use of biofuels in the European Union is governed by the 2009 "Renewable Energy Directive" (RED) that regulated the footprint allowable for biofuel feedstocks and the 2015 "Indirect Land Use Change" (ILUC) Directive. Most of the palm oil greenhouse gasses emission studies using the life cycle analysis approach (Siregar et al., 2015; de Vries, 2012; Kittithammavong et al., 2014; Souza et al., 2010) have focused on the carbon footprint expressed in CO_2 equivalent but not compared it to EU standards. Only Yee et al. (2009) who conducted a carbon footprint analysis of palm oil in Malaysia reported that 38% reduction of CO_2 emission can be achieved, and concluded that palm oil is a more sustainable feedstock for biodiesel production than rapeseed oil. This thesis has made the additional step by exploring the possibilities to meet the emerging standards for 'emissions saving' of the RED. This thesis did not address the ILUC issue.

Based on the sampled companies with good agriculture practices, 25% of Indonesian palm oil production can meet the 60% emissions savings standards for net emission reduction when used as biofuel. This is more than what is currently exported to the EU for that purpose. When the EU threshold will increase to more than 70% in the near future further efficiency increases, including in the use of N fertilizer and in dealing with emissions at the mill will be needed.

The rationale for the ILUC debate (Searle and Giuntoli, 2018) is that even if the footprint of specific products used in biofuel matches the existing standards, its use as biofuel might displace current other uses of the same product (e.g. in the food industry) and lead to expansion of production elsewhere. As such, it is not informed by data of the types presented and discussed here. As ILUC calculations are generic, they don't provide any incentives for or recognition of attempts to improve practice on the production side. Their primary target is the consumer/user side, nudging away from commodities with high ILUC tax (such as vegetable oils with current (or at least recent) expansion in high-carbon-stock-density parts of the world) and towards those with low ILUC tax (such as vegetable oils grown in areas where conversion took place long ago). A major challenge of the ILUC concept, however, is that the choice of the level at which it is applied (commodities such as 'palm oil' with its global markets and expansion) appears to be arbitrary. One could equally argue that a generic ILUC tax should apply to all vegetable oils that are interchangeable for at least some of their uses.

The European Parliament (EP) recently declared that production of biofuels in the European Union (EU) should be free from palm oil feedstock by 2020, in order to halt deforestation of rainforests in mainly Indonesia and Malaysia. As argued by Klepper (2018)[10] this decision may increase the market share of other vegetable oil feedstocks with a much lower productivity per unit area like soy, canola, rapeseed. The companies that are most unlikely to contribute to deforestation and that are certified according to the standards of RSPO (or equivalent) will be affected most by this policy, as it affects companies currently trading with the EU. A number of further questions is raised by this policy decision: by which pathway (if any) will it reduce deforestation? Will this policy induce lower global market prices of palm oil and increase demand in other segments of the global food industry to balance it? Will lower farm-gate prices ultimately lead farmers to choose other crops? If so, with what consequences? The 'Induced Land Use Change' debate seems to draw a rather arbitrary boundary of accountability for indirect consequences in complex, interlinked systems.

Through the moratorium of Sept 2018, the Government of Indonesia has given itself three years to sort out the overlapping and partially contradictory existing permits for conversion to oil palm in areas with current forest status. This may help to improve the general applicability of internationally agreed standards and gradually reduce the footprint of palm oil at national scale. Just as the increasing share of 'independent smallholders', without much reason to doubt their Free and Prior Informed Consent (FPIC), has improved the public profile of oil palm, it could well be that intercropping can reduce the footprint, calculated with current standards. At least, that is what our analysis in chapter 6 suggested.

7.4. Intercropping oil palm as diversification strategy

The analysis of intercropping oil palm is driven by the massive expansion of oil palm from small scale to large scale and from suitable climate (Northern part of Sumatra and Western part of Kalimantan) to less suitable climate (Eastern part of Kalimantan, Southern part of Sumatra and Sulawesi) (Directorate general of estate crops, 2016a). Diversification of oil palm plantation with cash crops may not only be seen as a strategy to reduce the

---

10 https://www.eco-business.com/opinion/winners-and-losers-from-the-eus-proposed-ban-on-palm-oil/

level of smallholder livelihood vulnerability with its social and economic risks because of depending on a single cash crop, but also as a strategy to increase oil palm production that grows in less suitable climate and soil conditions.

Figure 7.2. Male inflorescence (left) as indicator of stress in less suitable climate, and growth well oil palm (right)

This thesis explored oil palm – cocoa and oil palm – pepper intercrop and analysed it from a set of economic and environmental indicators including carbon footprint if the palm oil were used as biofuel. Certainly, the mixed system is feasible and provided considerable economic and environmental improvements. Other benefits of intercropping oil palm and not the focus of this thesis is that intercropping oil palm may reduce the cost of weeding (Nchanji et al., 2016) and increase soil fertility (Erhabor and Filson, 1999). However, there is a complexity of decision making and defining a farming practice as the most sustainable option from economic and environmental perspectives as the analysed systems provided different set of indicators.

Weighing factors applied to the set of indicators might reduce the complexity of decision making. However, when the national and international contexts clearly influence farmers' decisions, local people seem more responsive to economic opportunities rather than to environmental opportunities (Feintrenie et al., 2010b), while for environmental activists the opposite seems to be true.

7.5. Conclusions

Two general conclusions can be drawn are (1) Higher oil palm yields per unit of land through increased fertilizer use will reduce the drive to expand plantation area, but can increase the carbon footprint of palm oil, (2) Mixed cropping systems with oil palm as 'land sharing' practice can achieve 'land sparing' through efficient use of land. More detail conclusion for each research chapters are in the following sub sections.

7.5.1. Aboveground C stock of oil palm plantation

In the calculation of the carbon footprint of palm oil production using a life cycle analysis approach, a potential carbon-debt incurred at land-use conversion. If a new plantation is established in an area with high carbon stock (natural forest and/or on peat soils), net emissions will be high (large carbon footprint). In chapter 2, survey and data collection (field measurement) were conducted in more than 20 selected plantations representing the wide range of oil palm production in Indonesia differing in plantation management (*nucleus*, *plasma*, and independent smallholders) and soil types (mineral and peat) to generate time averaged aboveground time-averaged C stock of oil palm plantation. . The time average aboveground C stock of oil palm plantation ranges from 37.8 ± 0.33 Mg C ha^{-1} to 42.1 ± 0.03 Mg C ha^{-1}. Soil type and plantation management regimes account for the variation in the estimated values. The resulting estimate of time-averaged C stock is slightly higher than obtained in previous studies. Previous studies have been generally based on smaller data sets.

These results imply that establishing oil palm plantations in areas with preceding carbon stock higher than 40 Mg C ha^{-1} (as ballpark figure) will lead to carbon debt and net release of carbon to the atmosphere. This carbon debt might be the highest contributing emission factor with changes in soil pools, recurrent emissions due to fertilization as other emission factors.

7.5.2. Belowground C stock of oil palm plantation

Changes of soil properties also contribute to the dynamic of carbon footprint of palm oil production. In chapter 3, the changes of mineral soil properties for the top 30 cm over a production cycle were estimated and expressed as belowground mineral C stock. The analysis and estimation were based on data of more than 20 plantations surveyed and collected in chapter 2. In the top 30 cm across the four management zones (weeded circle, interrow, frond stacks, and harvest paths) from plantations with "good practice" management, belowground C stock did, on average, not change significantly over the plantation cycle. This apply for both oil palm plantations derived from forest or non-forest.

These results imply that current retention of organic plant residues and pruned fronds in the field compensates for the initial soil C loss and maintains mineral soil C stock when assessed over a production cycle. Thus, there was no detectable net carbon emission from soil at a scale relevant for national C accounting. Increments that are supposed to accrue for oil palm established in non-forest backgrounds were not evident. With current soil management practices, it is appropriate for life-cycle assessments to assume that soil C stock on mineral soils neither increase nor decrease due to oil palm cultivation.

7.5.3. Peat subsidence and CO_2 emission

Peatland area that has been drained for agricultural use is continuously producing CO_2 emissions. Chapter 4 estimated CO_2 emissions of smallholder drained peatland of four different land-uses in relation to the length of time after drainage and fertilizer application based on peat subsidence and peat characteristics and taking into account microtopography. The four-smallholder managed land-uses were rubber (*Hevea brasiliensis*) agroforest, mixed coconut *(Cocos nucifera*) and coffee (*Coffea liberica*), mixed betel nut (*Areca catechu*) and coffee, oil palm (*Elaeis guinensis*) monoculture.

Fertilizer application did not have a consistent effect on inferred emissions. Estimated emission based on peat subsidence can be improved by taking microtopography into account, using multiple readings around measurement rods. The partial independence of local surface dynamics relates to the dynamics of water-table depth and root activity. Accumulation of litter on the soil surface may need to be included in estimates of the rate of peat CO_2 emissions of drained peatlands. The rate of peat CO_2 emissions based on the subsidence rate between two different measuring times in combination with peat characteristics (bulk density and C organic content) provided a better estimation than an ash-based 'internal tracer' method. Long-term drainage can be expected to decrease the rate of CO_2 emissions at a given groundwater depth, with additional emissions in early stages of the same order as decayed root biomass of the preceding vegetation, while fertilizer application did not show a strong effect on the rates of peat subsidence and emissions. A recently established oil-palm plantation had the highest rate of peat subsidence and emission (4.7 cm yr^{-1} or 121 Mg CO_2 ha_{-1} yr^{-1}) while the remnant forest had the lowest (1.8 cm yr^{-1} or 40 Mg CO_2 ha^{-1} yr^{-1}). Other land-use types subsided by 2–3 cm yr^{-1}, emitting 70–85 Mg CO_2 ha^{-1} yr^{-1}. The emission of recently established oil-palm plantation is significantly lower than what was reported in a review on peat CO_2 emissions from oil palm and pulpwood large plantations (Page et al. 2011a). The emission of other land uses is slightly lower than what was reported in the same review. These results imply that peatland for agricultural use under smallholder management have CO_2 emissions close to, but above current IPCC defaults.

7.5.4. Footprint of oil palm production

Net greenhouse gas (GHG) footprints per unit product vary depending on the context, scale, and accounting method and life cycle analysis is globally accepted as method to calculated carbon footprint. Chapter 5 analysed carbon footprint of palm oil production in Indonesia when the palm oil is used for biofuel feedstock. The level of fertilizer application was included in its calculation of production and footprints, to derive the level of intensification that can minimize the footprint per unit biofuel using (Biofuel Emission Reduction Estimator Scheme) BERES scheme. The analysis and estimation were based on comprehensive data of more than 20 plantations surveyed and collected during survey of above and belowground studies. The EU threshold requiring at least 35% emission saving for biofuel use can never be achieved by palm oil if it is produced: (i) on peat soils, or (ii) on mineral soils where the C-debt due to conversion is larger than 20 Mg C h^{a-1}, when the footprint is calculated using an emission ratio of N_2O-N/N-fertilizer of 4%. At current fertilizer price levels in Indonesia the economically optimized N fertilizer rate is 344-394 kg N ha^{-1}, while the reported mean N fertilizer rate is 141 kg N ha^{-1} yr^{-1} and rates of 74-277 kg N ha^{-1} would minimize footprints, for a N_2O-N/N-fertilizer ratio of 4-1%, respectively. At a C-debt of 30 Mg C ha^{-1} these values are 200-310 kg N ha^{-1}. Sustainable weighting of ecology and economics would require a higher fertilizer/yield price ratio, depending on C-debt. Increasing production by higher fertilizer use from current 67 to 80% of attainable yields would not decrease footprints in current production conditions.

7.5.5. Oil palm diversification

Interest in mixed oil palm systems is increasing as it might be a strategy to diversify oil palm growth, reduce farmer risk and decrease GHG emissions. We explored mixed oil palm + cocoa and oil palm + pepper intercrop by modifying its planting pattern using the process-based Water, Nutrient and Light Capture in Agroforestry System (WaNuLCAS) model for Indonesian contexts. We estimated the carbon footprint of the mixed systems using the Biofuel Emission Reduction Estimator Scheme (BERES). The mixed systems were further analysed for multifunctional land equivalent ratio (LER_m), economic and environmental performance indicators. The oil palm-cocoa intercrop provided high LER (1.4), increased water percolation to ground water reserves and reached 60% emission savings with a maximum carbon debt of 10 Mg C ha^{-1}. Oil palm – cocoa had more water percolating to groundwater reserves, and higher benefit cost ratio (BCR) than oil palm monoculture. Oil palm – cocoa intercropping was also more resistant to the uncertainty of price of oil palm and production of oil palm and cocoa. Considerable economic and environmental system improvements appear to be feasible through mixed oil palm systems.

7.6. Recommendation for future researches

Within the context of Indonesia, the findings reported in this thesis may be relevant for stakeholders to support the current debate on sustainable biofuel and for smallholder oil palm plantations for options for more resilient cropping systems. To support the debate, we propose to investigate even more diverse sites representing the diversity of management practices including those of smallholders as the current study represents only the companies' perspective on 'best management practice'. As a second line of research investigations in diversification are proposed as they may be as important as 'intensification' aimed at improving monocultures. Exploration of mixed oil palm system beyond the current study might increase options for resilient systems. The additional complexity can become a strength rather than a burden.

References

Abood, S.A., Lee, J.S.H., Burivalova, Z., Garcia-Ulloa, J., Koh, L.P. 2015 Relative contributions of the logging, fiber, oil palm, and mining industries to forest loss in Indonesia. Conservation Letters 8(1): pp. 58-67.

Adachi, M., Ito, A., Ishida, A., Kadir, W., Ladpala, P., Yamagata, Y. 2011. Carbon budget of tropical forests in Southeast Asia and the effects of deforestation: An approach using a process-based model and field measurements. Biogeosciences, 8, 2635–2647. http://dx.doi.org/10.5194/bg-8-2635-2011

Adam, H., Collin, M., Richaud, F., Beulé, T., Cros, D., Omoré, A., Nodichao, L., Nouy, B., Tregear, J.W. 2011. Environmental regulation of sex determination in oil palm: current knowledge and insights from other species. Annals of Botany, Vol. 108, No. 8, pp 1529–1537, https://doi.org/10.1093/aob/mcr151.

Agung, P., Galudra, G., van Noordwijk, M., Maryani, R. 2014. Reform or reversal: the impact of REDD+ readiness on forest governance in Indonesia. Climate Policy 4(6): pp. 748-768.

Agus, F., Hairiah, K., Mulyani, A. 2011. Measuring carbon stock in peat soils: practical guidelines World agroforestry Centre-ICRAF Southeast Asia and Indonesian Centre for Agricultural Land Resources Research and Development, Bogor.

Agus, F., Henson, I.E., Sahardjo, B.H., Harris, N., van Noordwijk, M., Killeen, T.J. 2013a. Review of emission factors for assessment of CO_2 emission from land use change to oil palm in Southeast Asia. In: Killeen, T.J., Goon, J. (Eds.), Reports from the technical panels of the second greenhouse gas working group of the roundtable for sustainable palm oil (RSPO). RSPO, Kuala Lumpur, pp. 7–27. http://www.rspo.org/file/GHGWG2/3_review_of_emission_factors_Agus_et_al.pdf.

Agus, F., Gunarso, P., Sahardjo, B.H., Harris, N., van Noordwijk, M., Killeen, T.J. 2013b. Historical CO_2 emissions from land use and land cover change from the oil palm industry in Indonesia, Malaysia and Papua New Guinea. In T. J. Killeen & J. Goon (Eds.), Reports from the technical panels of the second greenhouse gas working group of the roundtable for sustainable palm oil (RSPO). RSPO, Kuala Lumpur, pp. 65–88. http://www.rspo.org/file/GHGWG2/5_historical_CO2_emissions_Agus_et_al.pdf

Aldrian, E., Susanto, R.D. 2003. Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. International Journal of Climatology, 23, 1435–1452. http://dx.doi.org/10.1002/(ISSN)1097-0088

Alkabbashi, A.N., Alam, M.E.Z, Mirghani, M.E.S., Al-Fusaiel, A.M.A. 2009. Biodiesel production from crude palm oil by transesterification process. Journal of Applied Science, 9, 3166–3170.

Amoah, F.M., Nuertey, B.N., Baidoo-Addo, K., Oppong, F.K., Osei-Bonsu, K., Asamoah, T.E.O., 1995. Underplanting oil palm with cocoa in Ghana. *Agroforestry Systems*, *30*(3), pp.289-299.

Angelsen, A., Kaimowitz, D. 2001. Agricultural Technologies and Tropical Deforestation. CABI, Wallingford.

Badalikova, B. 2010. Influence of soil tillage on soil compaction. In: Dedousis, A.P., Bartzanas, T. (Eds.), Soil Engineering. Springer, pp. 19–30.

Badan Pusat Statistik (Centre of Statistic) Kabupaten Tanjung Jabung Barat. 2014. Tanjung Jabung Barat in numbers year 2014 (In Indonesian) Statistics Bureau in cooperation with Regency Development Planning Agency Tanjung Jabung Barat Jambi.

Bakar, R.A., Darus, S.Z., Kulaseharan, S., Jamaluddin, N. 2011. Effects of ten-year application of empty fruit bunches in an oil palm plantation on soil chemical properties. Nutr. Cycl. Agroecosyst. 89 (3), 341–349.

Barlow, C., Zahari, Z., Ria, G. 2003. The Indonesian palm oil industry. Oil Palm Industry Economic Journal, 3, 8–15.

Bayala, J., Heng, L.K., van Noordwijk, M., Ouedraogo, S.J. 2008. Hydraulic redistribution study in two native tree species of agroforestry parklands of West African dry savanna. Acta Oecolo., http://doi:10.1016/j.actao.2008.06.010

Belcher, B., Rujehan, Imang, N., Achdiawan, D. 2004. Rattan, rubber, or oil palm: cultural and financial considerations for farmers in Kalimantan. Economic Botany 58 pp. S77-S87.

Benscoter, B.W., Wieder, R.K., Vitt, D.H. 2005. Linking microtopography with post-fire succession in bogs. Journal of Vegetation Science 16(4): pp. 453–460. http://doi:10.1111/j.1654-1103.2005.tb02385.x

Benscoter, B.W., Greenacre, D., Turetsky, M.R. 2015. Wildfire as a key determinant of peatland microtopography. Canadian Journal of Forest Research 45(8): pp. 1132-1136. https://doi.org/10.1139/cjfr-2015-0028

Bentrup, F., Palliere, C. 2008. Energy efficiency and greenhouse gas emissions in European nitrogen fertilizer production and use. International Fertiliser Society – Proceeding 639.

Breure, C.J. 1982. Factors affecting yield and growth of oil palm tenera in West New Britain. Journal Oleagineux Vol. 37 No. 5 pp. 213-22.

Bruun, T.B., De Neergaard, A., Lawrence, D., Ziegler, A.D. 2009. Environmental consequences of the demise in swidden cultivation in Southeast Asia: carbon storage and soil quality. Hum. Ecol. 37 (3), 375–388.

Budidarsono, S., Susanti, A., Zoomers, A. 2013. Oil palm plantations in Indonesia: The implications for migration, settlement/resettlement and local economic development. In Z. Fang (Eds.), Biofuels—Economy, environment and sustainability (pp. 173–193). Rijeka: InTech. doi:10.5772/53586

Busch, J., Ferretti-Gallon, K., Engelmann, J., Wright, M., Austin, K.G., Stolle, F., Baccini, A. 2015. Reductions in emissions from deforestation from Indonesia's moratorium on new oil palm, timber, and logging concessions. Proc. Natl. Acad. Sci. U. S. A. 112, 1328–1333.

Cadisch, G., de Willigen, P., Suprayogo, D., Mobbs, D.C., van Noordwijk, M., Rowe, E.C. 2004. Catching and competing for mobile nutrients in soils. pp 171-191, in: van Noordwijk M, Cadisch G, Ong CK (Eds.) Belowground Interactions in Tropical Agroecosystems. CAB International, Wallingford (UK).

Carlson, K.M., Curran, L.M., Ratnasari, D., Pittman, A.M., Soares-Filho, B.S., Asner, G.P., Trigg, S.N., Gaveau, D.A., Lawrence, D., Rodrigues, H.O. 2012. Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia. Proceedings of the National Academy of Sciences, 109, 7559–7564. http://dx.doi.org/10.1073/pnas.1200452109

Carlson, K.M., Goodman, L.K., May-Tobin, C.C. 2015. Modeling relationships between water table depth and peat soil carbon loss in Southeast Asian plantations. Environ Res Lett 10, 074006, doi:10 1088/1748-9326/10/7/074006.

Carter, C., Finley, W., Fry, J., Jackson, D., Willis, L. 2007. Palm oil markets and future supply. Eur. J. Lipid Sci. Technol. 109: pp 307–314.

Cassman, K.G., Plant, R.E. 1992. A model to predict crop response to applied fertilizer nutrients in heterogeneous fields. Fertilizer Research, 31, 151–163.

Chimner, R.A., Ewel, K.C. 2005. A tropical freshwater wetland: II Production, decomposition, and peat formation Wetlands Ecology and Management 13: pp. 671-684.

Choo, Y., Muhamad, H., Hashim, Z., Subramaniam, V., Puah, C., Tan, Y. 2011. Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. International Journal of Life Cycle Assessment, 16, 669–681. http://dx.doi.org/10.1007/s11367-011-0303-9

Choong, C.G., McKay, A. 2014 Sustainability in the Malaysian palm oil industry. Journal of Cleaner Production, 85, 258–264.

Colchester, M, Chao, S. ed. 2011. Oil palm expansion in South East Asia: trends and implications for local communities and indigenous peoples. Forest Peoples Programme.

Corley, R.H.V., Hardon, J.J., Tan, G.Y. 1971. Analysis of growth of the oil palm (*Elaeis guinensis* jacq.) 1. Estimation of growth parameters and application in breeding. Euphytica, 20, 307–315.

Corley, R.H.V., Tinker, P.B. 2003. The oil palm (4th ed., 562 p.). John Wiley & Sons, Chichester, UK. http://dx.doi.org/10.1002/9780470750971

Corley, R.H.V., Tinker, P.B. 2016. The oil palm (5th ed., 562 p). John Wiley & Sons, Chichester, UK.

Couwenberg, J., Dommain, R., Joosten, H. 2010. Greenhouse gas fluxes from tropical peatlands in South-East Asia. Glob. Change Biol. 16, 1715–1732.

Couwenberg, J., Hooijer, A. 2013. Towards robust subsidence-based soil carbon emission factors for peat soils in south-east Asia, with special reference to oil palm plantations. Mires and Peat 12(1): pp. 1–13.

Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucch, M., Faaij, A., Fargione, J. 2015. Bioenergy and climate change mitigation: an assessment. GCB Bioenergy, 7, 916–944.

Crill, P.M., Martikainen, P.J., Nykanen, H., Silvola, J. 1994. Temperature and N fertilization effects on methane oxidation in a drained peatland soil. Soil Biol Biochem 26: pp. 1331-1339.

Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W. 2008. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics, 8, 389–395.

Danielsen, F., Beukema, H., Burgess, N.D., Parish, F., Brühl, C.A., Donald, P.F., Murdiyarso, M., Phalan, B., Reijnders, L., Struebig, M., Fitzherbert, E.B. 2009. Biofuel plantations on forested lands: Double jeopardy for biodiversity and climate. Conservation Biology, 23, 348–358. http://dx.doi.org/10.1111/cbi.2009.23.issue-2

Dar, J.A., Sundarapandian, A. 2013. Soil organic carbon stock assessment in two temperate forest types of western Himalaya of Jammu and Kashmir, India. For. Res. 3, 1.

Davis, S.C., Anderson-Teixeira, K.J., DeLucia, E.H. 2009. Life-cycle analysis and the ecology of biofuels. Trends in Plant Science, 14, 140–146. http://dx.doi.org/10.1016/j.tplants.2008.12.006

Davis, S.C., Boddey, R.M., Alves, B.J.R., Cowie, A., Davies, C., George, B., Ogle, S.M., Smith, P., van Noordwijk, M., van Wijk, M. 2013. Management swing potential for bioenergy crops. Glob. Change Biol. Bioenergy 5, 623–638. http://dx.doi.org/10.1111/gcbb.2013.5.issue-6 de Blécourt, M., Brumme, R., Xu, J., Corre, M.D., Veldkamp, E, 2013. Soil stocks decrease following conversion of secondary forests to rubber (*Hevea brasiliensis*) plantations. PLoS ONE 8 (7), e69357. http://dx.doi.org/10.1371/journal.pone.0069357.

de Vries, S.C. 2011. Resource use efficiency and environmental performance of biofuel cropping systems. PhD thesis. Wageningen University. The Netherlands.

de Wit, C.T. 1992. Resource use efficiency in agriculture. Agricultural Systems, 40, 125–151.

Demirbas, A. 2007. Importance of biodiesel as transportation fuel. Energy Policy, 35, 4661–4670. http://dx.doi.org/10.1016/j.enpol.2007.04.003

Dewi, S., Khasanah, N., Rahayu, S., Ekadinata, A., van Noordwijk, M. 2009. Carbon footprint of Indonesian palm oil production: A Pilot study. Bogor: World Agroforestry Centre - ICRAF, SEA Regional Office.

Dewi, S., Ekadinata, A. 2013. Analysis of Land Use and Cover Trajectory (ALUCT). In: Negotiation-Support Toolkit for Learning Landscapes (eds van Noordwijk M, Lusiana B, Leimona B, Dewi S, Wulandari D), pp. 157–162. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program, Bogor, Indonesia.

Di Gregorio M, Nurrochmat DR, Paavola J, Sari IM, Fatorelli L, Pramova E, Locatelli B, Brockhaus M. Kusumadewi SD (2017) Climate policy integration in the land use sector: Mitigation, adaptation and sustainable development linkages. Environmental Science & Policy 67: pp. 35-43.

Dib, J.B., Krishna, V.V., Alamsyah, Z., Qaim, M. 2018. Land-use change and livelihoods of non-farm households: The role of income from employment in oil palm and rubber in rural Indonesia. Land Use Policy, 76, pp.828-838.

DID and LAWOO. 1996. Western Johore integrated agricultural development project: peat soil management study. Department of irrigation and drainage (DID), Kuala Lumpur, Malaysia and land and water research group (LAWOO) Wageningen, The Netherlands.

Directorate general of estate crops (Direktorat Jenderal Perkebunan). 2014. Statistik perkebunan Indonesia (tree crop estate statistics of Indonesia), 2013–2015, Kelapa Sawit (oil palm). Jakarta

Directorate general of estate crops (Direktorat Jenderal Perkebunan). 2016a. Statistik perkebunan Indonesia (tree crop estate statistics of Indonesia), 2015-2017, Kelapa Sawit (oil palm). Jakarta.

Directorate general of estate crops (Direktorat Jenderal Perkebunan). 2016b. Statistik perkebunan Indonesia (tree crop estate statistics of Indonesia), 2015-2017, Cocoa. Jakarta.

Directorate general of estate crops (Direktorat Jenderal Perkebunan). 2016c. Statistik perkebunan Indonesia (tree crop estate statistics of Indonesia), 2015-2017, Lada (pepper). Jakarta.

Don, A., Schumacher, J., Freibauer, A. 2011. Impact of tropical land-use change on soil organic carbon stocks—a meta-analysis. Glob. Change Biol. 17, 1658–1670.

Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Japan: Institute for Global Environment Strategies.

Ellert, B.H., Bettany, J.R. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75, 529–538.

EPA. 2010. Renewable fuel standard program (RFS2) regulatory impact analysis. Washington, DC: US Environmental Protection Agency.

Erhabor, J.O., Filson, G.C. 1999. Soil Fertility Changes Under an Oil Palm-Based Intercropping System. Journal of Sustainable Agriculture 14, 2-3

EU Union. 2009. Directive on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union.

Euler, M., Krishna, V., Schwarze, S., Siregar, H., Qaim, M. 2017. Oil palm adoption, household welfare, and nutrition among smallholder farmers in Indonesia. World Development, 93, pp.219-235.

European Commission. 2010. Guideline for the calculation of land carbon stocks for the purpose of Annex V of Directive 2009/28/EC (notified under document C (2010) 3751) (2010/335/EU). Official Journal of the European Union.

European Communities Commission. 2008. Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources.

Evers, S., Yule, C.M., Padfield, R., O'reilly, P., Varkkey, H. 2017 Keep wetlands wet: the myth of sustainable development of tropical peatlands–implications for policies and management. Global change biology 23(2): pp. 534-549.

Fairhurst, T. 1996. Management of Nutrients for Efficient Use in Smallholder Oil Palm Plantations. Department of Biological Sciences, Wye College, University of London.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P. 2008. Land clearing and the biofuel carbon debt. Science, 319, 1235–1238. http://dx.doi.org/10.1126/science.1152747

Farmer, J., Matthews, R., Smith, P., Langan, C., Hergoualc'h, K., Vercho, L., Smith, J.U. 2014. Comparison of methods for quantifying soil carbon in tropical peats. Geoderma 214: pp. 177-183.

Feintrenie, L., Chong, W.K., Levang, P. 2010a. Why do farmers prefer oil palm? lessons learnt from Bungo district, Indonesia. Small-scale Forestry 9:379–396.

Feintrenie, L., Schwarze, S., Levang, P. 2010b. Are local people conservationists? Analysis of transition dynamics from agroforests to monoculture plantations in Indonesia. Ecology and Society 15(4): 37. [online] URL: http://www.ecologyandsociety.org/vol15/iss4/art37/

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S., 2009. Recent developments in life cycle assessment. *Journal of environmental management*, *91*(1), pp.1-21.

Flynn, H.C., Milà i Canals, L., Keller, E., King, H., Sim, S., Hastings, A., Wang, S., Smith, P. 2011. Quantifying global greenhouse gas emissions from land use change for crop production. Glob. Change Biol. 18 (5), 1622–1635.

Frazão, L.A., Paustian, K., Pellegrino Cerri, C.E., Cerri, C.C. 2013. Soil carbon stocks and changes after oil palm introduction in the Brazilian Amazon. Glob. Change Biol. Bioenergy 5, 384–390.

Frolking S, Roulet NT, Tuittila E, Bubier JL, Quillet A, Talbot J, Richard PJH (2010) A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation. Earth System Dynamics 1: pp. 1–21.

Galudra, G., van Noordwijk, M., Agung, P., Suyanto, S., Pradhan, U. 2014. Migrants, land markets and carbon emissions in Jambi, Indonesia: land tenure change and the prospect of emission reduction. Mitig Adapt Strateg Glob Change 19(6): pp. 715-732.

GanLian, T. 2012. Creating shared value in oil palm smallholder schemes in Indonesia - experiences from Musim Mas group plantations. Planter; 2012. 88: 1031, 109-118.

García-Palacios, P., McKie, B.G., Handa, I.T., Frainer, A,. Hättenschwiler, S. 2016. The importance of litter traits and decomposers for litter decomposition: a comparison of aquatic and terrestrial ecosystems within and across biomes. Functional Ecology 30: pp. 819–829.

Gatto, M., Wollni, M., Asnawi, R., Qaim, M. 2017. Oil palm boom, contract farming, and rural economic development: village-level evidence from Indonesia. World Development, 95, pp.127-140.

Gawankar, M.S., Devmore, J.P., Jamadagni, B.M., Sagvekar, V.V., Khan, H.H. 2003. Effect of water stress on growth and yield of Tenera oil palm. Journal of Applied Horticulture Vol. 5 No. 1 pp. 39-40.

George, B., Cowie, A. 2011. Bioenergy systems, soil health and climate change. In B. Singh, A. Cowie, K. Chang (Eds.), Soil health and climate change (pp. 369–397). Springer Berlin Heidelberg.

Gérard, A., Wollni, M., Hölscher, D., Irawan, B., Sundawati, L., Teuscher, M., Kreft, H. 2017. Oil-palm yields in diversified plantations: initial results from a biodiversity enrichment experiment in Sumatra, Indonesia. Agriculture, Ecosystems & Environment, Vol. 240, pp 253-260.

Germer, J., Sauerborn, J. 2008. Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. Environment, Development and Sustainability, 10, 697–716. http://dx.doi.org/10.1007/s10668-006-9080-1

Gibbs, H. K., Johnston, M., Foley, J. A., Holloway, T., Chad, M., Ramankutty, N., Zaks, D. 2008. Carbon payback times for crop-based biofuel expansion in the tropics: The effects of changing yield and technology. Environmental research letters, 3, 1–10.

Grau, R., Kuemmerle, T., Macchi, L. 2013. Beyond 'land sparing versus land sharing': environmental heterogeneity, globalization and the balance between agricultural production and nature conservation. Current Opinion in Environmental Sustainability, 5, 477–483.

Green, R.E., Cornell, S.J., Scharlemann, J.P.W., Balmford, A. 2005. Farming and the fate of wild nature. Science, 307, 550–555.

Groeneveld, J.H., Tscharntke, T., Moser, G., Clough, Y. 2010. Experimental evidence for stronger cocoa yield limitation by pollination than by plant resources. *Perspectives in Plant Ecology, Evolution and Systematics*, *12*(3), pp.183-191.

Grønlund, A., Atle, H., Anders, H., Daniel, P.R. 2008. Carbon loss estimates from cultivated peat soils in Norway: a comparison of three methods. Nutrient Cycling in Agroecosystems 81: pp. 157–167.

Gumbricht, T., Roman-Cuesta, R.M., Verchot, L., Herold, M., Wittmann, F., Householder, E., Herold, N., Murdiyarso, D. 2017. An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. Global Change Biology 23(9): pp. 3581-3599.

Guo, L.B., Gifford, R.M. 2002. Soil carbon stocks and land use change: a meta-analysis. Glob. Change Biol. 8, 345–360.

Hairiah, K., Sitompul, S.M., van Noordwijk, M. and Palm, C., 2001. *Methods for sampling carbon stocks above and below ground* (pp. 1-23). Bogor: ICRAF.

Hairiah, K., Dewi, S., Agus, F., Velarde, S. J., Ekadinata, A., Rahayu, S., van Noordwijk, M. 2011. Measuring carbon stocks across land use systems: A manual (p. 154). Bogor: World Agroforestry Centre - ICRAF, SEA Regional Office.

Handayani, E.P. 2009. Emisi karbon dioksida (CO_2) dan metan (CH_4) pada perkebunan kelapa sawit di lahan gambut yang memiliki keragaman dalam ketebalan gambut dan umur tanaman. PhD thesis, Sekolah Pascasarjana Institut Pertanian Bogor, Bogor.

Haron, K., Brookes, P.C., Anderson, J.M., Zakaria, Z.Z. 1998. Microbial biomass and soil organic matter dynamics in oil palm (*Elaeis guineensis* jacq.) plantations, West Malaysia. Soil Biol. Biochem. 30 (5), 547–552.

Hassan, M., Jaramillo, P., Griffin, W. 2011. Life cycle GHG emissions from Malaysian oil palm bioenergy development: The impact on transportation sector's energy security. Energy Policy, 39, 2615–2625. http://dx.doi.org/10.1016/j.enpol.2011.02.030

Heege, H.J. 2015. Precision in Crop Farming. Springer, Dordrecht.

Henson, I.E. 1999. Comparative ecophysiology of oil palm and tropical rain forest. In G. Singh, L. K. Huan, T. Leng, D. L. Kow (Eds.), Oil palm and the environment—A Malaysian perspective (pp. 9–39). Kuala Lumpur: Malaysian Oil Palm Growers Council.

Henson, I.E. 2003. The Malaysian national average oil palm: Concept and evaluation. Oil Palm Bulletin, 14, 15–27.

Henson, I.E. 2004. Modelling carbon sequestration and emissions related to oil palm cultivation and associated land use change in Malaysia (MPOB Technology bulletin 27). Kuala Lumpur: Malaysian Palm Oil Board.

Hergoualc'h, K., Verchot, L.V. 2011. Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: a review. Glob. Biogeochem. Cycl. 25 (2) GB2001.

Hidayat, N.K., Offermans, A., Glasbergen, P. 2018. Sustainable palm oil as a public responsibility? On the governance capacity of Indonesian Standard for Sustainable Palm Oil (ISPO). Agriculture and Human Values 35(1): 223-242.

Hoefnagels, R., Smeets, E., Faaij, A. 2010. Greenhouse gas footprints of different biofuel production systems. Renewable and Sustainable Energy Reviews, 14, 1661–1694.

Hoffmann, M., Castaneda Vera, A., van Wijk, M.T., Giller, K.E., Oberthür, T., Donough, C., Whitbread, A.M. 2014. Simulating potential growth and yield of oil palm (*Elaeis guineensis*) with PALMSIM: Model description, evaluation and application. Agricultural Systems 131, Pages 1-10.

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H., Jauhiainen, J. 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. Biogeosciences 7, 1505–1514.

Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A., Anshari, G. 2012. Subsidence and carbon loss in drained tropical peatlands, Biogeosciences 9: pp. 1053–1071.

Houghton, R.A., Greenglass, N., Baccini, A., Cattaneo, A., Goetz, S., Kellndorfer, J., Laporte, N., Walker, W. 2010. The role of science in reducing emissions from deforestation and forest degradation (REDD). Carbon Manag. 1, 253–259.

Hutabarat, S., Slingerland, M., Rietberg, P., Dries, L. 2018. Costs and benefits of certification of independent oil palm smallholders in Indonesia. *International Food and Agribusiness Management Review* 21(6): 681-700

Huth, N.I., Banaba, M., Nelson, P.N., Webb, M. 2014. Development of an oil palm cropping systems model: Lessons learned and future directions. Environmental Modelling & Software 62, Pages 411-419.

Ickowitz, A., Rowland, D., Powell, B., Salim, M.A., Sunderland, T. 2016. Forests, trees, and micronutrient-rich food consumption in Indonesia. *PloS one*, *11*(5), p.e0154139.

IFC. 2013. Diagnostic Study on Indonesian Oil Palm Smallholders: Developing a Better Understanding of Their Performance and Potential. International Finance Corporation, Washington.

Index Mundi. 2017. Palm Oil Production by Country. Index Mundi. Retrieved from https://www.indexmundi.com/agriculture/?commodity=palm-oil&graph=production

IPCC. 1997. Land use change & forestry. In J. T. Houghton, L. G. Meira Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, … B. A. Callander (Eds.), Revised 1996 IPCC guidelines for National Greenhouse Inventories. Paris: IPCC/OECD/IEA.

IPCC. 2006. Intergovernmental Panel on Climate Change: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Hayama, Japan.

IPCC. 2007. Intergovernmental panel on climate change: technical summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor

IPCC. 2014. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. In: T Hiraishi, T Krug, K Tanabe, N Srivastava, J Baasansuren, M Fukuda and T G Troxler (eds). Switzerland: Intergovernmental Panel on Climate Change (IPCC).

Ishikura, K., Hirano, T., Okimoto, Y., Hirata, R., Kiew, F., Melling, L., Aeries, E.B., San-Lo, K., Musin, K.K., Waili, J.W., Wong, G.X. 2018. Soil carbon dioxide emissions due to oxidative peat decomposition in an oil palm plantation on tropical peat. Agriculture, Ecosystems & Environment 254: pp. 202-212.

Jackson, L.E., Pulleman, M.M., Brussaard, L., Bawa, K.S., Brown, G., Cardoso, I.M., de Ruiter, P., García-Barrios, L., Hollander, A.D., Lavelle, P., Ouédraogo, E., Pascual, U., Setty, S., Smukler, S.M., Tscharntke, T., Van Noordwijk, M. 2012. Social-ecological and regional adaptation of agrobiodiversity management across a global set of research regions. Global Environmental Change, 22, 623–639.

Jauhiainen, J., Hooijer, A., Page, S.E. 2012. Carbon dioxide emissions from an Acacia plantation on peatland in Sumatra, Indonesia. Biogeosciences 9: pp. 617–630.

Jauhiainen, J., Kerojoki, O., Silvennoinen, H., Limin, S., Vasander, H. 2014. Heterotrophic respiration in drained tropical peat is greatly affected by temperature—a passive ecosystem cooling experiment. Environ Res Lett 9: 105013.

Jelsma, I., Schoneveld, G.C., Zoomers, A., van Westen, A.C.M. 2017. Unpacking Indonesia's independent oil palm smallholders: An actor-disaggregated approach to identifying environmental and social performance challenges. Land Use Policy 69: 281-297.

Joshi, L., Wibawa, G., Beukema, H.J., Williams, S.E., van Noordwijk, M. 2003. Technological change and biodiversity in the rubber agroecosystem. pp 133-157, in: Vandermeer J (Eds.) Tropical Agroecosystems: New Directions for Research. CRC Press, Boca Raton (Florida, USA).

Jourdan, C., Rey, H. 1997. Modelling and simulation of the architecture and development of the oil palm (Elaeis guineensis Jacq.) root system. Plant and Soil, 190, 235–246. http://dx.doi.org/10.1023/A:1004270014678

Kamahara, H., Widiyanto, A., Tachibana, R., Atsuta, Y., Goto, N., Daimon, H., Fujie, K. 2008. Greenhouse Gas Balance on Life Cycle of Biodiesel: A case of palm biodiesel production in Indonesia. Paper presented at the 8th International Conference on EcoBalance, Tokyo. 10–12 December 2008.

Kamahara, H., Hasanudin, U., Widiyanto, A., Tachibana, R., Atsuta, Y., Goto, N., Daimon, H., Fujie, K. 2010. Improvement potential for net energy balance of biodiesel derived from palm oil: A case study from Indonesian practice. Biomass and Bioenergy 34, 1818–1824.

Khalid, H., Zin, Z.Z., Anderson, J.M. 1999. Quantification of oil palm biomass and nutrient value in a mature plantation. I Above-ground Biomass. Journal of Oil Palm Research, 1, 23–32.

Khasanah, N., van Noordwijk, M., Ekadinata, A., Dewi, S., Rahayu, S., Ningsih, H., Setiawan, A., Dwiyanti, E., Octaviani, R. 2012. The carbon footprint of Indonesian palm oil production. Technical Brief No 25: Palm Oil Series. World Agroforestry Centre—ICRAF, SEA Regional Office, Bogor, Indonesia p. 10.

Khasanah, N., van Noordwijk, M., Ningsih, H., Rahayu, S. 2015a. Carbon neutral? No change in mineral soil carbon stock under oil palm plantations derived from forest or non-forest in Indonesia. Agriculture, Ecosystems and Environment, 211, 195–206. http://dx.doi.org/10.1016/j.agee.2015.06.009

Khasanah, N., van Noordwijk, M., Ningsih, H. 2015b. Aboveground carbon stocks in oil palm plantations and the threshold for carbon-neutral vegetation conversion on mineral soils. Cogent Environmental Science, 1, 1119964.

Khasanah N, Perdana A, Rahmanullah A, Manurung G, Roshetko J, van Noordwijk M. 2015c. Intercropping teak (*Tectona grandis*) and maize (Zea mays): bioeconomic trade-off analysis of agroforestry management practices in Gunungkidul, West Java. Agroforestry Systems 89(6), 1019-1033.

Kittithammavong, V., Arpornpong, N., Charoensaeng, A., Khaodhiar, S. 2014. Environmental life cycle assessment of palm oil- based biofuel production from transesterification: greenhouse gas, energy and water balances. International Conference on Advances in Engineering and Technology (ICAET'2014), Singapore.

Koh, L.P., Wilcove, D.S. 2008. Is oil palm agriculture really destroying tropical biodiversity? Conservation Letters, 1, 60–64. http://dx.doi.org/10.1111/j.1755-263X.2008.00011.x

Koh, L.P., Miettinen, J., Liew, S.C., Ghazoul, J. 2011. Remotely sensed evidence of tropical peatland conversion to oil palm. PNAS vol. 108 no. 12: 5127–5132.

Koh, L.P., Gibbs, H.K., Potapov, P.V., Hansen, M.C. 2012. REDDcalculator.com: A web-based decision-support tool for implementing Indonesia’s forest moratorium. Methods in Ecology and Evolution, 3, 310–316. http://dx.doi.org/10.1111/j.2041-210X.2011.00147.x

Kotowska, M.M., Leuschner, C., Triadiati, T., Meriem, S., Hertel, D. 2015. Quantifying above- and below-ground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia). Glob. Change Biol. doi: 10.1111/gcb.12979 (accepted).

Kubitza, C., Krishna, V.V., Alamsyah, Z., Qaim, M. 2018. The economics behind an ecological crisis: livelihood effects of oil palm expansion in Sumatra, Indonesia. Human Ecology, 46(1), pp.107-116.

Kurnianto, S., Warren, M., Talbot, J., Kauffman, B., Murdiyarso, D., Frolking, S. 2015. Carbon accumulation of tropical peatlands over millennia: a modeling approach. Global change biology 21(1): pp. 431-444.

Kwatiwada, D., Palmén, C., Silveira S. 2018. Evaluating the palm oil demand in Indonesia: production trends, yields, and emerging issues. Biofuels, DOI:10.1080/17597269.2018.1461520

Lamade, E., Djegui, N., Leterme, P. 1996. Estimation of carbon allocation to the roots from soil respiration measurements of oil palm. Plant Soil 181 (2), 329–339.

Lamade, E., Bouillet, J.P. 2005. Carbon storage and global change: the role of oil palm. Ol. Corps Gras Lipides 12, 154–160.

Lambin, E.F., Meyfroidt, P., Rueda, X., Blackman, A., Börner, J., Cerutti, P.O., Dietsch, T., Jungmann, L., Lamarque, P., Lister, J., Walker, N.F. 2014. Effectiveness and synergies of policy instruments for land use governance in tropical regions. Global Environmental Change, 28, 129–140.

Lampela M, Jauhiainen J, Kämäri L, Koskinen M, Tanhuanp T, Valkeapää A, Vasandera H (2016). Ground surface microtopography and vegetation patterns in a tropical peat swamp forest. CATENA 139: pp. 127-136. https://doi.org/10.1016/j.catena.2015.12.016

Larsen, R.K., Osbeck, M., Dawkins, E., Tuhkanen, H., Nguyen, H., Nugroho, A., Gardner, T., EcoNusantara, Z., Wolvekamp, P. 2018. Hybrid governance in agricultural commodity chains: Insights from implementation of 'No Deforestation, No Peat, No Exploitation'(NDPE) policies in the oil palm industry. Journal of Cleaner Production 183: pp. 544–554.

Laurance, W.F., Koh, L.P., Butler, R., Sodhi, N.S., Bradshaw, C.J.A., Neidel, J.D., Consunji, H., Vega, J.M. 2010. Improving the performance of the roundtable on sustainable palm oil for nature conservation. Conserv. Biol. 24, 377–381.

Law, M.C., Balasundram, S.K., Husni, M.H.A., Ahmed, O.H., Harun, M.H. 2009. Spatial variability of soil organic carbon in oil palm. Int. J. Soil Sci. 4 (4), 93–103.

Lee, D.R., Barrett, C.B. 2001. Tradeoffs or Synergies? Agricultural Intensification, Economic Development and the Environment. CAB-International, Wallingford.

Lee, J., Hopmans, J.W., Rolston, D.E., Baer, S.G., Six, J. 2009. Determining soil carbon stock changes: simple bulk density corrections fail. Agric. Ecosyst. Environ. 134(3), 251–256.

Lee, J.S.H., Ghazoul, J., Obidzinski, K., Koh, L.P. 2014. Oil palm smallholder yields and incomes constrained by harvesting practices and type of smallholder management in Indonesia. Agronomy for Sustainable Development, Vol. 34, No. 2, pp 501–513.

Loague, K., Green, R.E. 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. J Contaminant Hydrol 7:51–73.

Manohara, D., Wahyuno, D. 2013. Pedoman budidaya merica. Pepper cultivation guide. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program.

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F. and Hansen, M.C., 2014. Primary forest cover loss in Indonesia over 2000–2012. Nature Climate Change 4(8): p. 730.

Martin-Guay, M., Paquette, P., Dupras, J., Rivest, D. 2018. The new Green Revolution: Sustainable intensification of agriculture by intercropping. Science of The Total Environment, 615, 767-772. https://doi.org/10.1016/j.scitotenv.2017.10.024.

Marwanto, S., Agus, F. 2014. Is CO_2 flux from oil palm plantations on peatland controlled by soil moisture and/or soil and air temperatures? Mitigation and adaptation strategies for global change 19(6): pp. 809-819.

Maswar, M. 2011. Kajian cadangan karbon pada lahan gambut tropika yang didrainase untuk tanaman tahunan. Sekolah Pascasarjana Institut Pertanian Bogor.

McCarthy, J. F. 2010. Processes of inclusion and adverse incorporation: oil palm and agrarian change in Sumatra, Indonesia. Journal of Peasant Studies, 37, 821–850. http://dx.doi.org/10.1080/03066150.2010.512460

McCarty, G.W., Reeves, J.B., Yost, R., Doraiswamy, P.C., Doumbia, M. 2010. Evaluation of methods for measuring soil organic carbon in West African soils. Afr. J. Agric. Res. 5 (16), 2169–2177.

Mertz, O., Mertens, C.F. 2017. Land Sparing and Land Sharing Policies in Developing Countries – Drivers and Linkages to Scientific Debates, World Development 98, 523-535. https://doi.org/10.1016/j.worlddev.2017.05.002.

Miettinen, J., Shi, C., Liew, S.C. 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. Global Ecology and Conservation 6: pp. 67–78.

Miettinen, J., Hooijer, A., Vernimmen, R., Liew, S.C., Page, S.E. 2017. From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environmental Research Letters, 12(2): p. 024014.

Mignon, A.F. 2018. Assessing the possibilities of intercropping oil palm and pepper, under the double-row avenue system, MSc Thesis Wageningen University, 33 p.

Minang, P.A., van Noordwijk, M. 2013. Design challenges for achieving reduced emissions from deforestation and forest degradation through conservation: leveraging multiple paradigms at the tropical forest margins. Land Use Policy, 31, 61–70.

Minang, P.A., Duguma, L.A., Alemagi, D., van Noordwijk, M. 2015. Scale considerations in landscape approaches. In: Climate-Smart Landscapes: Multifunctionality in Practice (eds Minang PA, van Noordwijk M, Freeman OE, Mbow C, de Leeuw J, Catacutan D), pp. 121–133. World Agroforestry Centre (ICRAF), Nairobi, Kenya.

Mithöfer D, van Noordwijk M, Leimona B, Cerutti P. 2017 Certify and shift blame, or resolve issues? Environmentally and socially responsible global trade and production of timber and tree crop commodities. International Journal of Biodiversity Science, Ecosystem Services & Management.13(1): 72-85

Mokany, K., Raison, R.J., Prokushkin, A.S. 2006. Critical analysis of root: Shoot ratios in terrestrial biomes. Global Change Biology, 12, 84–96. http://dx.doi.org/10.1111/gcb.2006.12.issue-1

Molenaar, J.W., Persch-Ort, M., Lord, S., Taylor, C., Harms, J. 2013. Oil Palm smallholders—developing a better understanding of their performance and potential. International Finance Corporation, Jakarta.

Mulia, R., Widayati, A., Agung, P., Zulkarnain, M.T. 2014. Low carbon emission development strategies for Jambi, Indonesia: simulation and trade-off analysis using the FALLOW model. Mitigation and Adaptation Strategies for Global Change 19(6): pp. 773-788.

Murdiyarso, D., Hergoualc'h, K., Verchot, L.V. 2010. Opportunities for reducing greenhouse gas emissions in tropical peatlands. Proceedings of the National Academy of Sciences, 107, 19655–19660. http://dx.doi.org/10.1073/pnas.0911966107

Mutert, E. 1999a. Suitability of soils for oil palm in Southeast Asia. Better Crops International, Vol. 13, No. 1.

Mutert, E., Fairhurst, T.H., von Uexkull, H.R. 1999b. Agronomic management of oil palms on deep peat. Better Crops Int 13: pp. 22–27.

Nair, P.K.R., Saha, S.K., Nair, V.D., Haile, S.G. 2011. Potential for greenhouse gas emissions from soil carbon stock following biofuel cultivation on degraded lands. Land Degrad. Dev. 22 (4), 395–409.

Naylor, R.L., Liska ,A.J., Burke, M.B., Falcon, W.P., Gaskell, J.C., Rozelle, S.D., Cassman KG. 2007. The ripple effect: Biofuels, food security, and the environment. *Environment: Science and Policy for Sustainable Development*, *49*(9), pp.30-43.

Nchanji, Y.K., Nkongho, R.N., Mala, W.A., Levang, L. 2016. Efficacy of oil palm intercropping by smallholders. Case study in South-West Cameroon. Agroforestry Systems, Vol. 90, No. 3, pp 509–519

Nelson, D.W., Sommers, L.E. 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series No. 5. SSSA and ASA, Madison, WI, pp. 961–1010.

Niedermeyer, E.M., Sessions, A.L., Feakins, S.J., Mohtadi, M. 2014. Hydroclimate of the western Indo-Pacific warm pool during the past 24,000 years. Proceedings of the National Academy of Sciences, 111, 9402–9406. http://dx.doi.org/10.1073/pnas.1323585111

Nogueira, L. 2010. Does biodiesel make sense? Energy, 36, 3659–3666.

Ntsomboh-Ntsefong, G., Ngalle-Bille, H., Ajmbang, W., Likeng-Li-Ngue, B.C., Kingsley, T., Bell, J.M., Youmbi, E. 2016. Brief Review on the Controversies around Oil Palm (*Elaeis Guineensis Jacq.*) Production and Palm Oil Consumption. International Journal of Regional Development, 3-2

Nungesser, M.K. 2003. Modelling microtopography in boreal peatlands: hummocks and hollows. Ecological Modelling 165(2–3): pp. 175-207. https://doi.org/10.1016/S0304-3800(03)00067-X

Nurulita, Y. 2016. Tropical Peat Swamp Soils: The impact of agricultural and restoration practices on activity and diversity of the soil microbial community (Doctoral dissertation, RMIT University). https://researchbank.rmit.edu.au/eserv/rmit:161756/Nurulita.pdf Last accessed 6 May 2017.

Oktarita, S., Hergoualc, K., Anwar, S., Verchot, L.V. 2017. Substantial N_2O emissions from peat decomposition and N fertilization in an oil palm plantation exacerbated by hotspots. Environ. Res. Lett. 12: 104007. https://doi.org/10.1088/1748-9326/aa80f1

Okyere, S.A., Danso, F., Larbi, E., Danso, I. 2014. Residual effect of intercropping on the yield and productivity of oil palm. International Journal of Plant & Soil Science 3 (7): 854-862

Oosterveer, P., Adjei, B.E., Vellema, S. and Slingerland, M. 2014. Global sustainability standards and food security: Exploring unintended effects of voluntary certification in palm oil. *Global Food Security*, *3*(3-4), pp.220-226.

Orewa, S.I. 2008. Designing agricultural development projects for the small-scale farmers: some lessons from the world bank assistance small holder oil palm development scheme in Nigeria. Journal of Applied Sciences, 8: 295-301

Othman, H., Mohammed, A.T., Darus, F.M., Harun, M.H., Zambri, M.P. 2011. Best management practices for oil palm cultivation on peat: ground water-table maintenance in relation to peat subsidence and estimation of CO_2 emissions at Sessang. Sarawak J Oil Palm Res 23: pp. 1078–86.

Page, S.E., Rieley, J.O., Shotyk, Ø.W., Weiss, D. 1999. Interdependence of peat and vegetation in a tropical peat swamp forest. Philos Trans R Soc Lond B Biol Sci. 354(1391): pp. 1885–1897.

Page, S.E., Hoscilo, A., Wösten, H., Jauhiainen, J., Silvius, M., Rieley, J., Ritzema, H., Tansey, K., Graham, L., Vasander, H., Limin, S. 2009. Restoration ecology of lowland tropical peatlands in Southeast Asia: current knowledge and future research directions. Ecosystems 12(6): pp. 888-905.

Page, S.E., Morrison, R., Malins, C., Hooijer, A., Rieley, J.O., Jauhiainen, J. 2011a. Review of peat surface greenhouse gas emissions from oil palm plantations in Southeast Asia. ICCT White Paper 15, Indirect effects of biofuel production series. Washington: International Council on Clean Transportation.

Page, S.E., Rieley, J.O., Banks, C.J. 2011b. Global and regional importance of the tropical peatland carbon pool. Global Change Biology 17: pp. 798–818, doi: 10 1111/j 1365-2486 2010 02279 x.

Pahan, I. 2006. Panduan lengkap kelapa sawit: manajemen agribisnis dari hulu hingga hilir [complete guide of oil palm: agribusiness management from upstream to downstream] (411 p.). Jakarta: Penebar Swadaya.

Pahan I. 2015. Panduan teknis budidaya kelapa sawit. Penebar Swadaya, Jakarta.

Palm, C., Tomich, T., Van Noordwijk, M., Vosti, S., Gockowski, J., Alegre, J., Verchot, L. 2004. Mitigating GHG emissions in the humid tropics: Case Studies from the alternatives to slash-and-burn program (ASB). Environment, Development and Sustainability, 6, 145–162. http://dx.doi.org/10.1023/B:ENVI.0000003634.50442.ca

Paramananthan, S. 2010a. Malaysian soil taxonomy - revised, 2nd edition. Param Agricultural Soil Surveys (M) Sdn Bhd Petaling Jaya, Selangor, Malaysia.

Paramananthan, S. 2010b. Keys to the Identification of Malaysian Soils Using Parent Materials. Param Agricultural Soil Surveys (M) Sdn Bhd Petaling Jaya, Selangor, Malaysia.

Patthanaissaranukool, W., Polprasert, C. 2011. Carbon mobilization in oil palm plantation and milling based on a carbon-balanced model—a case study in Thailand. Environ. Asia 4, 17–26.

Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P.L. 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manag. 13, 230–244.

Petersen, B., Snapp, S. 2015. What is sustainable intensification? Views from experts. Land Use Policy Vol. 46, Pages 1-10

Petrenko, C., Paltseva, J., Searle, S. 2016. Ecological impacts of palm oil expansion in Indonesia. International Council on Clean Transportation

Phalan, B.T. 2018. What have we learned from the land sparing-sharing model?. Sustainability 10, 1760; doi:10.3390/su10061760

Porankiewicz, B., Iskra, P., Sandak, J., Tanaka, C., & Jóźwiak, K. 2006. High-speed steel tool wear during wood cutting in the presence of high-temperature corrosion and mineral contamination. Wood Science and Technology, 40, 673–682. http://dx.doi.org/10.1007/s00226-006-0084-7

Post, W.M., Kwon, K.C. 2000. Soil carbon sequestration and land-use change: processes and potential. Glob. Change Biol. 6 (3), 317–327.

Powers, J., Corre, M., Twine, T.E., Veldkamp, E. 2011 Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proceedings of the National Academy of Sciences (USA), 108, 6318–6322.

Pretty, J., Bharucha, Z.P. 2014. Sustainable intensification in agricultural systems. Annals of Botany 114: 1571 – 1596

Putra, E.T.S., Simatupang, A.F., Supriyanta, Waluyo, S., Indradewa, D. 2012. The growth of one-year-old oil palms intercropped with soybean and groundnut. Journal of Agricultural Science, Vol. 4, No. 5.

Raison, J., Atkinson, P., Chave, J., DeFries, R., Joo, G.K., Joosten, H., Navratil, P., Siegert, F. 2015. HCS+, A new pathway to sustainable oil palm development, draft extended summary. Retrieved October 7, 2015 from http://www.carbonstockstudy.com/carbonstockstudy/files/f6/f63fcf9e-10e1-47f8-bfbd-3b9e01505cec.pdf.

Ravindranath, N.H., Ostwald, M. 2008. Carbon Inventory Methods Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Round-wood Production Projects. Springer, Dordrecht, pp. 165–166.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P. and Pennington, D.W. 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment international*, *30*(5), pp.701-720.

Reeza, A.A., Hussin, A., Hanif, A.H.M., Sukari, M.A.M. 2014. Effect of liming and fertilizer application in hemic and sapric of tropical peat: phosphorus mineralization, infra-red spectroscopy and microscopy. American Journal of Agricultural and Biological Sciences 9 (3): pp. 321-333.

Reijnders, L., Huijbregts, M.A.J. 2008 Palm oil and the emission of carbon-based greenhouse gases. Journal of Cleaner Production, 16, 477–482. http://dx.doi.org/10.1016/j.jclepro.2006.07.054

Reijnders, L. 2011. The life cycle emission of greenhouse gases associated with plant oils used as biofuel. Renewable Energy, 36, 879–880. http://dx.doi.org/10.1016/j.renene.2010.07.003

Renwick, A., Schellhorn, N. 2016. A perspective on land sparing versus land sharing. In Ansel D, Gibson F, Salt D, eds. Learning from agri-environment schemes in Australia. ANU Press.

Richards, M., Metzel, R., Chirinda, N. Ly, P., Nyamadzawo, G., Vu, Q.D., de Neergaard, A., Oelofse, M., Wollenberg, E., Keller, E., Malin, D. 2016. Limits of agricultural greenhouse gas calculators to predict soil N_2O and CH_4 fluxes in tropical agriculture. Scientific Reports, 6, 26279.

Rist, L., Feintrenie, L., Levang, L. 2010. The livelihood impacts of oil palm: smallholders in Indonesia. Biodiversity and Conservation, Vol. 19, No 4, pp 1009–1024.

Ritzema, H., Limin, S., Kusin, K., Jauhiainen, J., Wösten, H. 2014. Canal blocking strategies for hydrological restoration of degraded tropical peatlands in Central Kalimantan, Indonesia. Catena 114: pp. 11-20.

Rival, A., Levang, P. 2014. Palms of controversies: Oil palm and development challenges. Bogor, Indonesia: CIFOR.

Romero M. 2018. Reducing ecological damages while preserving livelihoods: helping oil Palm farmers to protect their environment. Heinrich-Böll-Stiftung. Southeast Asia.

Rowaan, P. A. 1936. Palmoli [Oil palm]. De Indische Mercuur, 59, 353–363.

Rowe, E.C., Hairiah, K., Giller, K.E., van Noordwijk, M., Cadisch, G. 1999. Testing the safety-net role of hedgerow tree roots by 15N placement at depths. Agroforestry Systems 43: 81-93.

Rudel, T.K., Schneider, L., Uriarte, M., Turner, B.L., De Fries, R., Lawrence, D., Geoghegan, J., Hecht, S., Ickowitz, A., Lambin, E.F., Birkenholtz, T., Baptista, S., Grau, R. 2009. Agricultural intensification and changes in cultivated areas, 1970–2005. Proceedings of the National Academy of Sciences USA, 106, 20675–20680.

Salako, F.K., Lal, R., Swift, M.J. 1995. Intercropping oil palm (*elaeis guineensis*) with cocoyam (*xanthosoma sagittifolium*) on windrows and non-windrows in southern Nigeria. Journal of Sustainable Agriculture, Vol. 6, No. 1.

Salim, A., Wijanarko, R.D.T., Sutisna, E. 2009. Petunjuk teknis budidaya dan pasca panen kakao. Balai Pengkajian Teknologi Pertanian Sulawesi Tenggara.

Sanchez, P.A. 1994. Alternatives to slash and burn: a pragmatic approach for mitigating tropical deforestation. In: Agricultural Technology: Policy Issues for the International Community Wallingford (ed. Anderson JR), pp. 451–479. CAB International, Wallingford, UK.

Santoso, A. 2010. Plasma and its accounting implications. In Palm oil plantation: Industry landscape, regulatory and financial overview. Indonesia: PricewaterhouseCoopers.

Santoso, D., Adiningsih, S., Mutert, E., Fairhurst, T., Van Noordwijk, M. 1997. Site improvement and soil fertility management for reclamation of Imperata grasslands by smallholder agroforestry. Agrofor. Syst. 36, 181–202.

Schroth, G., D'Angelo, S.A., Teixeira, W.G., Haag, D., Lieberei, R. 2002. Conversion of secondary forest into agroforestry and monoculture plantations in Amazonia: consequences for biomass, litter and soil carbon stocks after 7 years. For. Ecol. Manag. 163, 131–150.

Schulte, E.E., 1995. Recommended soil organic matter tests. Recommended soil testing procedures for the northeastern United States. Northeast Reg. Bull. 493, 47–56.

Schwarze, S., Euler, M., Gatto, M., Hein, J., Hettig, E., Holtkamp, A. M., Moser, S. 2015. GOEDOC-Dokumenten-und Publikationsserver der Georg-August-Universität Göttingen.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Tun-Hsiang, Yu. 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science, 319, 1238–1240. http://dx.doi.org/10.1126/science.1151861

Searchinger, T.D., Hamburg, S.P., Melillo, J., Chameides, W., Havlik, P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Obersteiner, M., Oppenheimer, M., Philip Robertson, G. 2009. Fixing a critical climate accounting error. Science. 326(5952): 527.

Searle, S., Giuntoli, J. 2018. Analysis of high and low indirect land-use change definitions in European Union renewable fuel policy. International council on clean transportation, working paper 2017-29.

Sheil, D., Casson, A., Meijaard, E., van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., Wertz, K., Kanninen, M., 2009. The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know? Occasional paper no. 51. CIFOR, Bogor, Indonesia.

Shi, X., Thornton, P.E., Ricciuto, D.M., Hanson, P.J., Mao, J., Sebestyen, S.D., Griffiths, N.A., Bisht, G. 2015. Representing northern peatland microtopography and hydrology within the Community Land Model. Biogeosciences Discuss. 12: pp. 3381–3418. https://doi:10.5194/bgd-12-3381-2015

Siangjaeo, S., Gheewala, S., Unnanon, K., Chidthaisong, A. 2011. Implications of land use change on the life cycle greenhouse gas emissions from palm biodiesel production in Thailand. Energy for Sustainable Development, 15, 1–7. http://dx.doi.org/10.1016/j.esd.2011.01.002

Simeh, A., Ahmad, T.M.A.T. 2001. The case study on the Malaysian palm oil. In *Regional Workshop on commodity export diversification and poverty reduction in South and South-East Asia, Bangkok* (pp. 3-5).

Sirait, M. 2009. Indigenous peoples and oil palm plantation expansion in West Kalimantan, Indonesia. The Hague: Cordaid Memisa.

Siregar, K., Tambunan, A.H., Irwanto, A.K., Wirawan, S.S., Araki, T. 2015. A comparison of life cycle assessment on oil palm (*Elaeis guineensis jacq*.) and physic nut (*Jatropha curcas linn*.) as feedstock for biodiesel production in indonesia. Energy Procedia 65: 170 – 179.

Sitompul, S.M., Hairiah, K., Cadisch, G., Van Noordwijk, M. 2000. Dynamics of density fractions of macro-organic matter after forest conversion to sugarcane and woodlots, accounted for in a modified Century model. Neth. J. Agric. Sci. 48, 61–73.

Soeharto, B., Budidarsono, S., van Noordwijk, M. 2016. Gaharu (eaglewood) domestication: Biotechnology, markets and agroforestry options. Working paper no.247. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program. DOI: http://dx.doi.org/10.5716/WP16163.PDF

Sommer, R., Denich, M., Vlek, P.L.G. 2000. Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. Plant Soil 219, 231–241.

Song, C., Wang, L., Tian, H., Liu, D., Lu ,C., Xu, X., Zhang, L., Yang, G., Wan, Z. 2013. Effect of continued nitrogen enrichment on greenhouse gas emissions from a wetland ecosystem in the Sanjiang Plain, Northeast China: A 5 year nitrogen addition experiment Journal of geophysical research. Biogeosciences 118: pp. 741–751

Souza, S.P., Pacca, S., Avila, M,T., Borges, J.L.B. 2010. Greenhouse gas emissions and energy balance of palm oil biofuel. Renewable Energy Vol. 35, Issue 11, pp 2552-2561.

Stomph, D. 2017. Smallholder oil palm: space for diversification?, MSc Thesis Wageningen University, 78 p.

Suboh, I., Norkaspi, K., Zulfkifli, R.O. 2009. Double-row avenue system for crop integration with oil palm. MPOB Information Series No 465. http://palmoilis.mpob.gov.my/publications/TOT/TT-424.pdf

Sumarga, E., Hein, L., Hooijer, A., Vernimmen, R. 2016. Hydrological and economic effects of oil palm cultivation in Indonesian peatlands. Ecology and Society 21(2):52. http://dx doi org/10 5751/ES-08490-210252

Suprayogo, D., Van Noordwijk, M., Hairiah, K., Cadisch, G. 2002. The inherent 'safety-net'of an Acrisol: Measuring and modelling retarded leaching of mineral nitrogen. *European Journal of Soil Science*, *53*(2), pp.185-194.

Suprayogo, D., Widianto, C.G., van Noordwijk, M. 2003. A pedotransfer resource database (PtfRDB) for tropical soils: test with the water balance of WaNuLCAS. In: Post, D. (Ed.), MODSIM Proceedings, Townsville, Australia, July 2003.

Suwarno, A., van Noordwijk, M., Weikard, H.P., Suyamto, D. 2018a. Indonesia's forest conversion moratorium assessed with an agent-based model of Land-Use Change and Ecosystem Services (LUCES). Mitigation and Adaptation Strategies for Global Change 23: pp. 211–229.

Suwarno, A., Hein, L., Weikard, H.P., van Noordwijk, M., Nugroho, B. 2018b. Land-use trade-offs in the Kapuas peat forest, Central Kalimantan, Indonesia. Land Use Policy. *in press*.

Syahrinudin. 2005. The potential of oil palm and forest plantations for carbon sequestration on degraded land in Indonesia. In M. Denich, C. Martius, & C. Rodgers, N. van de Giesen (Eds.), Ecology and Development Series No. 28. Göttingen: Cuvillier Verlag.

Szumigalski, A. R., and R. C. Van Acker. 2008. Land Equivalent Ratios, Light Interception, and Water Use in Annual Intercrops in the Presence or Absence of In-Crop Herbicides. Agron. J. 100:1145-1154. doi:10.2134/agronj2006.0343.

Tan, K.T., Lee, K.T., Mohamed, A.R., Bhatia, S. 2009. Palm oil: Addressing issues and towards sustainable development. Renewable and Sustainable Energy Reviews, 13, 420–427. http://dx.doi.org/10.1016/j.rser.2007.10.001

Tata, H.L., van Noordwijk, M., Werger, M.J.A. 2008. Trees and regeneration in rubber agroforests and other forest-derived vegetation in Jambi (Sumatra, Indonesia). Journal of Forestry Research 5: 1-20. http://forda-mof.org/files/1-20%20Hesti%20L,%20et%20all.pdf.

Tata, H.L., van Noordwijk, M., Ruysschaert, D., Mulia, R., Rahayu, S., Mulyoutami, E., Widayati, A., Ekadinata, A., Zen, R., Darsoyo, A. Oktaviani, R. 2014. Will funding to Reduce Emissions from Deforestation and (forest) Degradation (REDD+) stop conversion of peat swamps to oil palm in orangutan habitat in Tripa in Aceh, Indonesia?. Mitigation and adaptation strategies for global change 19(6): pp. 693-713.

Tate, K.R. 2015. Soil methane oxidation and land-use change – from process to mitigation. Soil Biology and Biochemistry, 80, 260–272.

The European parliament and of the council. 2009. Directive 2009/28/EC: the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union.

Thoenes, P. 2006, October 24–25. Biofuels and commodity markets—Palm oil focus 1. In AgraInforma conference "The Impact of biofuels on commodity Markets". Brussels.

Thorburn, C.C., Kull, C.A. 2015. Peatlands and plantations in Sumatra, Indonesia: Complex realities for resource governance, rural development and climate change mitigation. Asia Pacific Viewpoint 56(1): pp. 153-168.

Tiemeyer, B., Kahle, P. 2014. Nitrogen and dissolved organic carbon (DOC) losses from an artificially drained grassland on organic soils. Biogeosciences 11: pp. 4123–4137.

Tomich, T.P., van Noordwijk, M., Vosti, S., Whitcover, J. 1998. Agricultural development with rainforest conservation: methods for seeking best bet alternatives to slashand-burn, with applications to Brazil and Indonesia. Agricultural Economics, 19,159–174.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biological conservation*, *151*(1), pp.53-59.

Turetsky, M.R., Benscoter, B., Page, S., Rein, G., van Der Werf, G.R., Watts, A. 2015. Global vulnerability of peatlands to fire and carbon loss. Nature Geoscience 8(1): p. 11.

van der Voet, E., Lifset, R.J., Lin Luo, L. 2010. Life-cycle assessment of biofuels, convergence and divergence. Biofuels, 1, 435–449.

van der Werf, G.R., Morton, D.C., de Fries, R.S., Olivier, J.G.J., Kasibhatla, P.S., Jackson, R.B., Collatz, G.J., Randerson, J.T. 2009. CO_2 emissions from forest loss. Nat. Geosci. 2, 737–738.

van Noordwijk, M., de Willigen, P. 1986. Quantitative root ecology as element of soil fertility theory. Netherlands Journal of Agricultural Science, 34, 273–281.

van Noordwijk, M., de Willigen, P. 1987. Agricultural concepts of roots: from morphogenetic to functional equilibrium. Netherlands Journal of Agricultural Science, 35, 487–496.

van Noordwijk, M., Wadman, W. 1992. Effects of spatial variability of nitrogen supply on environmentally acceptable nitrogen fertilizer application rates to arable crops. Netherlands Journal of Agricultural Science, 40, 51–72.

van Noordwijk, M., Scholten, J.H.M. 1994. Effects of fertilizer price on feasibility of efficiency improvement: case study for an urea injector for lowland rice. Fertilizer Research, 39, 1–9.

van Noordwijk, M., Tomich, T.P., Winahyu, R., Murdiyarso, D., Partoharjono, S., Fagi, A.M. (eds). 1995. Alternatives to Slash-and-Burn in Indonesia, Summary Report of Phase 1. ASB-Indonesia Report Number 4, Bogor, Indonesia, 154.

van Noordwijk, M., Cerri, C., Woomer, P.L., Nugroho, K., Bernoux, M. 1997. Soil carbon dynamics in the humid tropical forest zone. Geoderma, 79, 187–225. http://dx.doi.org/10.1016/S0016-7061(97)00042-6

van Noordwijk, M. 1999. Nutrient cycling in ecosystems versus nutrient budgets of agricultural systems. In: Nutrient Disequilibria in Agro-Ecosystems: Concepts and Case Studies (eds Smaling EMA, Oenema O, Fresco LO), pp. 1–26. CAB International, Wallingford.

van Noordwijk, M., Lusiana, B. 1999. WaNuLCAS a model of water, nutrient and light capture in agroforestry systems. Agroforestry System 43:217–242.

van Noordwijk, M., Cadisch, G. 2002. Access and excess problems in plant nutrition. Plant and Soil, 247, 25–39.

van Noordwijk, M., Rahayu, S., Hairiah, K., Wulan, Y.C., Farida, A., Verbist, B., 2002. Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis. *SCIENCE IN CHINA SERIES C LIFE SCIENCES-ENGLISH EDITION-*, *45*(SUPP), pp.75-86.

van Noordwijk, M., Mulyoutami, E., Sakuntaladewi, N., Agus, F. 2008. Swiddens in Transition: Shifted Perceptions on Shifting Cultivators in Indonesia. World Agroforestry Centre—ICRAF, SEA Regional Office, Bogor, Indonesia p. 48.

van Noordwijk, M., Lusiana, B., Khasanah, N., Mulia, R. 2011. WaNuLCAS version 4.0, Background on a Model of Water Nutrient and Light Capture in Agroforestry Systems. World Agroforestry Centre (ICRAF), Bogor, Indonesia

van Noordwijk, M., Tata, H.L., Xu, J., Dewi, S., Minang, P.A. 2012. Segregate or integrate for multifunctionality and sustained change through landscape agroforestry involving rubber in Indonesia and China. pp 69-104, in: Nair PKR, Garrity DP (Eds.) Agroforestry: The Future of Global Landuse. Springer, Dordrecht (the Netherlands).

van Noordwijk, M., Khasanah, N., Dewi S. 2013. Biofuel emission reduction estimator scheme (BERES): Land-use history, production systems and technical emission factors. In M. van Noordwijk, B. Lusiana, B. Leimona, S. Dewi, D. Wulandari (Eds.), Negotiation-support toolkit for learning landscapes (pp. 157–162). Bogor: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program.

van Noordwijk, M., Agus, F., Dewi, S., Purnomo, H. 2014a. Reducing emissions from land use in Indonesia: motivation, policy instruments and expected funding streams. Mitig. Adapt. Strateg. Glob. Change 19, 677–692.

van Noordwijk, M., Matthews, R.B., Agus, F., Farmer, J., Verchot, L., Hergoualc'h, K., Persch, S., Tata, H.L., Lusiana, B., Widayati, A., Dewi, S. 2014b. Mud, muddle and models in the knowledge value-chain to action on tropical peatland issues. Mitig. Adapt. Strateg. Glob. Change 19, 863–885.

van Noordwijk, M., Brussaard, L. 2014c. Minimizing the ecological footprint of food: closing yield and efficiency gaps simultaneously? Current Opinions on Environmental Sustainability, 8, 62–70.

van Noordwijk, M., Bizard, V., Wangkapattanawong, P., Tata, H.L., Villamor, G.B., Leimona, B. 2014d. Tree cover transitions and food security in Southeast Asia. Global Food Security 3, 200-208.

van Noordwijk, M., Goverse, T., Ballabio, C., Banwart, S., Bhattacharyya, T., Goldhaber, M., Nikolaidis, N., Noellemeyer, E., Zhao, Y. 2015a. Soil carbon transition curves: reversal of land degradation through management of soil organic matter for multiple benefits. In: Banwart, S.A., Noellemeyer, E., Milne, E. (Eds.), Soil Carbon: Science, Management and Policy for Multiple Benefits. CAB International, Harpenden (UK), pp. 26–46.

van Noordwijk, M., Minang, P.A., Freeman, O.E., Mbow, A., de Leeuw, J. 2015b. The future of landscape approaches: interacting theories of place and change. In: Climate- Smart Landscapes: Multifunctionality in Practice (eds Minang PA, van Noordwijk M, Freeman OE, Mbow C, de Leeuw J, Catacutan D), pp. 375–386. World Agroforestry Centre (ICRAF), Nairobi, Kenya.

van Noordwijk, M., Pacheco, P., Slingerland, M., Dewi, S., Khasanah, N. 2017. Palm oil expansion in tropical forest margins or sustainability of production? Focal issues of regulations and private standards. Working paper 274. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program. DOI: http://dx.doi.org/10.5716/WP17366.PDF

van Noordwijk, M., Duguma, L.A., Dewi, S., Leimona, B., Catacutan, D., Lusiana, B., Öborn, I., Hairiah, K., Minang, P.A. 2018. SDG synergy between agriculture and forestry in the food, energy, water and income nexus: reinventing agroforestry? Current Opinion on Environmental Sustainability 34, 33-42.

Veloo, R., van Ranst, E., Paramananthan, S. 2015. Peat characteristics and its impact on oil palm yield NJAS-Wageningen Journal of Life Sciences 72: pp. 33-40.

Verhoeven, J.T.A., Setter, T.L. 2010. Agricultural use of wetlands: opportunities and limitations. Ann. Bot. 105 (1), 155–163.

Vermeulen, S., Goad, N. 2006. Towards better practice in smallholder palm oil production. Natural Resources Issues Series No. 5. International Institute for Environment and Development. London. UK.

Villamor, G.B., Pontius, R.G., van Noordwijk, M. 2014. Agroforest's growing role in reducing carbon losses from Jambi (Sumatra), Indonesia. Regional Environmental Change, 14(2), pp.825-834.

Von Geibler, J. 2013. Market-based governance for sustainability in value chains: conditions for successful standard setting in the palm oil sector. Journal of Cleaner Production, 56, 39–53.

Wahyunto, Ritung, S., Subagjo, H. 2003. Peta luas sebaran lahan gambut dan kandungan karbon di pulau Sumatera / Maps of Area of Peatland Distribution and Carbon Content in Sumatera, 1990 – 2002. Wetlands International-Indonesia Program and Wildlife Habitat Canada (WHC).

Wakhid, N., Hirano, T., Okimoto, Y., Nurzakiah, S., Nursyamsi, D. 2017. Soil carbon dioxide emissions from a rubber plantation on tropical peat. Sci Total Environ 1; 581-582:857-865. doi: 10 1016/j scitotenv 2017 01 035.

Warren, M.W., Kauffman, J.B., Murdiyarso, D., Anshari, G., Hergoualc'h, K., Kurnianto, S., Purbopuspito, J., Gusmayanti, E., Afifudin, M., Rahajoe, J., Alhamd, L., Limin, S., Iswandi, A. 2012. A cost-efficient method to assess carbon stocks in tropical peat soil. Biogeosciences 9: pp. 4477–4485.

Warren, M.W, Frolking, S., Zhaohua, D., Kurnianto, S. 2017. Impacts of land use, restoration, and climate change on tropical peat carbon stocks in the twenty-first century: implications for climate mitigation. Mitigation and Adaptation Strategies for Global Change 22(7): pp. 1041-1061.

Wicke, B., Dornburg, V., Junginger, M., Faaij, A. 2008. Different palm oil production systems for energy purposes and their greenhouse gas implications. Biomass and Bioenergy, 32, 1322–1337.

Widayati, A., Johana, F., Zulkarnain, M.T., Mulyoutami, E. 2012. Perubahan Penggunaan Lahan, Faktor Pemicu dan Pengaruhnya terhadap Emisi CO_2 di Kabupaten Tanjung Jabung Barat (Tanjabar), Propinsi Jambi. Brief No 21. Bogor, Indonesia. World Agroforestry Centre - ICRAF, SEA Regional Office. 4p.

Wijedasa, L.S., Jauhiainen, J., Könönen, M., Lampela, M., Vasander, H., Leblanc, M.C., Evers, S., Smith, T.E., Yule, C.M., Varkkey, H., Lupascu, M. 2017. Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences. Global change biology 23(3): pp. 977-982.

Woittiez, L.S., van Wijk, M.T., Slingerland, M., van Noordwijk. M., Giller, K.E. 2017. Yield gaps in oil palm: a quantitative review of contributing factors. European Journal of Agronomy, 83, pp.57-77.

World growth. 2011. The Economic Benefit of Palm Oil to Indonesia. Available at: http://worldgrowth.org/site/wp-content/uploads/2012/06/WG_Indonesian_Palm_Oil_Benefits_Report-2_11.pdf

Wösten, J.H.M., Finke, P.A., Jansen, M.J.W. 1995. Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. Geoderma, 66: 227-237.

Wösten, J.H.M., Ismail, A.B., van Wijk, A.L.M. 1997. Peat subsidence and its practical implications: a case study in Malaysia. Geoderma 78: pp. 25–36.

Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas, C. 1998. Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning. Report 156. SC-DLO, Wageningen (The Netherlands) 106 pp.

Wösten, J.H.M., Clymans, E., Page, S.E., Rieley, J.O., Limin, S.H. 2008. Peat–water interrelationships in a tropical peatland ecosystem in Southeast Asia. Catena 73(2): pp. 212-224.

Yee, K.F., Tan, K.T., Zuhairi, A., Keat, A., Lee,T. 2009. Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability. Applied Energy Vol. 86, Supplement 1, pp S189-S196.

Yu, Y., Stomph, T.J., Makowski, D., van Der Werf, W. 2015. Temporal niche differentiation increases the land equivalent ratio of annual intercrops: a meta-analysis. *Field Crops Research*, *184*, pp.133-144.

Zoebl, D. 1996. Controversies around resource use efficiency in agriculture: shadow or substance? Theories of C. T. de Wit (1924–1993). Agricultural Systems, 50, 415–424.

Appendices

Additional information for chapter 5

Appendix 5A. Derivation of equation for pSWEET

Appendix 5B. The Biofuel Emission Reduction Estimator Scheme (BERES)

Appendix 5A. Derivation of equation for p_{SWEET}

Let the relationship between yield (Y) and fertilizer use (N) be approximated by a quadratic equation:

$$Y = Y_0 + f\,N + c\,N^2 \qquad [1]$$

where Y_0 is the yield level in the absence of fertilizer use, f is the initial marginal yield increment per unit fertilizer use, and c is the parameter of the quadratic term. The c parameter is related to the maximum attainable yield Y_{max} under local circumstances beyond fertilizer use:

$$c = - f^2/(4(Y_{max} - Y_0)) \qquad [2]$$

The derivation of this is as follows:

$$dY/dN = f + 2\,c\,N_{max} = 0$$

Y_{max} will be obtained for a fertilizer level N_{max}

$$N_{max} = -f/2c \qquad [3]$$

$$Y_{max} = Y_0 - f^{\,2}/(2c) + c\,f^{\,2}/(4\,c^2) = Y_0 - f^{\,2}/(4c) \qquad [4]$$

which implies

$$c = - f^2/(4\,(Y_{max} - Y_0)) \qquad [5]$$

An economic optimum fertilizer level N_{ecopt} can be derived by equating the marginal efficiency (derivative of Y with respect to N fertilizer) to a parameter p

$$N_{ecopt} = (p-f)/2c \qquad [6]$$

where p is the price equivalence ratio at the farm gate for fertilizer and yield.

A more detailed derivation is as follows:

Financial return can be expressed as:

$$R = Y \times p_y - N \times p_i - O \times p_o \qquad [7]$$

where R is profit, Y is yield and p_y is price per unit yield, N is fertilizer and p_i is price per unit fertilizer, O is other output component and p_o is price per unit other output.

The maximum return with regards to fertilizer only, R_{popt}, is reached when N_{ecopt} and Y_{maxben} are reached:

$dR/dN = f \times p_y + 2\ c\ N_{popt} \times p_y - p_i = 0$ [8]

If $p = p_i/p_y$ is the ratio between farm gate price per unit fertilizer and price per unit yield then

$N_{popt} = (p-f)/2c$ [9]

Greenhouse gas emissions due to the production process (E), generally expressed in CO_2 equivalents (CO_2eq) per ha per year, using IPCC equivalence standards for nitrous oxide and methane with respect to CO_2, can be grouped in three production phases:

$E = E_0 + e_0 + e_f\ N + \varepsilon\ Y$ [10]

where E_0 is attributable CO_2eq emissions per ha per year due to initial land conversion, e_0 is attributable CO_2eq emissions per ha per year in the production stage at zero fertilizer use, e_f is attributable CO_2eq emissions per ha per year per unit fertilizer use in the production stage, ε is post-production stage CO_2eq emissions per unit yield, due to transport and processing.

Fertilizer related emissions are calculated as:

N-fertilizer use [kg/ha] × (N_in_N_2O/N_in_fertilizer × N_2O/N_in_N_2O × CO_2eq / N_2O + CO_2em/kg N-fertilizer) × 0.001 [Mg/kg]

The yield may need to be expressed in terms of the 'active component' that is most relevant for subsequent for the next steps, e.g. sugar or oil yield instead of cane biomass or fresh fruit bunches in the case of sugar cane or oil palm.

The emissions per unit yield can now be obtained by combining equations [1] and [10] as

$E/Y = \varepsilon + (E_0 + e_0 + e\ N)/(\ Y_0 + f\ N + c\ N^2)$ [11]

By equating the derivative of E/Y with respect to N to zero we can calculate the N_{emin} fertilizer rate that minimizes emissions as:

$N_{emin}^2 – N_{emin}\ (2\ (E_0 + e_0)/e_f) – Y_0/c + f(E_0 + e_0)/(c\ e_f)$ [12]

With only a single positive root:

$N_{emin} = (E_0 + e_0)/e_f\ (\{1 + (Y_0/c)\ (e_f/(E_0 + e_0))^2 – f\ e_f/(c\ (E_0 + e_0))\}^{0.5} - 1)$ [13]

Two dimensionless groups emerge, in which c can be substituted from [2]

$f\ e/(c\ (E_0 + e_0)) = - 4\ e\ (Y_{max} - Y_0)/(f\ (E_0 + e_0)) = -4\ B$ [14]

with

$B = e\ (Y_{max} - Y_0)/(f\ (E_0 + e_0))$ [15]

and

$c\ Y_0/f^2 = -Y_0/(4(Y_{max} - Y_0)) = -y/4$ [16]

with

$y = Y_0/(Y_{max} - Y_0)$ [17]

$F_{minem} = (E_0 + e_0)/e\ (1 \pm \{ 1 + 4\ B - 4\ y\ B^2\}^{0.5})$ [18]

By equating F_{emin} to F_{popt} in equation [4] we can obtain the price ratio p_{SWEET} at which the economically optimum fertilizer rate equals the one that minimizes attributable emissions:

$p_{SWEET} = f\ (1 - (1/B)(1 \pm \{1 + 4\ B - 4\ y\ B^2\}^{0.5})$ [19]

Appendix 5B. The Biofuel Emission Reduction Estimator Scheme (BERES)

A comprehensive accounting system on carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions of biofuel production including biofuel production of palm oil has to include the whole life cycle. We developed a tool called Biofuel Emission Reduction Estimator Scheme (BERES) (van Noordwijk et al., 2013) to calculate net emissions of biofuel production and emission reduction factors (emission saving) compared to the use of fossil fuel using a life cycle approach. Upland soils can be expected to be a small CH_4 sink under conditions in forests and well-managed plantations. We assumed here that there is no change in this characteristic (Tate, 2014).

The scheme is an integrated assessment scheme for CO_2 and GHG emissions related to biofuel production. It includes three different phases of crop production processes within lifecycle analysis and is consistent with the life cycle analysis (LCA) of net emissions for biofuel production systems used by the RED of the EU. The three phases of the production process:

I. the initial conversion of preceding vegetation into an oil palm plantation, usually based on 'land clearing', leading to a 'Carbon (C) debt',
II. the emissions due to production of external inputs, such as fertilizer,
III. the balance of emission and absorption during the growth cycle of the oil palms, depending on growth rate, green manure and organic waste management and fertilizer practices, leading to a time-averaged C-stock that influences 'C debt' and repay time,
IV. transport to the refinery followed by CPO (Crude Palm Oil) and kernel production, transesterification into biofuel and further transport to the end users.

The number of years for payback time from C debt, the emissions saving from fossil fuel substitution and fossil fuel substitution efficiency can then be calculated from the balance between total sequestration and emissions (Table S2.1).

Stage	Parameter	Default	Description	Based on
Inputs				
I	P_{manag}	1	Estate management	Nucleus = 1, Plasma = 2, Independent = 3
	$S_{Peat?}$	0	Peatland?	Pre-condition (peat = 1, mineral = 0)
	FracPeat	0		Proportion of peat
	T_{cycle}	25	Accounting period for plantation [yr]	Policy decision, ideally linked to typical production cycle
	C_{before}	50	Attributable time-averaged aboveground C stock before the plantation crop was planted [Mg C ha^{-1}]; if conversion took place before 2008 the EU RED default equals $C_{oilpalm}$	Pre-condition (can normally range from 250 to 0 Mg C ha^{-1})
	FracRoot	0.25	Belowground biomass as fraction of aboveground biomasss	IPCC
II	$F_{FertProd}$	3.5	Emission due to fertilizer production, kg CO_2eq kg^{-1} N	Brentrup and Pallière, 2008
III	$C_{oilpalm}$	40	Time-averaged C stock of the plantation crop, Mg C ha^{-1}	Khasanah et al. (2015a)
	F_{N2O}	0.01	N-fraction of fertilizer-N lost as N_2O	Literature value to be updated by actual emission studies; 0.01 is current default, 0.04 is based on Crutzen et al. (2008)
	$E_{PeatPerDrainDepth}$	0.67	Peatland CO_2 loss per cm drain depth, Mg CO_2 ha^{-1} $year^{-1}$	(Maswar, 2011)
	E_{Soil}	0	Mineral soil CO_2 loss (depending on EFB and POME recycling to maintain C_{org} level	Khasanah et al. (2015b)

	$S_{PeatDrainDepth}$	60	Peatland drainage depth, cm	Management choice
	N_{fert}	141	N fertilizer use, kg N ha^{-1}, averaged over lifecycle	Management choice
	Y_{FFB}	18.8	FFB yield, Mg ha^{-1} $year^{-1}$, averaged over life cycle	Depending on management style
IV	*Y_{OER}*	*22.7*	*CPO extraction rate (OER), % CPO per FFB*	*Depending on management style*
	Y_{pKER}	4.87	Kernel extraction rate (pKER), % of FFB	Depending on management style
	Y_{PKO}	0.5	PKO kernel oil per kernel extracted	Technical coefficient (Corley and Thinker, 2016)
	C_{CPO}	0.759	C concentration of CPO	Technical coefficient (Kamahara et al., 2008)
	C_{KER}	0.735	C concentration of kernel oil	Technical coefficient (Kamahara et al., 2008)
	$F_{CH4Mill}$	0.4	Mill emissions of CH_4 expressed as CO_2eq Mg^{-1} C extracted	Mill dependent (Wicke et al., 2008)
	$F_{TransportEmissions}$	0.2	CO_2eq emissions processing and transport, Mg CO_2eq Mg^{-1} C extracted	Depends on distance to port
	$F_{BiodieselConversion}$	0.94	Biodiesel production, Mg Mg^{-1} CPO	Technical coefficient (Alkabbashi et al., 2009)
Constants	CO_2/C	3.67	CO_2/C	
	N_2O/N	1.57	N_2O/N	
	$GWPN_2O$	296	GWP of N_2O relative to CO_2	IPCC
	$H_{PalmBiodiesel}$	40	Heating value of palm biodiesel, MJ kg^{-1} biodiesel	Demirbas, 2007

	$Em_{FossilFuel}$	83.8	Total net emissions from the fossil fuel comparator, g CO_{2eq} MJ^{-1}	EU Directive, 2008
Intermediate steps	Y_{OilC}	3.58	Annual oil harvest, Mg C ha^{-1} $year^{-1}$	
	$E_{TotPerHa}$	1.15	Annual CO_{2eq} emissions due to production, Mg CO_2eq ha^{-1} $year^{-1}$	
	$T_{Payback}$	4.67	Payback time, years	
	Em_{Cdebt}	1.47	Emission due to C-debt, Mg CO_2eq ha^{-1} $year^{-1}$	
	$Em_{SoilFert}$	1.15	Emission from soil and fertilizer application, Mg CO_2eq ha^{-1} $year^{-1}$	
	Em_{Mill}	1.43	Emission of CH_4 from mill, Mg CO_2eq ha^{-1} $year^{-1}$	
	EmTrans	0.72	Emission from processing and transport, Mg CO_2eq ha^{-1} $year^{-1}$	
Outputs	C_{NetEm_I}	4.76	Net C emission during 1st production cycle: Mg CO_2eq ha^{-1} $year^{-1}$	
	C_{NetEm_II}	3.29	Net C emission during 2nd (or subsequent) production cycle: Mg CO_2eq ha^{-1} $year^{-1}$	
	C_{NetEm_I}	1.08	Net C emission during 1st production cycle, Mg CO_2eq Mg^{-1} biofuel	
	C_{NetEm_II}	0.74	Net C emission during 2nd (or subsequent) production cycle, Mg CO_2eq Mg^{-1} biofuel	
	C_{NetEm_I}	1.01	Net C emission during 1st production cycle, Mg CO_2eq Mg^{-1} CPO	
	C_{NetEm_II}	0.7	Net C emission during 2nd (or subsequent) production cycle, Mg CO_2eq Mg^{-1} CPO	
	C_{NetEm_I}	26.88	Net C emission during 1st production cycle, g CO_2eq MJ^{-1}	
	C_{NetEm_II}	18.6	Net C emission during 2nd (or subsequent) production cycle, g CO_2eq MJ^{-1}	
	$SE_{\_I}$	0.68	Emission saving during 1st production cycle	
	$SE_{\_II}$	0.78	Emission saving during 2nd production cycle	

Summary (English)

Oil palm (*Elaeis guineensis*) is a uniquely valuable palm originating in Africa, producing oil that can be used for a wide range of food and non-food end products, and as biofuel feedstock. The success and method of its expansion (monoculture plantation) especially in Indonesia and Malaysia as two largest palm oil producers, however, have made it one of the most controversial crops of the world, with strongly negative and positive opinions competing for attention. Global concerns aligned with local, social and ecological issues has led to consumer boycotts. One of the policy consequences is the Renewable Energy Directive (RED) of European countries that includes a commitment to substitute part of its transport fuel with biofuels to reduce the CO_2 emissions, but sets binding targets for the emission savings to be achieved. In response to such regulations, exporting countries such as Indonesia need to have reliable data on the carbon footprint of their product across production systems and the products' lifecycle. On the other side, diversification of oil palm plantations starts to gain attention as a strategy to increase farmer resilience and reduce carbon footprint.

The overall research objectives of this thesis were (1) to estimate the carbon footprint of palm oil production in Indonesia when it is used as biofuel and express it as CO_2 equivalent and emission saving compared to the use of fossil fuel, and (2) to explore mixed oil palm systems as diversification strategy to increase farmer benefit and to reduce carbon footprint. To answer these objectives, five research questions (RQs) were formulated that associate with five research chapters of this thesis:

1. What is the range of aboveground time-averaged C stocks (Mg C ha^{-1}) of various types of oil palm plantations in Indonesia? Are there relevant differences between the three main plantation management conditions found in Indonesia: nucleus, plasma, and independent smallholders, and between soil types (mineral versus peat)?
2. What is the belowground time-averaged C stock (Mg C ha^{-1}) on mineral soil of oil palm plantations in Indonesia and how does temporal variations of soil organic content (C_{org}, %) and soil bulk density (BD, g cm^{-3}) influence the results for the top 30 cm used in C accounting?
3. How does variation in subsidence (cm yr^{-1}) and CO_2 emission (Mg CO_2 ha^{-1} yr^{-1}) rates of smallholder oil palm plantations on peat compare to that for other land-use types, in relation to conversion history (recent or earlier drainage), and fertilizer application?

4. How does intensification level (fertilizer use) influence the carbon footprint of palm oil production in Indonesia and its attributed emission savings when used as substitute for fossil fuel? Do environmentally and economically optimized intensification levels match the current carbon footprint per unit biofuel?
5. Can the development of mixed oil palm systems be a strategy to not only reduce farmer risk and address some of the associated social concerns, but also reduce the footprint of palm oil?

The five research questions are accompanied by five hypotheses:

1. Aboveground time-averaged C stock of oil palm plantation varies in relation to soil types and plantation management regimes
2. The belowground time-averaged C stock of plantations on mineral soil differs between those derived from forest and non-forest as preceding vegetation
3. There is variation in peat subsidence and CO_2 emission rate of different land uses due to differences in conversion history and fertilizer application
4. Palm oil used for biofuel and produced in plantations derived from low C stock land covers on mineral soils can achieve current targets for emissions saving when compared to the use of fossil fuel, when fertilizer levels are adjusted
5. Selected mixed oil palm systems achieve land saving through a land equivalent ratio above 1, improve farmer benefits and reduce the carbon footprint compared to monoculture oil palm

In chapter 2, time-averaged aboveground C stock of oil palm plantation was generated based on survey and data collection in more than 20 selected plantations representing the wide range of oil palm production in Indonesia differing in plantation management (nucleus, plasma, and independent smallholders) and soil types (mineral and peat). The time average aboveground C stock of oil palm plantation ranges from 37.8 ± 0.33 Mg C ha^{-1} to 42.1 ± 0.03 Mg C ha^{-1}. Soil type and plantation management regimes account for the variation in estimated value. These results imply that establishing oil palm plantations in areas with preceding carbon stock higher than 40 Mg C ha^{-1} (as ballpark figure) will lead to carbon debt and net release of carbon to the atmosphere.

Chapter 3 estimated the changes of belowground mineral C stock for the top 30 cm over a production cycle based on data of more than 20 plantations surveyed and collected in chapter 2. Across the four management zones (weeded circle, interrow zone, frond stack and harvest path), for plantations with “good practice” management, belowground C stock did, on average, not change significantly over the plantation cycle. This applied for both oil palm plantations derived from forest or non-forest. These results imply that current retention of organic plant residues and pruned fronds in the field compensates for the initial soil C loss and maintains mineral soil C stock when assessed over a production cycle.

Thus, there was no detectable net carbon emission from the soil at a scale relevant for national C accounting. Increments that are supposed to accrue for oil palm established in non-forest backgrounds were not evident. With current soil management practices, it is appropriate for life-cycle assessments to assume that soil C stock on mineral soils neither increase nor decrease due to oil palm cultivation.

Chapter 4 estimated CO_2 emissions of smallholder drained peatland of four different land-uses in relation to the length of time after drainage and fertilizer application based on peat subsidence and peat characteristics and taking into account microtopography. The four-smallholder managed land-uses were rubber (*Hevea brasiliensis*) agroforest, mixed coconut *(Cocos nucifera*) and coffee (*Coffea liberica*), mixed betel nut (*Areca catechu*) and coffee, oil palm (*Elaeis guinensis*) monoculture. Fertilizer application did not have a consistent effect on inferred emissions. A recently established oil-palm had the highest rate of peat subsidence and emission (4.7 cm yr^{-1} or 121 Mg CO_2 ha^{-1} yr^{-1}) while the remnant forest had the lowest (1.8 cm yr^{-1} or 40 Mg CO_2 ha^{-1} yr^{-1}). Other land-use types subsided by 2–3 cm yr^{-1}, emitting 70–85 Mg CO_2 ha^{-1} yr^{-1}. These results imply that peatland for agricultural use under smallholder management have CO_2 emissions close to, but above current IPCC defaults.

Chapter 5 analyzed carbon footprint of palm oil production in Indonesia if the palm oil is used for biofuel feedstock. The level of fertilizer application was included in its calculation of production and footprints, to derive the level of intensification that can minimize the footprint per unit biofuel using (Biofuel Emission Reduction Estimator Scheme) BERES scheme. The analysis was based on comprehensive data of more than 20 plantations surveyed and collected during survey of above and belowground studies. The EU threshold requiring at least 35% emission saving for biofuel use can never be achieved by palm oil if it is produced: (i) on peat soils, or (ii) on mineral soils where the C-debt due to conversion is larger than 20 Mg C h^{a-1}, when the footprint is calculated using an emission ratio of N_2O-N/N-fertilizer of 4%. At current fertilizer price levels in Indonesia the economically optimized N fertilizer rate is 344-394 kg N ha^{-1}, while the reported mean N fertilizer rate is 141 kg N ha^{-1} yr^{-1} and rates of 74-277 kg N ha^{-1} would minimize footprints, for a N_2O-N/N-fertilizer ratio of 4-1%, respectively. At a C-debt of 30 Mg C ha^{-1} these values are 200-310 kg N ha^{-1}. Sustainable weighting of ecology and economics would require a higher fertilizer/yield price ratio, depending on C-debt. Increasing production by higher fertilizer use from current 67 to 80% of attainable yields would not decrease footprints in current production conditions.

Chapter 6 explored mixed oil palm – cacao and oil palm - pepper intercropping by modifying its planting pattern using the process-based Water, Nutrient and Light Capture in Agroforestry System (WaNuLCAS) model for Indonesian contexts. The palm oil carbon

footprints were estimated using Biofuel Emission Reduction Estimator Scheme (BERES). Economic and environmental performance indicators for the intercropping systems were also analyzed. Selected mixed oil palm systems can provide considerable economic and environmental system improvements. Mixed oil palm – cacao has more water percolating to groundwater reserves, and higher benefit cost ratio (BCR) than oil palm monocultures. The Land Equivalent Ratio can be 1.4, showing considerable 'land sparing' potential relative to monocultures for each commodity separately. Oil palm – pepper systems may have the highest Net Present Value (returns to land), but will have lower returns to labour. Without sharing the load of carbon debt with intercropped trees and with the current target of emission saving (60%), oil palm-cacao intercrop can meet the target for a maximum carbon debt of 10 Mg C ha^{-1}; the saving can be higher if carbon debt load is shared with intercropped trees.

In conclusions, the larger the areas that were converted from high-C stock forest, the larger the fraction of peat, the larger the emissions from fertilizers, transportation and processing (incl. methane) and the lower the yield of Fresh Fruit Bunches (FFB), the harder it is to achieve emission savings. The mentioned factors occur in a mix of production situations that is accounted for jointly in the case for 'company' level assessments. A large part of Indonesia's palm oil cannot meet the RED requirement for 2018 and onwards, depending on the historical cut-off date for inclusion of carbon debt. Based on the sampled companies with good agriculture practices, 40% and 25% of Indonesian palm oil production can meet the 35% (2015) and 60% (2018) emissions savings standards. This is more than what is currently exported to the EU for that purpose, suggesting a segmentation of the market, rather than reduction of the environmental problems, as primary effect of regulation that has not been globally agreed. From the perspective of land sharing versus land sparing debate, mixed oil palm can be a superior way to achieve land sparing as a goal of efficient use of land. With the current target of emission saving (60%), oil palm-cacao intercrop can meet the target for a maximum carbon debt of 10 Mg C ha^{-1}. Diversification should be a valid counterpart of current intensification research and policies to help make palm oil more sustainable from both social and environmental perspectives.

Samenvatting (Dutch)

De oliepalm (*Elaeis guineensis* Jacq.) is een unieke en waardevolle palm uit Afrika. De oliepalm produceert olie die kan worden gebruikt voor een breed scala van voedsel en andere producten, en als grondstof voor biodiesel. Oliepalm wordt geteeld in plantages als monocultuur, en het grootste deel van de productie vindt plaats in Maleisië en Indonesië. Door de snelle uitbreiding van de plantages is oliepalm een van de meest controversiële gewassen ter wereld geworden, en het debat heeft sterke negatieve en positieve meningen opgeroepen die veel aandacht vragen in de publieke discussie. Wereldwijde zorgen om de lokale, sociale en milieu-gerelateerde gevolgen van palmolieproductie hebben geleid tot boycots. Een van de beleidsconsequenties van deze zorgen rondom palmolie is de Europese Renewable Energy Directive waarin is vastgelegd dat de deelnemende landen een deel van de brandstof voor transport vervangen door biodiesel, om zo de CO_2-uitstoot van transport te verminderen. Hierin worden verplichte doelstellingen gehanteerd voor de vermindering van de uitstoot. Om aan dit soort regelgeving te voldoen hebben palmolie-exporterende landen zoals Indonesië behoefte aan betrouwbare data op het gebied van de koolstofvoetafdruk van oliepalmproductie, voor verschillende productiesystemen en voor de volledige levenscyclus van het product. Aan de andere kant begint er ook steeds meer aandacht te komen voor diversificatie in oliepalmplantages als strategie voor het verbeteren van de veerkracht van oliepalmboeren en het verlagen van de koolstofvoetafdruk.

De algemene doelen van het onderzoek waren: (1) bepalen hoe groot de koolstofvoetafdruk van palmolieproductie op plantages is wanneer deze olie gebruikt wordt als grondstof voor biodiesel en hoeveel CO_2-equivalent-emissie bespaard kan worden door het gebruik van biodiesel in plaats van fossiele brandstoffen, en (2) het verkennen van de mogelijkheden voor het toepassen van mengteelten (van oliepalm en andere gewassen) als diversificatiestrategie voor kleine producenten om risico's te beperken en de koolstofvoetafdruk te verkleinen. Op basis van deze algemene doelen zijn vijf onderzoeksvragen geformuleerd die de basis vormen voor de vijf onderzoeks-hoofdstukken in dit proefschrift:

1. Hoeveel koolstof (in Mg C ha^{-1}), gewogen over de levenscyclus van een oliepalmplantage, wordt bovengronds opgeslagen in diverse typen plantages in Indonesië? Zijn er in dit opzicht relevante verschillen tussen de drie voornaamste productiesystemen, te weten de nucleus-plantages (eigen plantages van grote bedrijven), de plasma-plantages (plantages van kleine boeren die gelieerd zijn

aan grote bedrijven), en de onafhankelijke plantages (plantages van onafhankelijke kleine producenten)? En zijn er verschillen tussen minerale gronden en veengronden?
2. Hoeveel koolstof (in Mg C ha^{-1}), gewogen over de levenscyclus van een oliepalmplantage, wordt ondergronds opgeslagen in diverse typen plantages op minerale grond in Indonesië? En op welke manier beïnvloeden fluctuaties in de koolstofconcentratie (C_{org}, %) en de bodemdichtheid (BD, g cm^{-3}) over de tijd de koolstofvoorraad in de bovenste 30 cm van de grond, zoals die gebruikt wordt voor koolstofregistratie?
3. Hoe groot zijn de variaties in bodemdaling (cm yr^{-1}) en CO_2-uitstoot (Mg CO_2 ha^{-1} yr^{-1}) in oliepalmplantages van kleine boeren op veengronden in vergelijking met variaties bij ander landgebruik, en wat is de invloed van recente of langdurige afwatering en bemesting?
4. Hoe beïnvloedt de mate van intensivering (toenemend gebruik van kunstmest) de koolstofvoetafdruk van palmolieproductie in Indonesië, en wat betekent dit voor de emissiebesparing bij gebruik als biodiesel? Hoe verhouden de milieukundig en economisch optimale intensiveringsniveaus zich tot de huidige koolstofvoetafdruk per eenheid biodiesel?
5. Kunnen mengteelten van oliepalm en andere gewassen tegelijk de risico's voor kleine producenten en de sociale problemen veroorzaakt door oliepalmproductie verminderen en de koolstofvoetafdruk verkleinen?

Deze vijf onderzoeksvragen zijn gekoppeld aan vijf toetsbare hypothesen:

1. De hoeveelheid bovengrondse koolstofopslag in oliepalmplantages hangt af van de bodemgesteldheid en van de toegepaste landbouwpraktijken,
2. Ondergrondse koolstofopslag in oliepalmplantages op minerale gronden verschilt tussen plantages die direct na bos zijn geplant en plantages die zijn geplant na andere teelten.
3. Er bestaan verschillen in bodemdaling en CO_2-emissies op veengronden bij verschillende vormen van landgebruik, en die worden veroorzaakt door verschillen in de aanvang van afwatering en in het gebruik van meststoffen.
4. Biodiesel uit palmolie die is geproduceerd op koolstofarme minerale gronden kan voldoen aan de gestelde eisen voor emissiebesparing voor het gebruik als grondstof voor biodiesel, mits het gebruik van kunstmest wordt aangepast.
5. Geselecteerd mengteelten van oliepalm en andere gewassen kunnen land sparen omdat ze 'land-equivalentie ratio' van meer dan 1 hebben. Mengteelten leveren ook een hogere winst aan boeren en een kleinere koolstofvoetafdruk dan monoculturen.

In hoofdstuk 2 is de gemiddelde bovengrondse koolstofopslag in oliepalmplantages tijdens een volledige palmcyclus berekend. Hiervoor zijn metingen gedaan in meer dan 20 plantages verspreid over de drie productiesystemen (nucleus-plantages, plasma-plantages en onafhankelijke plantages) op minerale gronden en veengronden in Indonesië. De gemiddelde bovengrondse koolstofopslag over de levenscyclus was tussen de 37.8 ± 0.33 en 42.1 ± 0.03 Mg C ha^{-1}, afhankelijk van de bodemsoort en de toegepaste landbouwpraktijken. De koolstof werd vooral opgeslagen in de stammen en bladeren van de oliepalmen. De resultaten suggereren dat het planten van oliepalmen in gebieden waar de bovengrondse koolstofopslag méér is dan 40 Mg C ha^{-1} leidt tot een zogenaamde koolstofschuld en een netto emissie van CO_2.

In hoofdstuk 3 is een schatting gemaakt van de verandering in de ondergrondse koolstofopslag, gemeten in de bovenste 30 cm van de bodem. De data is verzameld in dezelfde plantages als voor hoofdstuk 2 en de berekeningen zijn gemaakt voor een volledige levenscyclus van de oliepalmen. De metingen werden gedaan in verschillende zones in de plantages: de onkruidvrije palmcirkels, de tussenrij-zones, de bladstapels, en de oogstpaden. In plantages waar 'goede landbouwpraktijken' werden toegepast waren er, gemiddeld over de verschillende zones, geen significante veranderingen in de ondergrondse koolstofopslag. Dit gold zowel voor plantages die direct na bos waren geplant als voor plantages die na ander landgebruik waren gepland. De resultaten suggereren dat de huidige landbouwpraktijken rondom het recyclen van organische reststromen en gesnoeide bladeren in de plantage compenseren voor het koolstofverlies direct na de omzetting naar oliepalm, en ervoor zorgen dat de koolstofvoorraad in de bodem gedurende de levenscyclus van de plantages behouden blijft. Er werden geen netto CO_2-emissies gedetecteerd die groot genoeg waren om van invloed te zijn op de koolstofboekhouding, maar er waren ook geen duidelijke toenames in koolstofopslag in plantages die waren geplant op land dat al langer geleden was ontbost. Als het bodembeheer in plantages min or meer hetzelfde blijft als nu dan is het correct om er bij levenscyclusanalyses vanuit de gaan dat de koolstofopslag in de bodem door oliepalmteelt toeneemt noch afneemt.

In hoofdstuk 4 zijn de CO_2-emissies uit veengronden bij vier verschillende vormen van landgebruik door kleine boeren geschat, gebaseerd op bodemdaling. De emissies werden gerelateerd aan de tijdsduur sinds afwatering en aan het gebruik van kunstmest, en er is rekening gehouden met de eigenschappen van het veen en met de micro-topografie. De vier vormen van landgebruik die werden vergeleken waren rubber (*Hevea brasiliensis*) agroforest, mengteelt van kokosnoot *(Cocos nucifera*) en koffie (*Coffea liberica*), mengteelt van betelpalm (*Areca catechu*) en koffie, en oliepalm (*Elaeis guineensis*) in monocultuur. Het gebruik van kunstmest had geen eenduidig effect op de CO_2-emissies. In de jonge oliepalmplantage waren de bodemdaling en de emissies het grootst (4.7 cm yr^{-1} bodemdaling ofwel 121 Mg CO_2 ha^{-1} yr^{-1} emissies), terwijl overgebleven bos de laagste bodemdaling en emissies toonde (respectievelijk 1.8 cm yr^{-1} ofwel 40 Mg CO_2 ha^{-1} yr^{-1}). De andere vormen van landgebruik leidden tot een bodemdaling van 2–3 cm yr^{-1} ofwel emissies van 70–85 Mg CO_2 ha^{-1} yr^{-1}. Deze resultaten suggereren dat landbouw door kleine boeren op veengronden leidt tot CO_2-emissies die net boven de huidige IPCC-standaarden liggen.

In hoofdstuk 5 is de koolstofvoetafdruk van oliepalmplantages in Indonesië berekend in het geval dat de geproduceerde palmolie voor biodiesel wordt gebruikt. Het gebruik van kunstmest werd meegenomen in de berekeningen van de palmolieproductie en de voetafdruk, zodat het BERES-systeem (Biofuel Emission Reduction Estimator Scheme) kon worden gebruikt om het intensiveringsniveau te berekenen dat resulteert in de laagste voetafdruk per eenheid biodiesel. Voor de berekeningen is de uitgebreide dataset gebruikt met daarin de data uit de 20 verschillende plantages waarmee de bovengrondse en ondergrondse koolstofopslag werden geschat in hoofdstuk 2 en 3. Biodiesel gemaakt van palmolie kan niet voldoen aan de standaard van de EU (een vermindering van CO_2-emissies van tenminste 35% ten opzichte van fossiele brandstoffen) wanneer de oliepalmen zijn geteeld op veengronden of wanneer de koolstofschuld door de omzetting van ander landgebruik naar oliepalm groter is dan 20 Mg C ha^{-1}. Dit geldt wanneer de berekening van de voetafdruk van de palmolie uitgaat van een emissiefactor van 4% N_2O-N per eenheid N-kunstmest. De economisch optimale stikstofgift in Indonesië is 344–394 kg N ha^{-1}, uitgaande van de huidige kunstmestprijzen, maar in praktijk is de gemiddelde stikstofgift maar 141 kg N ha^{-1}. De koolstofvoetafdruk van biodiesel uit palmolie is minimaal bij stikstofgiften van 74–277 kg N ha^{-1} (met een respectievelijke emissiefactor van 4–1% N_2O-N per eenheid N-kunstmest). In het geval van een koolstofschuld van 30 Mg C ha^{-1} is de koolstofvoetafdruk minimaal bij een stikstofgift van 200–310 kg N ha^{-1}. Verkleining van de kloof tussen ecologisch en economisch geoptimaliseerde intensiveringsniveaus vereist een toename in de verhouding tussen kunstmestprijs en opbrengstprijs, en hangt af van de koolstofschuld. Het verhogen van de opbrengst van 67% naar 80% van de ‘haalbare’ opbrengst door hoger kunstmestgebruik leidt onder de huidige productieomstandigheden in Indonesië niet tot een kleinere koolstofvoetafdruk.

In hoofdstuk 6 zijn opties voor mengteelten van oliepalm met cacao of zwarte peper onderzocht, waarbij de plantdichtheid en de uitlijning van de oliepalm aangepast waren. Hiervoor werd gebruik gemaakt van het simulatiemodel WaNuLCAS (Water, Nutrient and Light Capture in Agroforestry Systems), dat was aangepast aan Indonesische omstandigheden. De koolstofvoetafdruk van de verschillende mengteelten werd berekend met het BERES-rekenschema. Ook werden er verschillende economische en milieu-indicatoren meegenomen in de analyse. Bepaalde mengteelten presteerden duidelijk beter dan monoculturen op het gebied van economie en milieu. Mengteelten van oliepalm en cacao leiden tot het percoleren van meer water naar grondwaterreserves, en geven een betere kosten-batenverhouding dan oliepalmen in monocultuur. De ‘land-equivalentie ratio’ van mengteelten kan oplopen tot 1.4, waaruit blijkt dat deze teelten een behoorlijke landbesparing kunnen opleveren in vergelijking met monoculturen. Mengteelten van oliepalm en zwarte peper hebben de hoogste netto contante waarde (rendement op land) maar geven minder rendement op arbeid. Zelfs wanneer alle koolstofschuld aan de oliepalmen wordt toegerekend kan de voor 2018 vereiste 60% emissiereductie worden gehaald in een mengteelt van oliepalm en cacao bij een koolstofschuld van 10 Mg C ha^{-1}. Wanneer de koolstofschuld gedeeltelijk wordt toegerekend aan de andere gewassen in de mengteelt zijn de emissiereducties zelfs nog groter.

Er kan geconcludeerd worden dat hoe groter het gebied is dat ontleend is aan koolstof-rijk bos, hoe groter het aandeel veengrond, hoe groter de uitstoot door kunstmest, transport, en verwerking (methaan valt hieronder), en hoe lager de oogst, hoe moeilijker het is om emissiereducties te bereiken. Al deze verschillende factoren zijn in meer of mindere mate aanwezig in de mix van productiesituaties per bedrijf, en ze worden allemaal samengevoegd wanneer er op bedrijfsniveau analyses worden gedaan. Een groot deel van de Indonesische oliepalmplantages kan niet voldoen aan de REDD-normen voor 2018 en daarna, maar dit hangt ervan af tot hoe ver terug in de tijd de koolstofschuld wordt toegerekend. Uitgaande van de bemonsterde bedrijven die gebruik maken van goede landbouwpraktijken kunnen respectievelijk 40% en 25% de normen voor emissiereductie van 35% (2015) en 60% (2018) halen. Dit aandeel is groter dan het aandeel palmolie dat op dit moment naar Europa wordt getransporteerd voor biodiesel, wat suggereert dat het primaire effect van regels die niet op globaal niveau gelden vooral zit in de segmentatie van de markt, en niet in het verminderen van negatieve milieueffecten persé. Vanuit het perspectief van het debat rondom land besparen versus land delen (land sparing versus land sharing) kan mengteelt met oliepalm een uitstekende oplossing zijn om land te besparen en efficiënt te gebruiken. In het geval van een koolstofschuld van 10 Mg C ha^{-1} kan een mengteelt van oliepalm en cacao het doel van 60% emissiereductie halen. Diversificatie moet als een volwaardig alternatief worden meegenomen in de het huidige onderzoek en beleid rondom intensivering, zodat oliepalmproductie verduurzaamd kan worden op zowel het sociale als het milieu-gerelateerde vlak.

Ringkasan (Bahasa)

Minyak sawit dihasilkan dari buah kelapa sawit (*Elaeis guineensis*) yang merupakan tanaman asli Afrika. Minyak sawit digunakan untuk berbagai bahan baku industri, baik industri pangan maupun non-pangan termasuk bahan bakar minyak nabati dengan harga relatif lebih murah bila dibandingkan dengan harga bahan baku minyak nabati lainnya. Permintaan pasar minyak sawit yang tinggi memicu perluasan kebun kelapa sawit dengan sistem budidaya monokultur terutama di Indonesia dan Malaysia yang merupakan dua negara penghasil minyak sawit terbesar di dunia. Perluasan kebun kelapa sawit yang dilakukan dengan mengganti tutupan hutan atau kebun campur (*agroforestry*) menyebabkan kelapa sawit dianggap sebagai salah satu tanaman kontroversial di dunia. Perhatian dunia saat ini sedang tertuju pada dampak positif dan negatif akibat perluasan kebun kelapa sawit baik dari sisi sosial ekonomi (peningkatan kesejahteraan masyarakat desa) maupun sisi lingkungan (deforestasi, hilangnya keanekaragaman hayati, emisi gas rumah kaca). Bentuk perhatian dunia adalah munculnya berbagai kebijakan terkait perluasan kebun kelapa sawit hingga boikot konsumen tentang penggunaan minyak sawit. Salah satu peraturan/kebijakan yang muncul adalah peraturan mengenai energi terbarukan (*renewable energy directive*/RED) dari negara-negara Eropa, termasuk komitmen untuk mengganti sebagian bahan bakar fosil untuk transportasi dengan bahan bakar minyak nabati dengan menetapkan target pengurangan emisi (*emission saving*) tertentu untuk mencapai target pengurangan emisi CO_2 jika dibandingkan dengan penggunaan bahan bakar fosil. Menanggapi peraturan tersebut, negara-negara pengekspor minyak sawit seperti Indonesia perlu memiliki data tentang jejak karbon dalam sistem produksi minyak sawit untuk satu daur hidup kelapa sawit. Di sisi lain, diversifikasi tanaman dalam kebun kelapa sawit mulai mendapat perhatian sebagai strategi untuk meningkatkan ketahanan petani terhadap fluktuasi harga dan mengurangi jejak karbon.

Tujuan penelitian ini adalah (1) menghitung jejak karbon produksi minyak sawit di Indonesia ketika digunakan sebagai bahan bakar minyak nabati yang dinyatakan dalam CO_2-eq dan pengurangan emisi (*emission saving*) jika dibandingkan dengan penggunaan bahan bakar fosil, dan (2) mengeksplorasi sistem kelapa sawit campuran sebagai strategi diversifikasi untuk meningkatkan keuntungan petani dan mengurangi jejak karbon. Tujuan penelitian ini dicapai dengan lima pertanyaan penelitian (*research questions*/RQs) yang dijawab dalam Bab 2 – Bab 6 adalah:

1. Berapa rerata cadangan karbon di atas permukaan tanah (Mg C ha^{-1}) pada berbagai jenis perkebunan kelapa sawit di Indonesia? Apakah ada perbedaan diantara tiga jenis pengelolaan kebun yang ditemukan di Indonesia yaitu: inti, plasma, dan petani swadaya; dan diantara jenis tanah yaitu: mineral dan gambut?.
2. Berapa rerata cadangan karbon tanah mineral (Mg C ha^{-1}) perkebunan kelapa sawit di Indonesia? Bagaimana variasi kandungan organik tanah (C_{org}, %) dan kerapatan tanah (BD, g cm^{-3}) dari waktu ke waktu yang mempengaruhi cadangan karbon tanah mineral hingga kedalaman 30 cm?.
3. Berapa tingkat penurunan permukaan gambut (*subsidence*) (cm $tahun^{-1}$) dan emisi CO_2 (Mg CO_2 ha^{-1} $tahun^{-1}$) pada perkebunan kelapa sawit skala kecil di lahan gambut bila dibandingkan dengan jenis penggunaan lahan lainnya? Apakah ada variasi diantara umur kebun sejak pembukaan lahan dan pembuatan drainase, dan aplikasi pupuk?.
4. Apakah intensifikasi (penggunaan pupuk) mempengaruhi jejak karbon produksi minyak sawit di Indonesia dan pengurangan emisi (*emission saving*) jika minyak sawit digunakan sebagai pengganti bahan bakar fosil?.
5. Apakah sistem kelapa sawit campuran dapat menjadi strategi, tidak hanya sekedar untuk mengurangi risiko petani tetapi juga mengurangi jejak karbon dari minyak sawit?.

Lima hipotesis yang menyertai lima pertanyaan penelitian adalah:

1. Rerata cadangan karbon di atas permukaan tanah dari perkebunan kelapa sawit bervariasi antar jenis tanah dan jenis pengelolaan kebun.
2. Rerata cadangan karbon pada tanah mineral di perkebunan kelapa sawit berbeda antara kebun yang dibuka dari hutan dan non-hutan.
3. Penurunan pemukaan gambut dan laju emisi CO_2 dari berbagai penggunaan lahan bervariasi tergantung pada sejarah pembukaan lahan dan aplikasi pupuk.
4. Minyak kelapa sawit yang digunakan sebagai bahan bakar minyak nabati dan diproduksi dari perkebunan yang berasal dari tutupan lahan dengan cadangan karbon di atas permukaan tanah rendah, dapat mencapai target pengurangan emisi jika dibandingkan dengan penggunaan bahan bakar fosil, bila kelapa sawit dibudidayakan dengan tingkat penggunaan pupuk yang sesuai.
5. Sistem kelapa sawit campuran dapat menghemat penggunaan lahan dengan nilai rasio setara lahan (*land equivalent ratio*/LER) lebih dari 1, mampu meningkatkan keuntungan petani dan mengurangi jejak karbon bila dibandingkan dengan sistem kelapa sawit monokultur.

Bab 2 dari buku ini membahas mengenai rerata cadangan karbon di atas permukaan tanah pada perkebunan kelapa sawit yang dihitung berdasarkan data lebih dari 20 perkebunan terpilih. Perkebunan yang dipilih dalam pengambilan contoh mewakili variasi produksi kelapa sawit di Indonesia berdasarkan sistem pengelolaan perkebunan, yaitu perkebunan inti, plasma, dan petani swadaya; dari jenis tanah yaitu mineral dan gambut. Rerata cadangan karbon di atas permukaan tanah dari perkebunan kelapa sawit berkisar antara 37,8 ± 0,33 Mg C ha^{-1} hingga 42,1 ± 0,03 Mg C ha^{-1} tergantung pada jenis tanah dan pengelolaan kebun. Jika perkebunan kelapa sawit dibangun pada lahan dengan cadangan karbon lebih tinggi dari 40 Mg C ha^{-1} (sebagai angka rerata) akan menyebabkan hutang karbon (*carbon debt*) dan terjadi pelepasan CO_2 ke atmosfer.

Bab 3 membahas mengenai perubahan cadangan karbon pada tanah mineral hingga kedalaman 30 cm dalam satu daur hidup kelapa sawit. Penghitungan cadangan karbon dilakukan berdasarkan data yang dikumpulkan dari 20 perkebunan terpilih seperti pada Bab 2. Dalam satu daur hidup kelapa sawit yang dikelola dengan baik, rerata cadangan karbon tanah tidak menunjukkan perubahan secara nyata pada kebun kelapa sawit yang berasal baik dari hutan maupun non-hutan. Hal ini mengindikasikan bahwa masukan bahan organik dari pangkasan pelapah yang dikembalikan ke lahan mampu menggantikan kehilangan karbon tanah yang hilang pada periode awal pembukaan kebun dan mampu mempertahankan cadangan karbon tanah dalam satu daur hidup kelapa sawit. Hal tersebut menunjukkan tidak adanya emisi bersih dari karbon tanah pada skala yang relevan untuk menghitung karbon pada skala nasional. Belum ada bukti yang melatar-belakangi adanya peningkatan cadangan karbon pada kebun sawit yang dibuka dari lahan non-hutan. Praktek pengelolaan kebun yang dilakukan saat ini, kajian penilaian cadangan karbon tanah dalam siklus hidup kelapa sawit sesuai untuk mengasumsikan bahwa cadangan karbon tanah tidak bertambah atau berkurang karena adanya budidaya kelapa sawit.

Bab 4 membahas mengenai emisi CO_2 lahan gambut yang dikeringkan pada tutupan/penggunaan lahan dan aplikasi pupuk yang berbeda. Penghitungan emisi dilakukan pada: (1) agroforestri karet (*Hevea brasiliensis*), (2) campuran kelapa (*Cocos nucifera*) dan kopi (*Coffea liberica*), (3) campuran pinang (*Areca catechu*) dan kopi, (4) kelapa sawit (*Elaeis guinensis*) monokultur, dan (5) hutan sebagai referensi. Keempat tutupan/penggunaan lahan mempunyai perbedaan lama waktu setelah pengeringan. Estimasi emisi dilakukan berdasarkan penurunan permukaan gambut (*subsidence*) dan karakteristik gambut dengan memperhitungkan mikrotopografi gambut. Aplikasi pupuk tidak memiliki efek yang konsisten terhadap emisi CO_2. Kelapa sawit yang baru dibuka memiliki laju penurunan permukaan gambut dan emisi tertinggi yaitu 4,7 cm $tahun^{-1}$ atau 121 Mg CO_2 ha^{-1} $tahun^{-1}$. Sementara, hutan memiliki laju penurunan permukaan gambut dan emisi terendah yaitu 1,8 cm $tahun^{-1}$ atau 40 Mg CO_2 ha^{-1} $tahun^{-1}$. Jenis penggunaan lahan lainnya memiliki laju penurunan permukaan gambut dan emisi antara 2 – 3 cm $tahun^{-1}$ atau 70 – 85 Mg CO_2 ha^{-1} $tahun^{-1}$. Kajian tersebut menunjukkan bahwa lahan gambut yang dibuka untuk kegiatan pertanian skala kecil seperti kebun sawit dan lahan pertanian lainnya memiliki emisi CO_2 sedikit diatas standar IPCC saat ini.

Bab 5 menganalisis jejak karbon dari produksi minyak sawit di Indonesia jika minyak sawit digunakan sebagai bahan baku untuk bahan bakar minyak nabati. Perhitungan jejak karbon dilakukan berdasarkan dosis aplikasi pupuk untuk mendapatkan tingkat intensifikasi yang dapat meminimalkan jejak karbon per unit bahan bakar minyak nabati yang dihasilkan. Perhitungan jejak karbon menggunakan skema *Biofuel Emission Reduction Estimator Scheme* (BERES). Analisis ini dilakukan berdasarkan data yang dikumpulkan pada lebih dari 20 perkebunan seperti pada Bab 2 dan Bab 3. Target penurunan emisi dalam RED sebesar 35% tidak pernah dapat dicapai oleh minyak sawit yang dihasilkan dari kebun pada: (i) tanah gambut, atau (ii) tanah mineral yang memiliki hutang karbon pada saat konversi lahan dan lahan tersebut memiliki cadangan karbon lebih dari 20 Mg C ha^{-1}. Kondisi ini berlaku ketika jejak karbon dihitung menggunakan rasio emisi N_2O-N/N-pupuk sebesar 4%. Pada tingkat harga pupuk di Indonesia saat ini, dosis pupuk N yang optimal secara ekonomi adalah 344 – 394 kg N ha^{-1}, namun rerata dosis pupuk N yang digunakan adalah 141 kg N ha^{-1} $tahun^{-1}$. Pemakaian dosis pupuk 74 – 277 kg N ha^{-1} akan meminimalkan jejak karbon pada masing-masing rasio N_2O-N/N-pupuk antara 4 – 1%. Pada kebun yang memiliki hutang karbon 30 Mg C ha^{-1}, dosis pupuk 200 – 310 kg N ha^{-1} akan meminimalkan jejak karbon pada masing-masing rasio N_2O-N/N-pupuk antara 4 – 1%. Peningkatan produksi dengan meningkatkan dosis pupuk yang lebih tinggi dari 67 hingga 80% dari hasil yang dicapai saat ini tidak akan mengurangi jejak karbon dalam kondisi produksi saat ini.

Bab 6 mengkaji praktek budidaya kelapa sawit campuran, yaitu campuran kelapa sawit - kakao (*Theobroma cacao*) dan kelapa sawit - lada (*Piper nigrum*) dengan memodifikasi pola penanaman menggunakan model Water, Nutrient, and Light Capture in Agroforestry (WaNuLCAS). Performa ekonomi dan lingkungan dari praktik budidaya kelapa sawit campuran juga disajikan dalam bab ini. Jejak karbon kelapa sawit diestimasi menggunakan skema *Biofuel Emission Reduction Estimator Scheme* (BERES). Sistem kelapa sawit campuran yang dipilih dapat memberikan perbaikan ekonomi dan lingkungan. Kelapa sawit – kakao dapat meresapkan air ke dalam tanah lebih besar dan rasio biaya-keuntungan (*benefit cost ratio*) lebih tinggi dibandingkan kelapa sawit monokultur. *Land equivalent ratio* sebesar 1,4, menunjukkan penggunaan lahan yang lebih efisien dibandingkan monokultur. Kelapa sawit – lada memiliki *Net Present Value* tertinggi, tetapi membutuhkan tenaga kerja lebih banyak, sehingga memiliki nilai *return to labour* lebih rendah. Tanpa membagi beban hutang karbon dengan pohon yang ditumpang-sarikan dan dengan target penurunan emisi 60%, kelapa sawit – kakao dapat memenuhi target dengan maksimum hutang karbon sebesar 10 Mg C ha^{-1}; penurunan emisi bisa lebih tinggi jika beban hutang karbon dibagi dengan pohon yang ditumpang-sarikan.

Secara umum dapat disimpulkan bahwa, semakin luas area yang dikonversi dari hutan dengan cadangan karbon tinggi, semakin besar luasan lahan gambut, semakin besar emisi dari pupuk, transportasi dan emisi metana dari pengolahan minyak sawit serta semakin rendah hasil tandan buah segar (TBS), maka semakin sulit satu perkebunan sawit mencapai target pengurangan emisi (*emission saving*). Faktor-faktor tersebut diperhitungkan secara terintegrasi dalam menilai jejak karbon pada tingkat perusahaan. Sebagian besar minyak sawit Indonesia tidak dapat memenuhi persyaratan RED untuk tahun 2018 dan seterusnya, tergantung pada tahun pemutusan (*cut-off*) pada saat hutang karbon diperhitungkan. Berdasarkan data pada lebih dari 20 perusahaan yang disurvei dengan praktik pengelolaan kebun yang baik, 40% dan 25% produksi minyak sawit Indonesia dapat memenuhi standar pengurangan emisi 35% (2015) dan 60% (2018). Nilai ini melebihi dari standar ekspor minyak sawit ke Eropa sebagai bahan baku bahan bakar minyak nabati, segmen pasar lebih diutamakan daripada pengurangan resiko masalah lingkungan sebagai akibat belum disepakatinya regulasi secara global. Dari sudut pandang *land sharing versus land sparing*, kebun kelapa sawit campur dapat menjadi cara untuk mencapai *land sparing* dalam hal penggunaan lahan yang efisien. Dengan target pengurangan emisi sebesar 60%, tumpangsari kelapa sawit – kakao dapat memenuhi target pengurangan emisi dengan maksimum hutang karbon 10 Mg C ha^{-1}. Diversifikasi dapat menjadi pilihan budidaya kelapa sawit berkelanjutan baik dari perspektif sosial dan lingkungan.

Acknowledgements

This work would not have been possible without involvement of Prof. Meine van Noordwijk, Maja Slingerland, and Prof. Ken Giller. I was lucky to have all of you with wide range of expertise and vast experience accompanying this journey. Prof. Meine van Noordwijk played a very significant role towards the achievement of this thesis, I wouldn't complete this thesis without your persistent guidance at each step of this thesis and your advice in every communication with a friendly approach. Maja Slingerland, you have no idea how much your valuable feedback and suggestions meant toward the end of the journey. Ken Giller, I can't thank you enough for your support throughout this journey and your valuable input on the 1st draft of belowground C stock chapter.

Many people were involved in the "*Reducing carbon emissions associated with oil palm plantations in Indonesia*" project. Dr. Rosediana Soeharto from the Indonesian Palm Oil Committee (IPOC), thank you for linking to oil palm companies and organizing the implementation of the survey. Dr. Sonya Dewi, Andree Ekadinata and Elissa Dwiyanti from ICRAF, your contribution to the design and implementation of the stratification scheme as the basis of sampling design of Chapter 2, 3 and 5 deserves special thanks. Dr. Jean Pierre Caliman of PT. Smart and Dr. Mukesh Sharma of PT. Asian Agri, thank you for your valuable input during the establishment of the methodology for oil palm biomass measurement in Chapter 2. Twenty-five oil palm plantations, which prefer to remain anonymous, are acknowledged for participating in the study. For Chapter 4 as part of "*Reduced Emissions from All Land Uses*" and "*Securing Ecosystems and Carbon Benefits by Unlocking Reversal of Emissions Drivers in Landscapes*" projects, colleagues at ICRAF, Dr. Atiek Widayati and Dr. Peter Minang, thank you for the opportunities and support to expand the research beyond the initial project deliverable; Jasnari, Dinna Tazkiana and Diendo Citasyari Putri Hendrawan thank you for your support and help during field work and data collection. Misran 'Amenk' Jaya, Khoirul Anam and Fadil for making the field work easier and always cheerful. For Chapter 6, Dienke Stomph and Adrien Francois Migeon for initiating to explore mixed oil palm systems using WaNuLCAS model. Finally, anonymous reviewers of published chapters for their valuable inputs.

I would also like to extend my acknowledgment to individuals who played essential role towards the completion of this achievement. Riza Nugraha and Dewi Pramanik as buddies during the starting period of my PhD journey, thank you for your generosity in finding my way around Wageningen also during the difficult time when I lost my father and had to fly back to Indonesia, heartfelt thanks for all your kind help. Juliana Tjew thank you for your great friendship and joy you shared during my short stay in Bornsesteeg. Diah Wulandari for taking care of the house in Bogor while I was away in the Netherland for 3 months, warm thanks for to all your help. Dr. Subekti Rahayu, thank you for proofreading and editing of the Bahasa Indonesia version of summary. Tikah Atikah for designing the cover and putting your finishing touch of the layout, *hatur nuhun pisan*. Rika Ratna Sari and Danny Dwi Putra thank you for flying with 2 kg of printed thesis for submission. Lotte Woittiez, thank you for translating the summary into Dutch and being my paranymph. Dr. Aritta Suwarno, thank you for being my paranymph. Prof. Kurniatun Hairiah, thank you for your love and encouragement. Last but not least, Dr. Betha Lusiana, Dr. Beria Leimona and a long list of other people at ICRAF Bogor especially in the Ecological Modelling Group that I couldn't list all but who deserve sincere thanks for helping me in one way or another.

I would also like to express my deepest gratitude to my late mother Mas Ruchiyah and father Achmad Dachlan, thank you for your endless amounts of love and all your support and everything, no matter what. My brother and sisters, thank you for letting me pursue university education and providing financial support during my bachelor's degree; I knew that you always believe in me so that I can reach this stage. I am happy to see all of you happy.

About the author

Ni'matul Khasanah was born on February 28, 1976 in Gresik, Indonesia and attended primary school (MI Banat NU, now called MI Banin Banat NU) and secondary school (SMP Mu'allimat NU and SMA NU 1) there. She obtained her bachelor's degree (Soil Science) from University of Brawijaya, Malang, Indonesia in 1999 with the thesis *"Estimation of root input on soil carbon using a minirhizotron under hedgerow intercropping system in North Lampung"*. From then, she joined the university to work on "Smallholder agroforestry options for degraded soils: tree establishment in cropped fields (SAFODS)" project where she gained more experience on tree – soil – crop interaction.

Since February 2002, she has been working for the World Agroforestry Centre (ICRAF) based in Bogor, Indonesia. While working for the research institute, she managed to get a masters degree (Agroclimatology) from Bogor Agriculture Institute, Bogor, Indonesia in 2008 with the thesis *"Water status and radiation environment in rubber (Hevea brasiliensis) systems: a comparison between monoculture and mixed rubber-Acacia mangium"*. Since she first joined ICRAF, her research focus gradually developed from tree-soil-crop interactions using a modelling approach to tropical – tree – cover changes and its consequences for ecosystem services (carbon and water) and restoration. In 2009, she involved in the *"Reducing carbon emissions associated with oil palm plantations in Indonesia"* project and led the biophysical research aspect. This became the basis of her PhD thesis.

Email address: nkhasanah07@gmail.com

List of Publications (selected)

Khasanah N, van Noordwijk M, Ningsih H. 2018. Subsidence and CO_2 emissions in a smallholder peatland mosaic in Sumatra, Indonesia. *Mitig Adapt Strateg Glob Change. https://doi.org/10.1007/s11027-018-9803-2*

van Noordwijk M, Khasanah N, Dewi S. 2016. Can intensification reduce emission intensity of biofuel through optimized fertilizer use? Theory and the case of oil palm in Indonesia. Global Change Biology Bioenergy: 1-13. DOI: 10.1111/gcbb.12398.

Khasanah N, van Noordwijk M, Ningsih H. 2015. Aboveground carbon stocks in oil palm plantations and the threshold for carbon-neutral vegetation conversion on mineral soils. Cogent Environmental Science 1: 1119964

Khasanah N, van Noordwijk M, Ningsih H, Rahayu S. 2015. Carbon neutral? No change in mineral soil carbon stock under oil palm plantations derived from forest or non-forest in Indonesia. Agric. Ecosyst. Environ 211: 195–206.

Khasanah N, Perdana A, Rahmanullah A, Manurung M, Roshetko J, van Noordwijk M. 2015. Intercropping Teak (*Tectona grandis*) and Maize (*Zea mays*): Bioeconomic Trade-off Analysis of Agroforestry Management Practices in Gunungkidul, West Java. Agroforestry System 89:1019-1033.

van Noordwijk M, Khasanah N, Dewi S. 2015. When can oil palm production qualify for a 'carbon neutral' claim?. ASB Policy Brief 49. Nairobi. ASB Partnership for the Tropical Forest Margins.

van Noordwijk M, Bayala J, Hairiah K, Lusiana B, Muthuri C, Khasanah N, Mulia R. 2014. Agroforestry solutions for buffering climate variability and adapting to change. In: Fuhrer JF and Gregory P (eds). Climate change impact and adaptation in agricultural systems. CABI Climate Change Series No.5. Wallingord. CABI. P. 216-232

van Noordwijk M, Khasanah N, Dewi S. 2013. Biofuel emission reduction estimator scheme (BERES): landuse history, production systems and technical emission factors. In: van Noordwijk M, Lusiana B, Leimona B, Dewi S and Wulandari D, (eds). Negotiation-support toolkit for learning landscapes. . Bogor, Indonesia. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program. P. 157-162

Dewi S, Khasanah N, Widayati A. 2013. Capacity-strengthening approach to vulnerability assessment (CaSAVA). In: van Noordwijk M, Lusiana B, Leimona B, Dewi S and Wulandari D, (eds). Negotiation-support toolkit for learning landscapes. Bogor, Indonesia. World Agroforestry Centre – ICRAF, SEA Regional Office. P. 234-238

Khasanah N, Lusiana B, Mulia R and van Noordwijk M. 2013. Water, nutrient and light capture in agroforestry systems (WaNuLCAS): at the plot level. In: van Noordwijk M, Lusiana B, Leimona B, Dewi S and Wulandari D (eds). Negotiation-support toolkit for learning landscapes. Bogor, Indonesia. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program. P. 98-102

Khasanah N, Tanika L, Lusiana B and van Noordwijk M. 2013. Generic river flow (GenRiver) at landscape level. In: van Noordwijk M, Lusiana B, Leimona B, Dewi S and Wulandari D (eds). Negotiation-support toolkit for learning landscapes. Bogor, Indonesia. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program. P. 163-170 van Noordwijk M, Agus F, Maswar M, Handayani EP, Marwanto S, Dariah A, Khasanah N. 2013. Reassessing peat-based emissions from tropical land use. ASB Polic ybrief 36. Nairobi. ASB Partnership for the Tropical Forest Margins.

Khasanah N, van Noordwijk M, Ekadinata A, Dewi S, Rahayu S, Ningsih H, Setiawan A, Dwiyanti E, Octaviani R. 2012. The carbon footprint of Indonesian palm oil production. Technical Brief No 25: palm oil series. World Agroforestry Centre - ICRAF, SEA Regional Office.

Dewi S, Ekadinata A, Rahmanulloh A, Khasanah N, Rahayu S, van Noordwijk M, Budidarsono S. 2012. The carbon efficiency of oil palm plantations: an opportunity cost analysis. Technical Brief No. 28: palm oil series. World Agroforestry Centre - ICRAF, SEA Regional Office.

van Noordwijk M, Lusiana B, Khasanah N, Mulia R. 2011. WaNuLCAS: WaNuLCAS version 3.1, Background on a model of water nutrient and light capture in agroforestry systems. International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia. 224 pp.

van Noordwijk M, Widodo RH, Farida A, Suyamto DA, Lusiana B, Tanika L, Khasanah N. 2011. GenRiver and FlowPer: Generic River Flow Persistence Models. User Manual Version 2.0. Bogor. World Agroforestry Centre - ICRAF, SEA Regional Office. 119 p.

Khasanah N, Mulyoutami E, Ekadinata A, Asmawan T, Tanika L, Said Z, van Noorwijk M, Leimona B. 2011. A Study of Rapid Hydrological Appraisal in Krueng Peusangan Watershed, NAD, Sumatra. Working paper No. 123. World Agroforestry Centre - ICRAF, SEA Regional Office.

van Noordwijk M, Khasanah N, Hairiah K, Suprayogo D, Macandog D, Lusiana B, Cadisch G. 2008. Agroforestation of Grasslands in Southeast Asia: WaNuLCAS Model Scenarios for Shade-Based Imperata Control During Tree Establishment In Snelder J.D, Lasco R.D. Smallholder Tree Growing for Rural Development and Environmental Services. Springer Science.

Khasanah N, Wijaya T, June T, Lusiana B, van Noordwijk M. 2008. Pertumbuhan Karet (Hevea brasiliensis) dalam Sistem Monokultur dan Campuran dengan Akasia (Acacia mangium). Studi Kasus di Sembawa, Sumatra Selatan: II. Simulasi dengan Menggunakan Model WaNulCAS. Jurnal Penelitian Karet 26(1): 49-64. http://balitsp.com/jurnal_list.php?id=27.

Khasanah N, Wijaya T, June T, Vincent G, van Noordwijk M, Wibawa G. 2008. Pertumbuhan Karet (Hevea brasiliensis) dalam Sistem Monokultur dan Campuran dengan Akasia (Acacia mangium). Studi Kasus di Sembawa, Sumatra Selatan: I. Pengukuran Status Air dan Lingkungan Radiasi. Jurnal Penelitian Karet 26(1): 31-48. http://balitsp.com/jurnal_list.php?id=27.

Suyamto DA, van Noordwijk M, Lusiana B, Ekadinata A, Khasanah N. 2006. Prospects of adoption of tree-based systems in a rural landscape and its likely impacts on carbon stocks and farmers' Welfare: the FALLOW model application in Muara Sungkai, Lampung, Sumatra, in a "Clean Development Mechanism' context. ICRAF Working Paper No. 14.

van Noordwijk M, Rahayu S, Williams S, Hairiah K, Khasanah N, Schroth G. 2004. Crop and tree root-system dynamics. In: van Noordwijk M, Cadisch G and Ong CK, (eds). Below-ground interactions in tropical agroecosystems: concepts and models with multiple plants components. . Wallingford, UK. CABI. P. 83-107

Joshi L, Schalenbourg W, Johansson L, Khasanah N, Stefanus E, Fagerstrom MH, van Noordwijk M. 2004. Soil and water movement: combining local ecological knowledge with that of modellers when scalling up from plot to landscape level. In: van Noordwijk M, Cadisch G and Ong CK,(eds). Below-ground interactions in tropical agroecosystems: concepts and models with multiple plants components. Wallingford, UK. CABI. P. 349-364

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- The literature review is part of both research chapters and non-research chapters

Writing of project proposal (4.5 ECTS)

- Oil palm (*Elaeis guineensis*) production in Indonesia: agronomic options to reduce the carbon footprint and diversify smallholder production systems

Post-graduate courses (5.5 ECTS)

- Multivariate analysis; PE&RC (2014)
- Land dynamic: getting to the bottom of Mount Kenya; PE&RC (2015)

Laboratory training and working visits (3 ECTS)

Exploration of management options of more diverse smallholder oil palm using WaNuLCAS model: visiting the existing experimental plot of mixed oil palm in Tome Acu, Brazil and discuss with EMBRAPA staff in Belem, Brazil on the experiment and modelling approach; EMBRAPA, Brazil (2015)

Deficiency, refresh, brush-up courses (6 ECTS))

- QUALUS (Quantitative Analysis Land Use System); PPS (2014)

Competence strengthening / skills courses (2.1 ECTS)

- APSIM Oil palm training course; SMARTRI, PT SMART, Tbk; Jakarta (2014)
- Techniques for writing and presenting scientific papers; PE&RC (2015)

PE&RC Annual meetings, seminars and the PE&RC weekend (0.9 ECTS)

- PE&RC Weekend (2014)

Discussion groups / local seminars / other scientific meetings (5.4 ECTS)

- Local seminars (ministry of environment) on peat land; Bogor, Indonesia (2013)
- ICRAF Science week; Bogor, Indonesia (2015)
- ICRAF Weekly shared learning; Bogor, Indonesia (2015)
- Open science meeting; Yogyakarta, Indonesia (2017)
- Sapienza-ICRAF knowledge-sharing event: from payments to co-investments in ecosystem services; Rome (2017)

International symposia, workshops and conferences (8.8 ECTS)

- Tropentag conference; oral presentation; Stuttgart, Germany (2013)
- Soil Conference; oral presentation; Wageningen, the Netherland (2015)
- Workshop on palm oil intercropping addressing climate change influence on systems; oral presentation; Kuala Lumpur, Malaysia (2015)
- International crop modelling symposium; poster presentation; Berlin, Germany (2016)

Supervision of MSc students

- Dienke Stomph: smallholder oil palm: space for diversification? WaNuLCAS model-based exploration of the environmental and economic impact of intercropping scenarios for Indonesian smallholders (2016)
- Adrien Francois Migeon: assessing the possibilities of intercropping oil palm and pepper, under the double-row avenue system (2017)

Funding

This thesis was financially supported by (1) the Dutch Government through the "Reducing carbon emissions associated with oil palm plantations in Indonesia" project, (2) the Climate and Forest Initiative of the Norwegian Agency for Development Cooperation through the "Reduced Emissions from All Land Uses" and "Securing Ecosystems and Carbon Benefits by Unlocking Reversal of Emission Drivers in Landscapes" projects, and (3) the CGIAR Forests, Trees and Agroforestry research program.