Monitoring the Bio-Economy

Assessing Local and Global Biomass Flows, Land-Use Change, Carbon Impacts and Future Land Resources

吴浚生

Chun Sheng Goh

Explanation of the cover:

The cover was developed based on the story of "The blind men and an elephant" from India. Interestingly, the word "elephant" in Chinese also means faces, shapes, symbols, representation, similarities and phenomena. As such, the elephant may be a metaphor for the bio-economy. The different pieces of elephant parts symbolise the different ways of monitoring the bio-economy, in particular the different sectorial focuses on the biomass flows (Chapter 2), the different settings of the key functions that determine the linkages of carbon stock change to consumption (Chapter 3 and 4), as well as the different perspectives on future land resources (Chapter 5 and 6).

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Monitoring the Bio-Economy

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Monitoring van de bio-economy

Bepaling van lokale en mondiale biomassastromen, veranderingen in landgebruik, gevolgen voor koolstof en toekomstig landgebruik

(met een samenvatting in het Nederlands)

P R O E F S C H R I F T

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof.dr. G.J. van der Zwaan, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op maandag 8 mei 2017 des middags te 12.45 uur

door

Chun Sheng Goh
geboren op 20 december 1985 te Pulau Pinang, Malaysia

Promotoren: Prof. dr. A.P.C. Faaij
Prof. dr. H.M. Junginger

Copromotor: Dr. B. Wicke

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CHAPTER 1

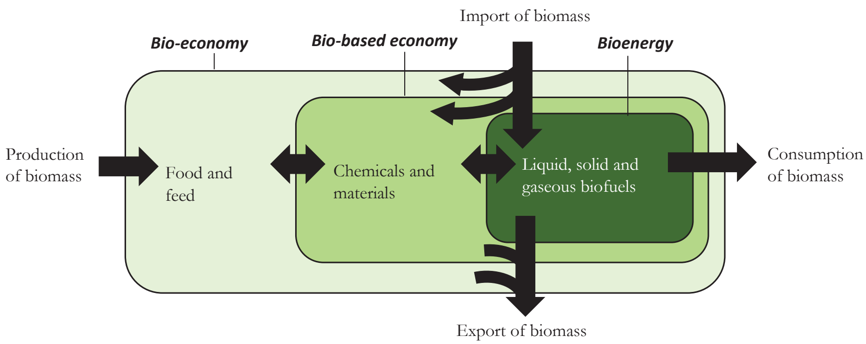
Introduction

"When there is an elephant in the room, *introduce* them." --- Randy Pausch

1

1.1 DEVELOPING THE BIO-ECONOMY

Interest in developing the 'bio-economy (BE)' and the 'bio-based economy (BBE)' has grown substantially since the beginning of the 21st century, not only in developed regions like Europe (Vandermeulen 2011, EC 2012, FAO 2016), but also in developing areas like Southeast Asia (van Meijl et al. 2012, AIM 2013, FAO 2016). To be more specific, the term BBE is used to describe economic activities that utilise bio-based materials and products, either in raw form, intermediates or finished products (hereafter referred to as 'biomass') for non-food purpose (FAO 2016). This concept falls under the larger BE framework which involves all end-uses of biomass, including food and feed. Sometimes these two terms are used interchangeably due to their crosscutting nature (Figure 1-1). As the BE and BBE share the same feedstock, particularly agricultural products that utilise land, they are therefore closely linked to each other and also the larger topics of food security, climate change and rural development. This is also characterised by complex cross-sector flows (e.g. from the food sector to the energy sector) and cross-border trade of biomass.



Note: Black arrows represent flows of biomass.

Figure 1-1. The broad framework of a bio-based economy (adapted from Meester et al. 2013).

Due to its multi-facetted character, the scope varies in the eyes of different stakeholders, although most regard the developing of the BE as a pathway that contributes to future sustainable development. Advocators in developed regions see the BE as a means of reindustrialisation by replacing fossil feedstocks with renewable feedstocks in order to reduce greenhouse gas (GHG) emissions for climate change mitigation and to decrease dependence on finite fossil resources (see e.g. EC 2012, El-Chichakli et al. 2016). Meanwhile, the agricultural producing countries in developing regions aim to add values to their agricultural sector (especially through export) alongside rural development, and to domestic growth, while reducing adverse effects to the environment (see e.g. AIM 2013). Although reducing global emissions is also one of the objectives, the considerations in these countries are more localised targets. A study by FAO (2016) has identified the gaps between countries by benchmarking the scope of 20 bio-economy strategies across the world. For example, countries with vast biomass resources like Malaysia place their focus on production of raw materials. Meanwhile, countries that have a strong industrial sector like Germany emphasize the innovative use of biomass. For countries like the US and Finland, which share both characteristics, the scope is broader to cover production and consumption.

Initially, the BE has a strong focus on the conversion of biomass for energy production. Since the early 2000's, the use of biomass for modern energy purpose, in the form of liquid, solid and gaseous fuels, has been increasing globally (Balat and Balat 2009, Yusuf et al. 2011). Following that, the ambition to further substitute fossil fuels with biomass in the chemical industry has received increasing attention in recent years (Langeveld et al. 2010, AIM 2013). In 2010, the total use of agricultural products for non-food purposes has doubled to 6 EJ compared to 1995. This is about 10% of the total consumption of agricultural products in energy terms (FAOSTAT 2014). While this number is largely due to conventional uses, e.g. the use of palm oil for detergent production, increasing shares relate to new products, e.g. the substitution of fossil materials in plastic bottles (Li 2014, Coca-cola, 2015).

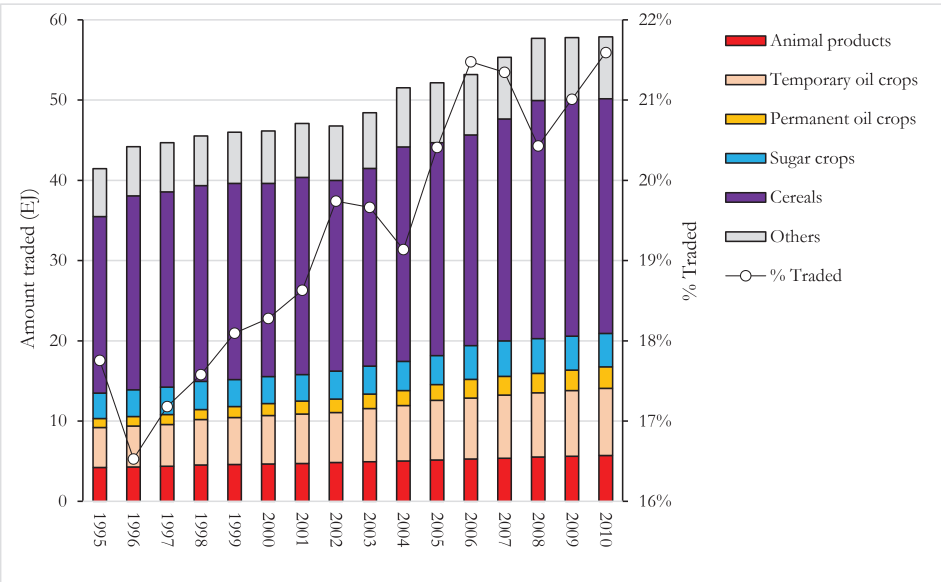


Figure 1-2. Total global trade of primary agricultural products in 1995-2010 by year. (Source: Calculated based on FAOSTAT 2014).

The development of the BE is emerging on a global scale, characterised by the rapid development in international trade of biomass (Lamers et al. 2011, 2012, Goh et al. 2013a). The traded volume has increased substantially from 7 EJ in 1995 to 12 EJ in 2010, while the share of traded products in total primary agricultural products has also increased from 18% in 1995 to nearly 22% in 2010[1](FAOSTAT 2014; see Figure 1-2). This number may further increase in the coming decades. In an ambitious scenario, Matzenberger et al. (2014) forecasted that the volume of agricultural-based liquid biomass traded as fuel can grow up to 2-11 EJ in 2030. With the steady growth of global trade, the additional demand from the BE is likely to cause cross-border impacts in different parts of the world. This will be further elaborated in the following section, focusing on the impacts on land-use change.

1.2 MONITORING THE LINKS BETWEEN A BIO-ECONOMY AND LAND-USE CHANGE

As one of the common goals of transitioning to the BE is to reduce GHG emissions from fossil feedstocks, it is crucial to monitor the associated GHG emissions along the global biomass supply chain. GHG emissions typically included in existing monitoring cover production and processing of raw materials, transportation and logistics from multilateral cross-border trade, and final consumption in different end-markets. Among these different components, the carbon stock change (CSC) as a consequence of land-use change (LUC) (hereafter referred to as CSC-LUC) is one of the major component in contributing to the overall emissions from the biomass supply chain. Total CSC-LUC has caused 8-20% of annual global anthropogenic CO_2 emissions in the past decades, is the major component that contributes to the carbon footprints of biomass (van der Werf et al. 2009, Bos et al. 2016). WRI (2009) and ECOFYS (2013) have illustrated the distribution of these emissions from different sources for 2005 and 2010 (Figure 1-3), respectively. CSC-LUC can happen through deforestation, forest degradation and peat emissions. Deforestation as the major source of carbon stock loss has increased substantially in tropical regions. FAOSTAT (2014) reported that close to 10% of forests in South America, Africa and Southeast Asia was lost between 1990 and 2010, amounting to about 190 million ha. At the same time, afforestation, the major carbon stock gain, has increased in other regions like East Asia and Europe, where forested area has increased by 45 and 16 million ha, respectively.

There is growing evidence showing that CSC-LUC due to agricultural expansion, e.g. the rapid deforestation in Indonesia, has been increasingly triggered by distant demand of biomass, e.g. the growing export of palm oil from Indonesia to Europe, India and China (Kastner et al. 2011, Henders et al. 2015). Furthermore, CSC-LUC is not only a direct result of additional demand for one product in one place, but can also be triggered by indirect causes. Among the different end-markets, the pioneer in monitoring of CSC-LUC is the biofuel sector. For example, the increasing use of biomass for energy is potentially related to indirect land-use change (ILUC) on a global scale, which occurs when existing

1 It is not clearly known how much in total is traded for non-food purposes as there is no reliable data source for that. However, the share of traded products for non-food purposes can be partly reflected by one of the actively traded commodities, i.e. palm oil – in 2010, about 66% of total palm oil consumption is for non-food purposes, and about 80% (1.4 EJ of 1.8 EJ) was consumed outside the producing countries. The trend is shared by other vegetable oils as well (FAOSTAT 2014).

agricultural land is converted for non-food production, triggering agriculture expansion elsewhere to fill the demand gap in the global market (Searchinger et al. 2008, Laborde et al. 2011, Wicke et al. 2012).

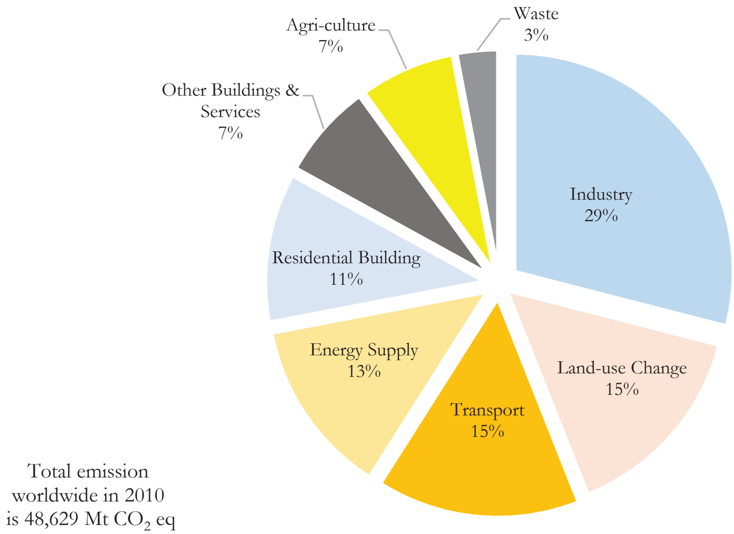


Figure 1-3. World GHG emission flow chart 2010 (adapted from ECOFYS 2013).

In the near future, it is expected that the increasing demand for biomass will still be largely met by conventional agricultural products, based on the current trends in biochemical industry (in which e.g. sugars and fatty acids are used as major feedstocks) (see e.g. Goh 2016). It is therefore imperative to understand the implication of creating new demand for biomass on CSC-LUC to ensure that the BE is developed in a sustainable way. To achieve this, effective monitoring of the role of additional demand in global CSC-LUC has become a main discussion point (Dornburg et al. 2003, DeFries et al. 2010, Weiss et al. 2012, Meyfroidt et al. 2013, Stupak et al. 2016). In the two following sub-sections, two major aspects of monitoring are further elaborated, i.e. tracking materials flows and linking consumption to CSC-LUC.

1.2.1 Tracking material flows: Production, consumption and trade

To understand the implication of creating new demand on global CSC-LUC, tracking the production, consumption and material flows related to BE across sectors and borders (e.g. countries) is the very first step. This helps to identify the consumption patterns for different end-uses, trends in cross-border trade to and from different places, and how do these affect the direction and volume of biomass. This requires a clear mapping of the flows of diverse forms of raw materials, intermediates, products, and by-products that go into different end-markets (i.e. energy, chemicals and food).

It has been challenging to explicitly map all the biomass flows, as both the direction and quantity of many flows are not entirely clear and may change significantly from year to year. As bioenergy is one of the key components in the BE, a number of studies on cross-border trade flows have been conducted particularly on biomass for energy purpose. For example, Lamers et al. (2011) found that world net liquid biofuel trade has reached 120–130 PJ in 2009, contributing to about 1% of total trade of primary agricultural products. It concluded that anecdotal information is indispensable due to the inadequate reporting of underlying, complex and interwoven links within the market. Meanwhile, some other studies assessed the flows of biomass into different end-markets (e.g. MVO 2011, Kalt and Kranzl 2012). By taking Austria as an example, Kalt and Kranzl (2012) discovered that of the total 1354 PJ of biomass consumed for energy, the share of domestic biomass is only 67% (instead of 84% reported by official statistics) after connecting the trade flows with the domestic flows across sectors. However, these types of information are sector-specific (e.g. with a strong focus on bio-energy sector) or product-specific (e.g. on vegetable oils or woody biomass only), and do not represent all biomass use in the BE.

Due to the growing concerns on sustainability of biomass, various sustainability certifications and labels, especially for their carbon footprints and land-use impacts, have been developed and applied across sectors and along supply chains. The idea of having certification is to help consumers identify goods that are being assessed for its performance in environmental and socio-economic aspects. Biofuels, vegetable oils and wood products are among the biomass for which several certification schemes have been developed (e.g. ISCC, RSPO, FSC). It is thus possible to further distinguish and quantify these flows by the certification applied. However, quantitative inventories of certified sustainable biomass flows for a variety of end-markets is currently largely absent. There are reports on the production by certification bodies (e.g. FSC, RSPO) and reports on the consumption for biofuels (by national agencies, e.g. NEa 2011), but not explicitly connecting both sides from origins to destinations. Goh et al. (2013b) have attempted to trace trade flows of certified solid and liquid biofuels taking the forerunners in biofuels certification, i.e. the UK and the Netherlands, as two case studies. Again, these reports do not cover cross-market monitoring.

Resolving the complexity of existing material flows is necessary to analyse the impacts of switching to the BE. This becomes more important especially when accounting for indirect substitution effects due to diverting of biomass from their original capacity to other purposes (e.g. from food to bioenergy), which could possibly result in increased utilisation of other biomass to fill the demand gap created in the original sectors. As biomass flows are largely monitored separately (typically for each feedstock, or use in one industry), the key challenge to gather all the relevant information for monitoring of the BE is to link data from different sources which may have uneven quality and lack compatibility. This has not been thoroughly addressed yet, especially when different methods and criteria were employed to quantify the biomass streams, e.g. in terms of specifications (physical and chemical characteristics) and spatio-temporal dimensions. In order to capture a more comprehensive picture of the BE on the consumption side, a monitoring framework that covers different types of biomass and multiple sectors still needs to be further improved.

1.2.2 Linking consumption to CSC-LUC: Local and global impacts

When putting the impact of the BE on CSC-LUC into a global context, identifying and monitoring the roles of biomass consumption in global CSC-LUC is an important exercise to ensure the sustainability of the BE, especially for countries that rely significantly on international trade of biomass and thus cannot be detached from land-use changes occur in different parts of the world. This consumption is one of the underlying causes closely related to direct drivers of CSC-LUC, such as logging and agricultural expansion (Henders et al. 2015). A way to come closer to quantification of the impacts of increasing demand for biomass at global level is associating CSC-LUC with measurable consumption and trade patterns in different locations and end-markets. Monitoring in this aspect requires developing mechanisms to link CSC-LUC to these flows. To do so, in-depth understanding of the direct drivers and complex underlying causes of CSC-LUC is needed.

An array of ideas and methodologies have been developed across disciplines, from local industrial ecology to global economics, to formulate and quantify links between CSC-LUC and distant consumption via international trade (Meyfroidt et al. 2013). However, they are largely built upon different methodological settings. Broadly speaking, these consumption-based assessments can be widely categorised as: (i) historical studies (e.g. Yu et al. 2013) which examine the historical consumption of agricultural commodities in general and linking this to CSC-LUC, and (ii) projection studies which examine potential CSC-LUC impacts of specific additional demand, including for example studies on ILUC induced by additional consumption of biofuels (e.g. Laborde et al. 2011).

For the historical studies, the major aim is to address the leakage issue of the national carbon accounting system (e.g. the reporting system employed by the United National Framework Convention on Climate Change), as it is only limited to national boundaries (e.g. Saikku et al. 2011, Henders et al. 2015). The principle of this approach is establishing linkages between consumption of imported biomass with CSC-LUC outside the national boundaries, by embodying CSC-LUC in biomass as part of their carbon footprints and allocating these emissions to distant consumers.

The projection studies, particularly the ILUC studies, consider the indirect effects of LUC propagated through international trade (e.g. Searchinger et al. 2008, Laborde et al. 2011). The ILUC concept illustrates that the diversion of lands or crops from original use to biofuel may trigger agricultural expansion and deforestation elsewhere to meet the demand gap (Wicke et al. 2012). For example, the increasing use of rapeseed in Europe for biofuel may trigger more imports of soybean from South America to replace the demand gap for food.

Under these two categories, a wide range of concepts and methodologies have been proposed to explain, monitor and establish links between consumption and distant CSC-LUC across the world. For both historical and projection studies, reviews (Wicke et al. 2012, Warner et al. 2013, Ahlgren and Di Lucia 2014, Bruckner et al. 2015, Schaffartzik et al. 2015, Hubacek and Feng 2016, Wiedmann 2016) have revealed the large discrepancies between quantitative results produced by different studies. As they have different objectives and policy perspectives, links are drawn with different scopes at different scales and therefore are often not compatible with each other. The issue is especially prominent with the ILUC accounting, which is still highly debatable due to lack of empirical evidence and great uncertainties in methodologies (Verstegen et al. 2015). While ILUC is extensively debated for projection of future production, historical studies basically employ bilateral trade analysis and do not account for indirect effects propagating across spatial boundaries (some have accounted for ILUC effects within the border, e.g. Persson et al. 2014).

Furthermore, biomass consumption is not the only cause of CSC-LUC. Abundant evidence reveals that non-productive drivers, such as improper land-use practices (e.g. land degradation and uncontrolled fire), are also major contributors to carbon stock loss (see e.g. Siegert and Hoffmann 2000, Turetsky et al. 2011, Kissinger et al. 2012). Most consumption-based studies, however, do not clearly distinguish between the impacts caused by agricultural expansion and non-productive drivers. Linking distant consumption, production and CSC-LUC must take into account the role of non-productive drivers as well as possible indirect effects to avoid over- or under-estimation of the impacts caused by additional demand for biomass.

Clearly, there is a need for clarifying the implications of these differences to assist decision makers from different sectors, in policymaking from agricultural to environment aspects. This requires careful examination of specific methods, algorithms and parameters embedded in the analysis to understand the policy implications of the results.

1.3 EXPLORING LAND RESOURCES FOR SUSTAINABLE PRODUCTION TO MEET ADDITIONAL DEMAND

In addition to the monitoring the role of global demand on local CSC-LUC, from the producer perspective, also another aspect is of high importance: avoiding CSC-LUC from the production system is the key for shaping a sustainable BE. With the identification of the role of different drivers on global CSC-LUC, the next step would be addressing CSC-LUC in local land-use systems, especially unsustainable demand-driven expansion (e.g. converting high carbon area into plantation) or inefficient local land-use practices (e.g. abandoning existing agricultural land due to soil erosion, poor water management or poor fire control).

One way proposed to avoid further CSC-LUC by additional consumption is shifting production onto less-productive land with low carbon stock and insignificant ecological services (Wicke 2011). The identification and utilisation of such land resources, however, varies from one location to another. This is not only due to local differences in agro-ecological and socio-economic aspects (Lambin et al. 2013), but also the definition of such land resources partially being subjective - actors from different sectors (e.g. agricultural and forestry) and with different technical and economic capabilities (e.g. large industry, small farmers or government) may perceive agro-ecological, legal or cultural aspects in different ways. To effectively mobilise these land resources for future production, it is therefore necessary to understand the land-use dynamics in a local context and the differences in perspectives of the multitude land-use actors.

In this context, various initiatives have attempted to explore land resources that are suitable and low risk for increasing agricultural production to adequately fulfil the growing demand while avoiding CSC-LUC and other environmental impacts (e.g. Gingold et al. 2013 in Indonesia). While various policies have been made by individual countries or local authorities, international cooperation has also been taking place through platforms like FAO, UNCCD and World Bank (FAO 2013, UNCCD and World Bank 2016). One potential land-use option is the mobilisation of less- and non-productive lands with low carbon stock and insignificant ecological services. Considerable efforts have been devoted to quantify such land resources under a wide range of names, e.g. 'unused', 'abandoned', 'degraded', 'marginal', 'critical' and 'sub-optimal' lands. But, the criteria in determining the available land can be quite different and some are not entirely clear (Suhariningsih 2009, Shortall 2013, Smit et al. 2013, Kosmas et al. 2015), e.g. abandoned land is not necessarily degraded, or vice versa. Ambiguous definitions have caused confusion and resulted in unintended consequences when it comes to policymaking. For example, it was reported that in some cases land degradation is used as an excuse for forest clearing with the suggested aim of reforestation, although the 'degraded' land may still be rich in carbon stock and biodiversity (Barr et al. 2010).

Taking Indonesia, one of the major deforestation hotspot globally, as an example, extensive work has been performed to quantify such land resources using top-down and bottom-up approaches. For the top-down approach, remote sensing is employed coupled with biophysical models by international institutions (e.g. Dehue et al. 2010, Gingold et al. 2012, Hadian et al. 2014 and Smit et al. 2013) and national institutions (Mulyani and Sarwani 2013, MoF 2001 and MoF 2013). Environmental constraints and technical potential are the main focus; but socio-economic aspects (e.g. land occupancy by indigenous communities) are often left out. Due to resource and data constraints, most analyses were performed with large time-intervals (up to several years), leading to considerable errors, especially in differentiating abandoned land from temporarily unused agricultural land, which may be still cultivated sporadically by local communities (Treitz and Rogan 2004). Meanwhile, the bottom-up approach integrates socio-economic information considering local variations based on expert opinions and household surveys (e.g. BPS 2013b, Lambin et al. 2013). The key advantage of this approach is that it includes more precise local information, but the drawback is the lack of consistency in methodology from one case to another. For both approaches, analyses have been performed in either spatially explicit (e.g. Gingold et al. 2013) or aggregated form at different scales (e.g. BPS 2013b, Mulyani and Sarwani 2013), causing difficulties in comparing and matching them. At the moment, these different methods have not been comparatively reviewed and reconciled to obtain a more complete picture of available land resources.

In addition, more aspects beyond physical land area quantification are required to gain further insights into mobilising the land resources for productive use. Issues like social acceptance, labour availability, economic performance of intensification and expansion on degraded land may largely affect the extent of land resources that can be mobilised for production (Potter 2011). These may be perceived as either opportunities or barriers to mobilising ULC land depending on the actor (e.g. private company, farmers, local communities, and government officials), their land-use preferences (e.g. mixed crop farming or monoculture oil palm) and business models (e.g. small-scale farming or industrial plantation). The viewpoints may also change from global, national to local level. Therefore, physical estimates based on a single approach at a single point of time without accounting for these aspects come with considerable uncertainties. Efforts to compare and combine information on different aspects and from various sources, especially including the actual experience and perspectives of local communities and other stakeholders, are still rare. These knowledge gaps need to be urgently addressed, especially for cases of deforestation hotspots like Indonesia, to ensure that these land resources will be used in a sustainable way without compromising environmental and socio-economic sustainability.

1.4 AIMS AND THESIS OUTLINE

In order to address the knowledge gaps described earlier, this thesis aims at improving monitoring efforts for the BE by (i) tracking the material flows for the BE, (ii) measuring the impacts of additional demand on CSC-LUC, and (iii) assessing land availability for future agricultural production so to contribute to the development of a sustainable BE. Figure 1-4 illustrates the three key monitoring aspects addressed in this thesis. Based on the literature review above, a distinction is made for the monitoring of consumers (section 1.2) and producers (section 1.3). The first monitoring aspect focuses on the flows of biomass across multiple processing sectors, different end-markets and territories from a consumer perspective. Due to increasing cross-border trade, the next aspect is to monitor the role of increasing global demand in the local CSC-LUC by linking both the consumer and producer sides. This is possible by tracking the flows of biomass and the associated CSC-LUC in spatial and temporal dimensions. The third monitoring aspect, which is on the producer side, requires examining local land-use dynamics in relation to additional demand (current land-use and potential area for future production).

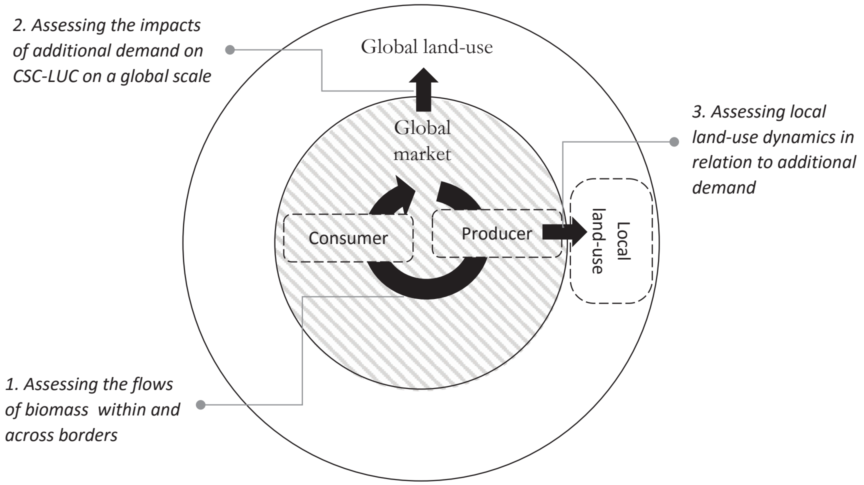
The following research questions were formulated to meet the aforementioned aims:

i. How can the biomass flows from production to consumption for the expanding bio-economy be monitored on local and global scales, and what are the patterns of the major flows?

ii. How can the carbon stock changes from land use change associated with the additional demand from the expanding bio-economy be monitored, and what are the effects of applying different methodological settings using different perspectives?

iii. What are the land resources that can be potentially utilised to meet the additional biomass demand without causing undesired carbon stock changes from land use change, and what are the key factors for effective mobilisation of these land resources?

Following this chapter of introduction, this thesis encompasses five research papers in Chapter 2 to 6, and ends with a summary and conclusions in Chapter 7. Table 1-1 is an overview of the chapters and how they address the research questions. Also indicated are the different research approaches and the geographical focus of each chapter.



Note: Black arrows represent the monitoring aspects. The shaded inner ring represents the global market (with consumer and producer as subsets) and the outer ring represents the land-use (with local land-use as subsets).

Figure 1-4. Monitoring the implications of the expanding BE on local and global CSC-LUC – relevant components for this thesis.

The research at the consumption side took the Netherlands as a case study in **Chapter 2**. By inspecting available datasets and monitoring instruments, a methodology framework was proposed for mapping domestic production-consumption and cross-border trade of biomass materials. The framework also investigates the respective share of sustainably-certified biomass in the Dutch market. Finally, the chapter ends with a discussion on methodological challenges in assembling data from various monitoring domains.

Chapter 3 is a review of the consumption-based CSC-LUC studies focusing on the disparities in methodological functions and their policy implications, addressing research question (ii). This was illustrated for the case of Indonesian palm oil as an important example of a product often associated with CSC-LUC. The causes of discrepancies between different studies were investigated by conceptually assessing key functions embedded in the methodologies.

Chapter 4 is a quantitative analysis that intends to cover research question (i), (ii) and (iii). A method was developed to associate consumption with distant CSC-LUC at global level and regional level. It was constructed transparently to reveal the implications of each step and how one can adjust the setting based on different arguments. A common conclusion derived is that the expansion of non-productive land (i.e. land abandonment, degradation or intensive logging) has become the key underlying cause for CSC-LUC. The immediate question is how to prevent land under-utilisation as a means to stop CSC-LUC from deforestation.

Following the conclusion in the previous chapter, in **Chapter 5** the focus was shifted to the production side to address research question (iii). A case study on Kalimantan was performed to explore the potential of under-utilised low carbon land resources that is available for future agricultural expansion and intensification. By analysing information from six monitoring domains, a range of indicators were derived to provide insights into the physical area of ULC land from various perspectives.

Chapter 6 is a follow-up work of the previous chapter for research question (iii). Cases of regencies in Kalimantan, a carbon loss hotspot, were studied to understand the key factors for mobilising ULC land via narrative interviews with a range of local land-use actors. Oil palm, as the major commercial crop in Kalimantan, was given extra attention. As an example, one of the key factors, labour availability was further analysed for its limiting effect on mobilising ULC land.

This thesis was finalised with a summary and conclusions in **Chapter 7** that highlighted the main findings from Chapter 2 to 6, answered the research questions, drew conclusions and gave recommendations for research and policymaking.

Table 1-1. Overview of geographical focus and research questions addressed in each chapter.

#	Key elements and features	Geographical focus	Research questions		
			i	ii	iii
2	Biomass flow analysis, Interviews, Surveys	The Netherlands	●		
3	Detailed literature review of the key methodological factors of linking consumption with CSC-LUC and benchmarking 12 quantitative studies on Indonesian palm oil	Indonesia		●	
4	Methodology development to quantitatively link CSC-LUC to consumption	Global and regional	●	●	●
5	Assessment of different domains for monitoring and evaluation of under-utilised low carbon land resources, data processing and analysis, GIS analysis, Interviews	Indonesia (Kalimantan)			●
6	Identification of opportunities and barriers for mobilising under-utilised low carbon land resources through primary data collection from field trips, interviews, labour availability analysis	Indonesia (Kalimantan)			●

CHAPTER 2

Monitoring sustainable biomass flows: General methodology development

Authors:
Chun Sheng Goh
Martin Junginger
André Faaij

"Whatever you do, do *not* think of an elephant." --- George Lakoff

ABSTRACT

Transition to a bio-based economy will create new demand for biomass, e.g. the increasing use of bioenergy, but the impacts on existing markets are unclear. Furthermore, there is a growing public concern on the sustainability of biomass. This study proposes a methodological framework for mapping national biomass flows based on domestic production-consumption and cross-border trade, and respective share of sustainably-certified biomass. A case study was performed on the Netherlands for 2010-2011, focusing on three categories: (i) woody biomass, (ii) oils and fats, and (iii) carbohydrates. In 2010-2011 few major shifts were found, besides the increasing biofuel production. The share of sustainably-certified feedstock is growing in many categories. Woody biomass used for energy amounted to 3.45 MT, including 1.3 MT imported wood pellets (>85% certified). About 0.6 MT of oils and fats and 1.2 MT (estimation) of carbohydrates were used for biofuel production. It is assumed that only certified materials were used for biofuel production. For non-energy purpose, more than 50% of woody biomass used was either certified or derived from recycled streams. Certified oils have entered the Dutch food sector since 2011, accounted for 7% of total vegetable oils consumption. It is expected that carbohydrates will also be certified in the near future. Methodological challenges encountered are: inconsistency in data definitions, lack of coherent cross-sectorial reporting systems, low reliability of bilateral trade statistics, lack of transparency in biomass supply chains, and disparity in sustainability requirements. The methodology may be expanded for future projection in different scenarios.

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Keywords: Bio-based economy; Monitoring; Biomass; Sustainability; Trade; Certification.

2.1 INTRODUCTION

Over the years, many countries have shown a growing interest in and ambition for the transition to a bio-based economy, i.e. increasing the use of biomass to substitute fossil fuels and materials. The term 'bio-based economy' is broadly used to describe economic activities that utilise bio-based materials and products, either in raw form, intermediates or finished products (hereafter referred to as 'biomass') for non-food purpose alongside food and feed application (Meester et al. 2013, see Figure 2-1). This could create new demand for biomass resources, which has already been reflected in the increasing production and trade of biomass for energy use over the last few years. Biodiesel, bioethanol, and wood pellets currently constitute the large majority of these international trade flows (Goh et al. 2013a, Lamers et al. 2011). Minimizing negative impacts of producing and utilizing biomass has become increasingly important. As a response to the public's concerns, biomass producers from the private sector as well as governmental and non-governmental organizations (NGOs) have initiated various efforts to define criteria for 'sustainable biomass production and utilization'. In recent years, dozens of biomass and biofuel sustainability certification and verification systems have been developed or implemented by a variety of private and public organizations (Goh et al. 2013b, van Dam et al. 2011). These systems may cover biomass production sectors (e.g. forests, agricultural crops), bioenergy products (e.g. wood fuels, ethanol, biodiesel, electricity), and whole or segmental supply chains (e.g. production system, chain of custody from growers to energy consumers).

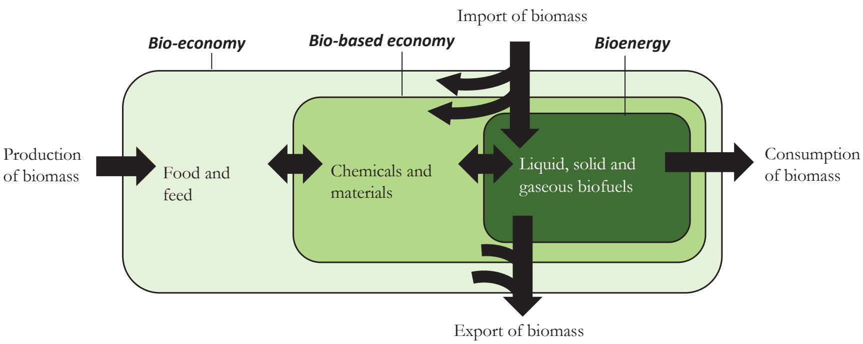

Figure 2-1. The broad framework of a bio-based economy (adapted from Meester et al. 2013).

A bio-based economy involves diverse forms of raw materials, intermediates, products, and by-products that go through different processes in different sectors, and flow in two dimensions, i.e. domestic and cross-border input and output. Understanding biomass flows is considered to be of high importance for the following reasons. First, a clear mapping of biomass flows is essential for policymakers in introducing a bio-based economy in multiple sectors. Due to the complexity of existing biomass flows, the potential and risks of switching to a bio-based economy are still unclear, such as direct and indirect substitution effects in supply chains. Shifting biomass from their original capacity to other purposes (e.g. for energy use) will directly and/or indirectly alter existing biomass flows (both intranational and international), possibly leading to increased utilization of other biomass to fill the demand gap created in the original sectors. Second, monitoring and quantifying international sustainable certified biomass flows is crucial in the context of global climate change policies. There is a need to distinguish biomass certified with sustainability schemes for greenhouse gas (GHG) emission analysis. This is complicated with the mushrooming of sustainability certifications and labels which have different scopes and purposes and are unevenly applied across sectors and along supply chains.

Capturing and mapping biomass flows is always fraught with difficulties, as both directions and quantity of many biomass flows are rarely entirely clear and may also change from year to year. A number of studies on cross-border bioenergy trade flows have been conducted (Lamers et al. 2011, Lamers et al. 2012, Sikkema et al. 2011), but these studies did not assess the mass flows within the countries. In this regard, a monitoring body, usually an industrial association, a governmental agency, or a non-profit institution, covers more detail of the products' mass flows within the country or region. However, these activities usually lack information on cross-sectoral flows. Knowledge of relevant cross-market mechanisms and trade flows is relatively limited. Recent studies by Heinimö (2008) and Kalt and Kranzl (2012) reported on the direct and indirect trade of both wood-based fuels and non-fuel products, taking Finland and Austria as case studies, respectively. However, other important biomass categories like oils and fats and carbohydrates are inadequately addressed.

On the other hand, a comprehensive quantitative inventory of sustainable certified biomass flows for a variety of end-uses is currently absent from the sustainability discussions. Often there are reports on the production by certification bodies (e.g. FSC, RSPO) that do not involve trade directly but focus more on the production side. On the consumption side, reporting of liquid and solid biofuels leads in this respect, but until 2012 only a few countries had annual reporting systems that indicate volume and origins of the biofuels used and corresponding sustainability schemes employed. Goh et al. (2013b) examined trade flows and market development of certified solid and liquid biofuels taking the forerunners in biofuels certification, i.e. the UK and the Netherlands as two case studies. Again, these reports did not intend to cover cross-market monitoring.

The main goal of this study is to propose a methodological framework for monitoring and mapping biomass and bioenergy by quantifying both cross-border trade and domestic cross-sectoral flows, and examining the share of sustainable certified biomass in different markets, taking 'country' or 'trade block' (e.g. the EU) as the base unit. To demonstrate the framework, a first quantitative assessment of sustainable biomass and bioenergy flows in the Netherlands was carried out as a case study. Due to limited domestic biomass resources, the Netherlands is competitive in biomass trade with its leading ports, traders, logistics, and market systems. Similar to other manufacturing industries, the Dutch biomass industry relies heavily on secondary processing and trade in both directions. However, domestic agricultural products also contribute a significant share to the market. The Netherlands is also the forerunner in promoting sustainability certification of biomass and bioenergy. Furthermore, data availability seems high for the Dutch case with various monitoring systems and statistics in the country. Therefore, the country is considered a suitable example to illustrate its intra- and international sustainable certified biomass flows using the proposed methodological framework. A number of countries also possess similar characteristics, such as Belgium and the UK.

This paper describes the methodology underlying this study and then presents the setting and results of the case study. It includes methodological discussion, conclusions, and recommendations.

2.2 METHODOLOGY

2.2.1 Scope of study

In view of the large diversity in biomass, this study limited the scope to three main categories: (i) woody biomass, (ii) oils and fats, and (iii) carbohydrates. Woody biomass includes timber, wood products, paper and cardboard, wood fuels, and their waste streams. Oils and fats include oil seeds, vegetable oils, animal fats, and biodiesel. Carbohydrates include grains, starch, sugars, and a possible connection to bio-ethanol. Only biomass that falls under these three categories was investigated. This selection was based on three characteristics:

- They are relatively large streams with a clear distinction compared with other biomass groups.
- They are relevant to the bio-based economy – they are either long-chain polymers (such as starch and lignocellulose) or high-quality monomers (such as fatty acids and sugars) and have high potential to substitute fossil materials.
- They are closely related to bioenergy carriers – wood pellets, biodiesel, and bioethanol (also considering their large share in waste streams that may end up in energy production).

The other biomass categories with large volumes in the Dutch economy, for example flowers, vegetables, fruit, meats, and processed food are not included in the case study. Nevertheless, waste streams from this biomass might be significant as bioenergy carriers. Data about this organic biomass in municipal waste streams usually can be derived at a highly aggregated level. However, the framework can also be expanded to the other biomass categories based on the three criteria. For example, agriculture residues could be very relevant to countries with a large agriculture industry, such as Malaysia and Indonesia.

2.2.2 Building mass flow diagrams

The framework consists of three dimensions: (i) cross-border input and output (import and export), (ii) domestic input and output (production and consumption), and (iii) share of sustainable certified biomass. The results are presented in the form of mass flow diagrams. The mass flow diagrams were built in three steps:

Step 1: Creating biomass chains and sustainability certification schemes inventory. First, an inventory of biomass supply chains was created. This inventory should cover in as much detail as possible inputs of raw materials to secondary, tertiary, end users and finally releases of materials to the environment. Sustainability certification schemes applied to these chains were also identified based on literature reviews.

Step 2: Setting system boundaries. Due to the relatively broad aims, this monitoring framework is unlikely to cover the whole life cycle, but largely depends on data availability and feasibility. It should be noted that the boundaries may change with time as the industry is developing rapidly. The system boundaries for the three selected categories were set at different degrees. For woody biomass, the flows of materials could be identified more clearly due to consistent chemical composition in the stream (little or without chemical processing), and therefore near to full life cycle of the biomass can be illustrated (from raw wood to combustion). For oils and fats, the end-uses were identified as for human consumption, animal consumption, for technical purposes, and for energy use. For carbohydrates, the biomass was assumed to be mostly consumed as food and feed, and therefore no further categorization was made.

Step 3: Quantitative analysis. In the final step, each flow was quantified in as much detail as possible. An overview of data sources are presented later. First, each mass flow was examined quantitatively in both dimensions (i) and (ii). The flows of the three selected categories are presented in three different mass flow diagrams. The diagrams consist of two pairs of axes, where the top and bottom axes indicate import and export, and the left and right axes indicate domestic input and output of the chain. All streams were drawn in ratio to their actual volume. For countries with huge transhipment volume due to their trading hub nature, such as the Netherlands, net trade balances (i.e. net import and export excluding transhipment) can be used to improve the visualization of mass flows. Finally, dimension (iii) was also assessed quantitatively in as much detail as possible.

2.2.3 Overview of data sources: availability and quality

Data quality is the main factor that determines the reliability of the analysis and therefore needs to be defined explicitly. As no single data source covers all required information, various data sources were identified and evaluated. When more than one source available was available, data was selected based on the following order:

Own data collection directly from the market actors: In some extreme cases, when reliable data of certain important biomass streams is not available anywhere, data can only be collected directly from industry in the form of surveys and interviews. Direct information collected from the industry is regarded as the most reliable first-hand source of information. However, many companies tend to withhold trade information to protect their business interests. Own data collection is considered the most time-consuming and difficult way, and it is only carried out when the particular flow is of very high importance (i.e. have high potential to substitute fossil fuels and/or materials) and other data sources are not available.

Monitoring bodies and general statistics portals: The core data contributors are usually monitoring bodies and general statistics portals. A monitoring body can be a governmental department or agency, an industrial association, or a non-profit institution that monitors the products' mass flows within the country or region. Some countries may have official general statistics systems that gather data from these monitoring bodies and/or directly from the industry. However, in this methodological framework, trade statistics collected at customs are separated as another category. The difference between these two sources can be viewed from two aspects: coverage and nature. Trade statistics portals capture trade flows at trading hubs, such as seaports, mainly at international level. Meanwhile monitoring bodies and general statistics portals may cover the flow of raw materials in secondary processing, post-processing and post-consumption (i.e. waste and residues) within a country or region. In terms of data nature, trade statistics are normally actual physical data (often the monetary values of physical goods) gathered directly from trading hubs, while monitoring bodies and general statistics portals may have various reporting systems that collect data for administrative purposes which do not necessarily equal the actual flows at a particular time due to various administrative reasons. A noticeable example is the consumption data of liquid biofuels that are reported in the EU to fulfil mandates. This kind of 'administrative data' has a policy dimension in the context of carbon mitigation policies, and therefore has a priority in data selection when there are discrepancies between data sources. An inadequacy of this data source is that a monitoring body usually has a very specific scope and interest in certain biomass or specific products, and seldom covers cross-sectoral flows.

Trade statistics portals: Trade statistics portals cover a large range of products categorized using combined nomenclature (CN) codes. Table S2-1 in the Supplementary materials lists CN codes for woody biomass, oils and fats, and carbohydrates. A number of studies on bioenergy trade flows have been conducted mainly using trade statistics (Heinimö 2008, Kalt and Kranzl 2012, Lamers et al. 2011, Lamers et al. 2012, Sikkema et al. 2011). This type of effort is often fraught with difficulties in differentiating the actual flows given that a number of different trade codes may be applied to similar products based on small differences in product nature, but they do not differentiate the end-uses of the materials explicitly. For example, ethanol can be imported under several different CN codes in different forms and blending levels, but it is not known how much has actually been used for energy purposes. Nevertheless, the CN system has been continuously improved; for example a new code has been introduced for energy pellets in recent years. Another weakness is that there are significant discrepancies between bilateral trade statistics reported by exporting and importing countries due to differences in timing, level of details, and classification (Sikkema et al. 2011, Wang et al. 2010). In this work, data reported by the case study country was given priority, to ensure a consistent set of data was used when trade flows were linked to biomass flows within the country.

Mass balance deductions: This category is placed at higher order than (v) when the base data comes from (i), (ii) and (iii). Volume of certain streams such as by-products, waste, and recycling streams can be deducted through mass balance calculations. Indicators from scientific literature can be used to complete the calculations. An example is the use of ratio method in derivation of glycerol flows, using the ratio of glycerol to monoalkyl esters proposed by scientific literature.

Fragmented data, assumptions, and data aggregation: Data may also be found scattered in many public available sources, such as press releases, news, reports by companies, or other organizations, and scientific literature. These pieces of information mostly come in fragments, and lack comprehensive descriptions and definitions. To complete the picture, assumptions can be made based on information fragments, related facts, extrapolation or interpolation, and other appropriate ways. For example, the sustainable share of certain biomass streams in the Dutch market might be assumed to be equal to that of the European market, as the country possesses the largest trading hub in Europe with a very active and complex intra-European trade, making identifying the final destination of sustainable products extremely difficult. The drawback of this data source is that it often lacks scientific justification and consistency, and therefore it is ranked lower. Ultimately, if there are still some missing details in the mass flow diagram, streams or part of the chain that data is not available for at a high level of detail can be merged to increase the efficiency of the study. For example, paper and cardboard were not separated into individual streams but considered as one general product group, as the specific type and volume of paper and cardboard recycled or combusted is unknown. Besides, streams with less distinction and small volumes, such as different forms of wheat powder, can also be grouped together to improve visualization. However, the conditions might change from one case study to another, depending on specific objectives.

This list shows that there are many discrete analyses and data available, but mostly in different forms, and not every single biomass flow is monitored. The main idea of this framework is to overcome these challenges by matching all data together, supplementing each one to illustrate the big picture of biomass flows. When there is more than one set of data available, only data with the highest rank is used. Harmonization of data should be performed to ensure a consistent set of metrics when data comes in different units, such as volume, mass, energy, and monetary values. Table S2-2 shows the conversion factors for biomass, as well as moisture contents. All units should be harmonized to a consistent unit to give meaningful comparisons, for example million tonnes (MT) in this study.

2.3 RESULTS

2.3.1 Case study setting

Table 2-1 lists the data sources employed in this case study, while more details of data sources for biomass streams are shown in Table S2-3 in the Supplementary materials.

Table 2-1. Data sources for this case study.

	Sources	Woody biomass	Oils and fats	Carbohydrates
i	**Own data collection directly from the market actors**	Wood pellet buyers	–	–
ii	**Monitoring bodies and general statistics portals**	Probos	Product board Margarine, Fats, Oils (MVO);	–
			Task Force of Sustainable Palm Oil, Sustainable Trade Initiative (IDH);	
			Liquid biofuels - Dutch Emission Authority	
		Waste - Afval database van Agentschap NL; General - Central Bureau of Statistics of the Netherlands (CBS)		
iii	**Trade statistics portals**	The Netherlands: Central Bureau of Statistics of the Netherlands (CBS); EU level: EUROSTAT; International level: FAOSTAT; UN COMTRADE; USDA Foreign Agricultural Service		
iv	**Mass balance deductions**	Derivations from the other sources		
v	**Fragmented data, assumptions, and data aggregation**	Various sources like press releases, news, reports by companies or other organizations, and scientific literature		

Note: See details for each stream in Table S2-3 in Supplementary materials.

2.3.2 Quantitative mass flows

Woody biomass. Figure 2-2 illustrates the flows of woody biomass in the Netherlands in 2010 and 2011. The moisture content may vary depending on humidity and therefore it is neglected in this study (Table S2-2). In the middle of the diagram there is a box indicating wood products, which represents the storage of woody biomass in the form of buildings, furniture, and other types of wood products that are non-consumable or not short-lived. In 2010 and 2011, the Netherlands produced considerable amounts of round wood, but about half of that was exported. On the other hand, a relatively large amount of sawn wood and wood panels was imported, mostly originating from adjacent countries. There were also significant imports of paper and cardboard into the Dutch market. A large amount of wood pellets was consumed in utilities. About 90% of wood pellets were imported. A considerable amount of woody biomass and paper and cardboard was incinerated to generate electricity and heat. Overall mass flows did not change much in 2010-2011.

Figure 2-3 shows the share of sustainability certified woody biomass in the Netherlands in 2010 and 2011. The use of woody biomass can be divided into two main markets based on end-use:

- **Non-energy use**: The market share of certified wood products (sawn wood and panels) for non-energy use increased from 33.5% in 2008 to 65.7% in 2011 (23.7% FSC certified and 42% PEFC certified). In 2011, sawn softwood recorded the highest certified percentage: 86% of the market volume (46% in 2008), as most of this sawn softwood came from countries where 60–97% of the forest area was certified. About 57% of the certified sawn timber and 73% of the certified wood based panels was consumed by the construction sector and civil engineering. On the other hand, the share of certified paper and paperboard in the Dutch market has increased to 32.8% in 2011 (Oldenburger et al. 2011). Most of the paper and cardboard consumed in the Netherlands was separated for recycling purposes. However, there was still a large portion of woody biomass and paper and cardboard that could not be separated and ended up in waste incineration.
- **Energy use**: A significant change between 2010 and 2011 would be the increase of certified woody biomass for energy purpose. In 2011, most of the wood pellets were certified with sustainability schemes. Figure 2-4 shows the origins and the share of sustainable certified biomass used by utilities. Most of the certified wood pellets came from Canada, the USA, the Baltic States, Russia, and southern Europe. However, still more than one-third of wood pellets from Western Europe were not certified. There are a few industrial sustainability schemes currently available for solid biomass, particularly for wood pellets, but many of them primarily serve the companies which developed them, such as Green Gold Label and Laborelec Label. New systems, such as NTA 8080 and ISCC PLUS, were not yet being widely applied. In the last few years, industrial pellet buyers (mainly utilities) have been working together to develop a harmonized sustainability system for wood pellets, namely IWPB[2].

Table 2-2 shows the market share of sustainability schemes in each selected categories in the Netherlands. It is expected that the share of certified wood products will grow steadily. The recent focus in this category is the energy use of woody biomass by utilities, particularly wood pellets. In 2011, the percentage of certified pellets in the market was very high (almost 90%), dominated by Green Gold Label (51.8%) and Laborelec Label (33.5%).

2 IWPB is a working panel grouping the major European utilities firing wood pellets in large power plants GDF SUEZ, RWE, E.On, Vattenfall, Drax Plc, and Dong, as well as certifying companies SGS, Inspectorate, and Control Union. Laborelec participates in this work panel as a technical expert. Available at http://www.laborelec.be/ENG/initiative-wood-pellet-buyers-iwpb/

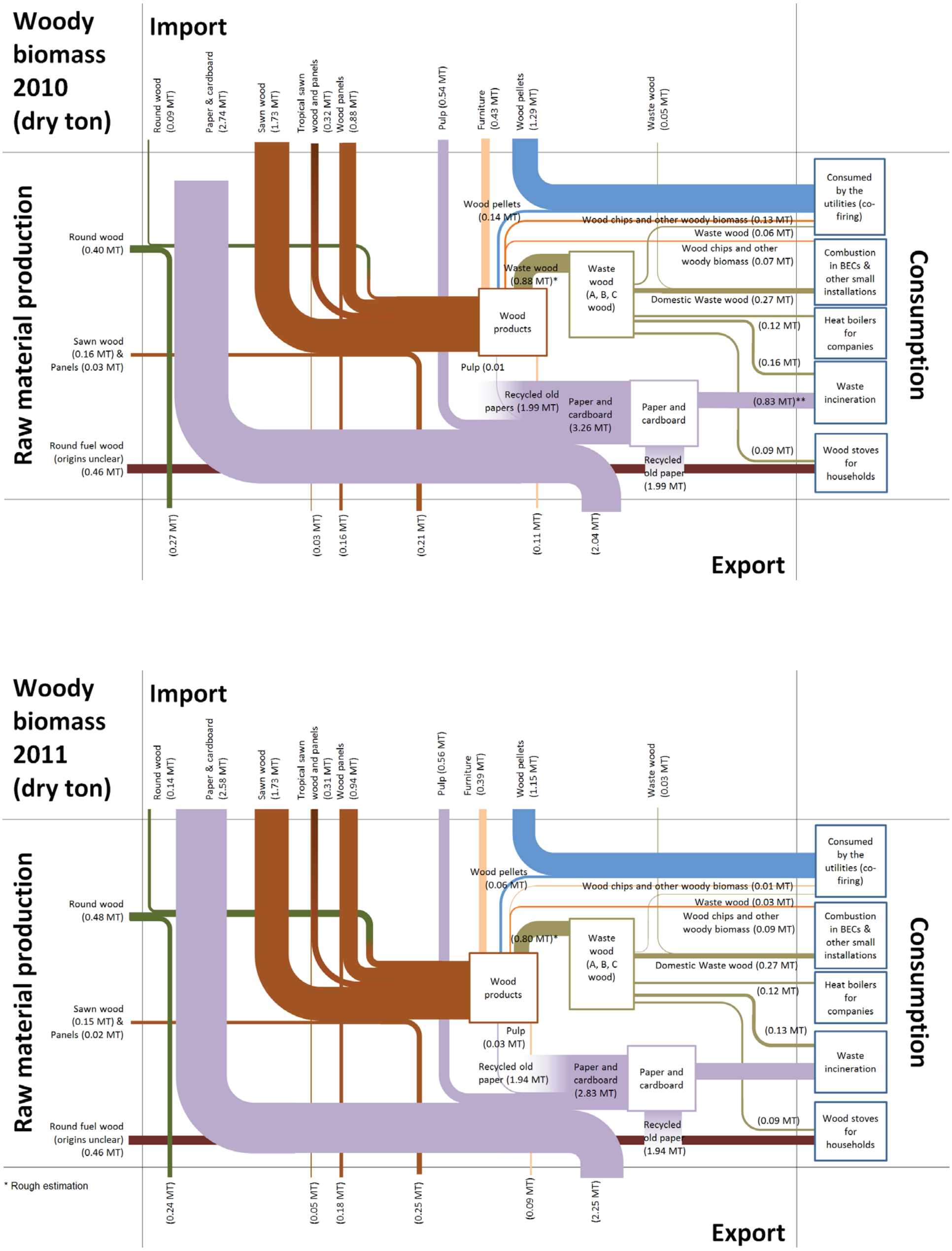

Figure 2-2. Mass flow diagram of woody biomass in the Netherlands in 2010 and 2011.

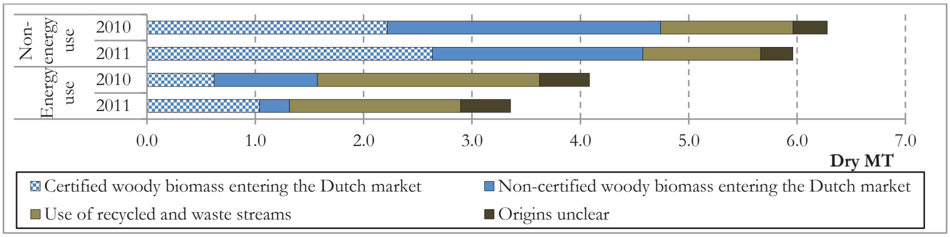

Figure 2-3. Use of certified, non-certified, recycled and waste woody biomass in the Netherlands.

Table 2-2. Market share of sustainability certification schemes in the Netherlands in 2011.

Type of biomass	Sustainability schemes	Market share (% of certified biomass per particular products group in the market)
Woody biomass: Sawn timber and wood based panels (Oldenburger et al. 2012)	FSC	23.7%
	PEFC	42.0%
Woody biomass: Paper and cardboard (Oldenburger et al. 2012)	FSC	23.9%
	PEFC	8.9%
Woody biomass: Wood pellets used by utilities (Self collection)	Green Gold Label	51.8%
	Laborelec Label	33.5%
Oils and fats: Total vegetable oils (The Dutch Taskforce Sustainable Palm Oil 2012, RTRS 2013)	RSPO (Palm oil)	6.7%
	RTRS (Soy bean)	0.3%
Carbohydrates: Grains	VVAK	Starts in 2012/13
	Stichting Veldleeuwerik	Starts in 2012/13
Biodiesel (NEa 2012)	ISCC	48.4%
	2BSvs	4.9%
	RTRS	1.8%
	Others	9.6%
		The rest is double counting or unknown
Bioethanol (NEa 2012)	ISCC	84%
	RBSA	4%
	Others	12%

FSC: Forest Stewardship Council.
PEFC: The Programme for the Endorsement of Forest Certification.
VVAK: Voedsel- en Voederveiligheid Akkerbouw.
RSPO: The Roundtable on Sustainable Palm Oil.
RTRS: The Round Table on Responsible Soy.
ISCC: International Sustainability and Carbon Certification.
RBSA: The RED Bioenergy Sustainability Assurance Standard.

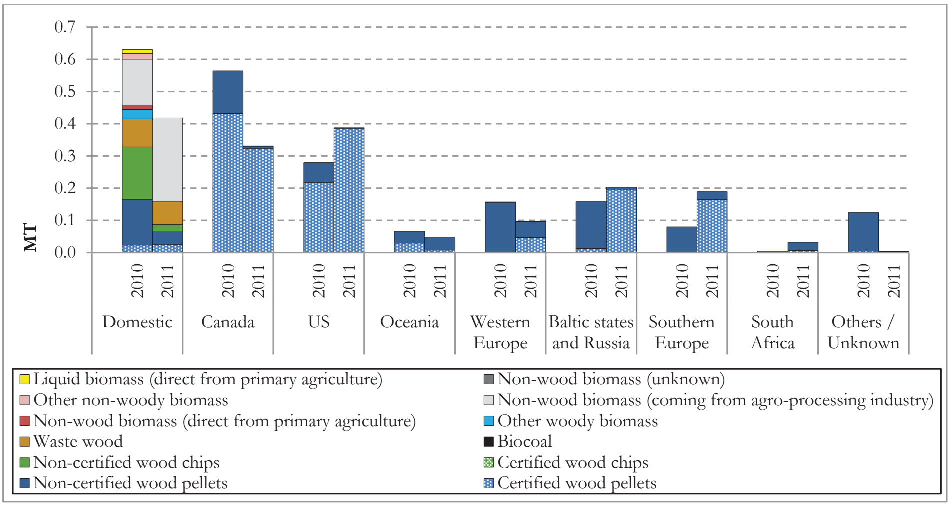

Figure 2-4. Biomass co-fired in the Dutch utilities in 2010 and 2011 (Source: Surveys with the utilities; Essent 2010).

Oils and fats. Figure 2-5 shows the mass balance for oils and fats flows in the Netherlands in 2010 and 2011. Different from woody biomass, the top and bottom axes indicate net trade instead of actual volume, to avoid the diagram becoming overcrowded with the large volume of vegetable oils transhipment. As shown in Figure 2-4, soybean has the largest mass flow in this group. Strictly speaking, soy is not primarily an oil crop but used mainly as a protein source. Therefore, a relatively small portion of oil was produced while most of the mass remained as meal after processing, mainly used as animal feeds. Palm oil was the largest oil source followed by rapeseed oil, soy oil and sunflower oil. Human consumption was the most important application of vegetable oils, recording ~67% in 2011, while ~17% was used for energy purpose, ~11% for animal consumption, and the rest for technical purposes. Rapeseed oil contributed the largest share in biodiesel production. From 2010 to 2011, there were no dramatic changes in the net flows of oil seeds and vegetable oils, but substantial increase in animal fats import owing to increasing demand for biodiesel in 2011. Production of biodiesel from these streams was favoured due to the double counting mechanism[3] (Goh et al. 2013b).

3 The double counting mechanism is generally applied for biofuels produced from wastes, residues, non-food cellulosic material, and lignocellulosic material. These biofuels are counted double for the annual obligation of renewable transport fuels.

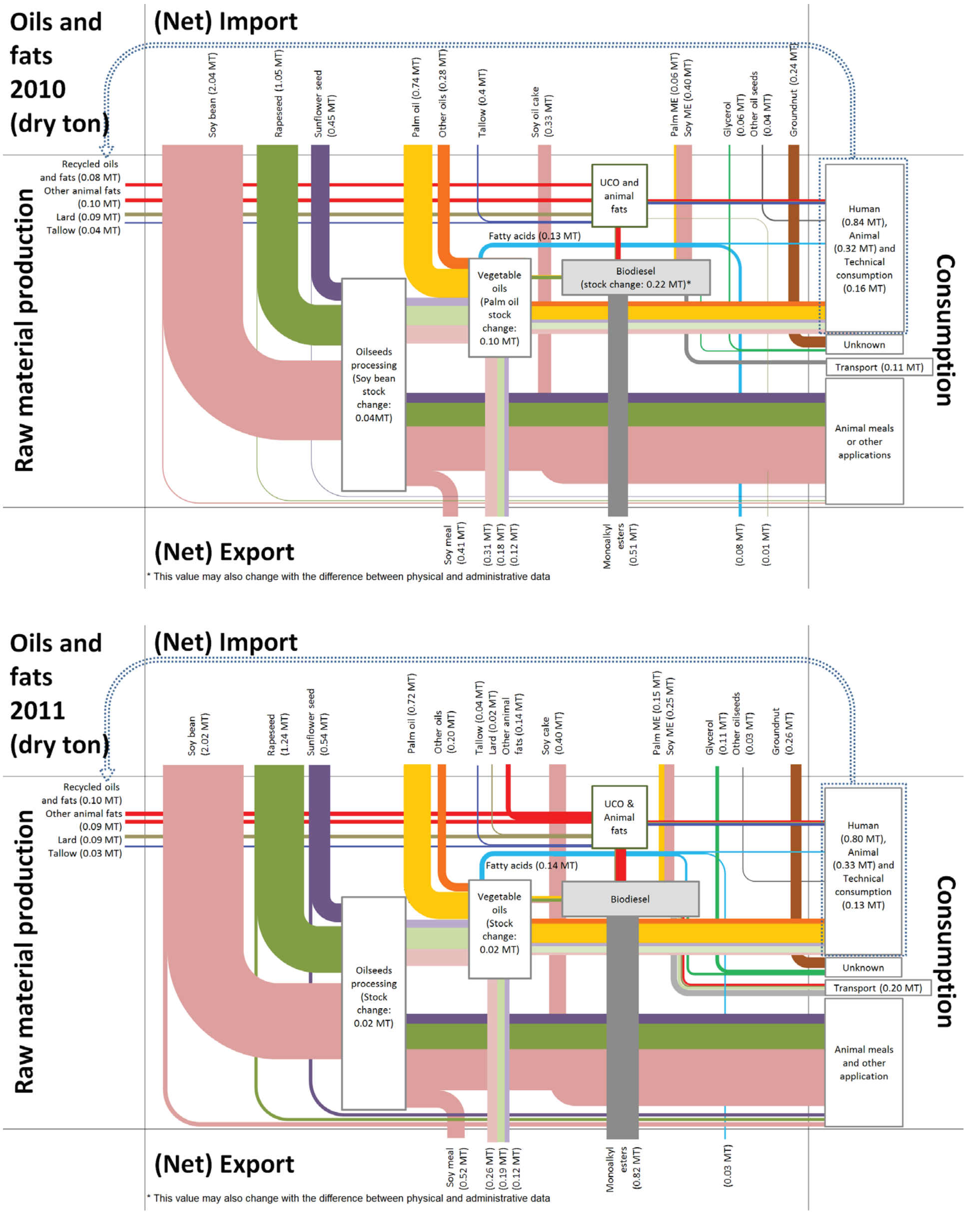

Figure 2-5. Mass flow diagram of oils and fats in the Netherlands in 2010 and 2011.

Figure 2-6 illustrates the consumption trend of oils and fats for different purposes since 2008. In the Netherlands, production companies have an obligation to provide these data to Product Board for Margarine, Fats and Oils (MVO). A steady increase was observed in the total consumption volume, mainly attributed to the increasing energy use of oils and fats, i.e. biodiesel production.

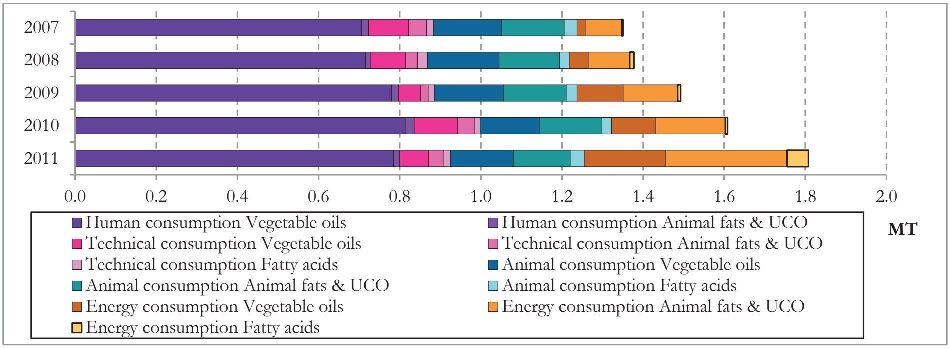

Figure 2-6. Consumptions of oils and fats for different purposes in the Netherlands (Source: MVO 2012) (Note: Animal fats include UCO).

Figure 2-7 depicts the trade balance of oil seeds and oils and fats by country or region. Net import of oil seeds reached the lowest in 2009 but bounced back in 2011. On the other hand, trade volume of oils and fats has been decreasing since 2008. Over the last few years, Brazil and the USA were the main suppliers of soybean, while Malaysia and Indonesia were the biggest suppliers of palm oil to the Netherlands. However, it was not entirely clear where the sustainable certified vegetable oils come from. Significant palm oil certified by RSPO and soybean certified by RTRS entered the Dutch market only in 2010/2011. However, the industrial players have set ambitious targets to completely shift to certified palm oil and soybean within a few years. On the other hand, starting from 2011, the Dutch government accepts only biofuels certified with sustainability schemes accepted by the Dutch government or originated from waste.

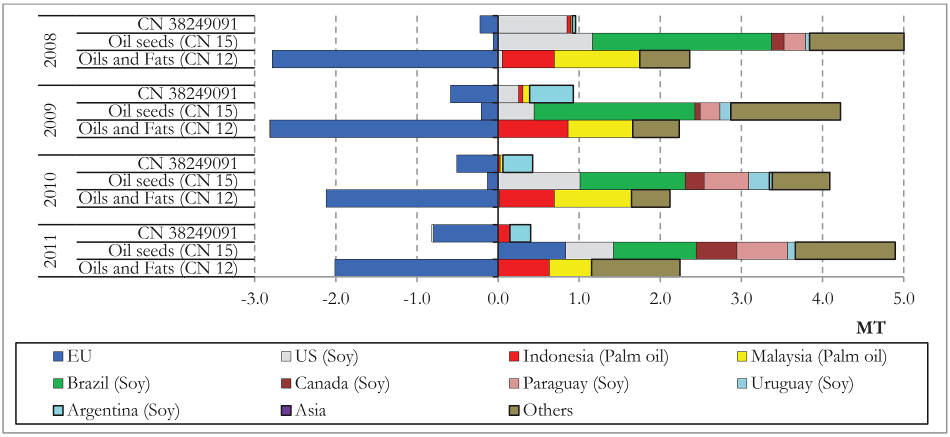

Figure 2-7. Monoalkyl esters, oil seeds and oils and fats trade flows (net by regions) for the Netherlands from 2008 – 2011 (Source: CBS 2013).

Figure 2-8 shows the use of certified and non-certified vegetable oils, used cooking oil (UCO) and animal fats, and fatty acids in the Netherlands. To some extent, the year 2011 can be regarded as the starting year for the significant use of sustainable certified vegetable oils in the Dutch market. In 2011, the Dutch food and feed industry imported the first batch of RTRS certified soybean, amounted to 85 ktonnes (RTRS 2013). Many Dutch food manufacturers also started to import RSPO-certified palm oil with ambitious targets in the next few years. The Dutch Task Force Sustainable Palm oil (2012) reported that 21% of total palm oil consumed for food purpose (about 81 ktonnes out of 385 ktonnes) in the Netherlands in 2011 was sustainable certified. It should be noted that an assumption was made in Figure. 7 that all vegetable oils used for biodiesel production in the Netherlands were 100% sustainable certified (including RSPO-certified palm oil which is not accepted by the EC but accepted in the Netherlands to demonstrate sustainability). With this assumption, about one-third of total palm oil and rapeseed oil imported into the Netherlands was sustainable certified. Data for certified vegetable oils used for biodiesel production in 2010 was not available. Since there was no mandatory requirement, it was assumed that all vegetable oils used for energy purposes in 2010 were not certified.

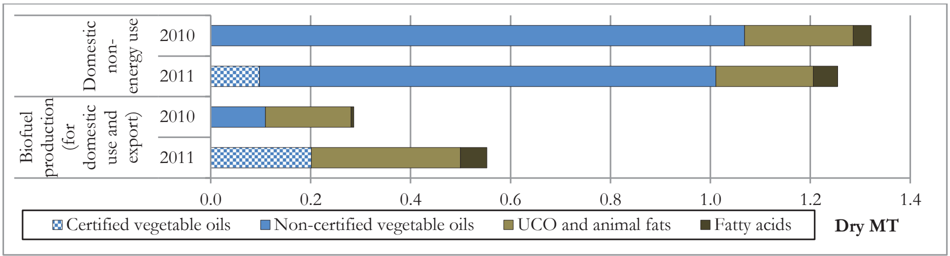

Figure 2-8. Use of certified and non-certified vegetable oils, UCO and animal fats, and fatty acids in the Netherlands.

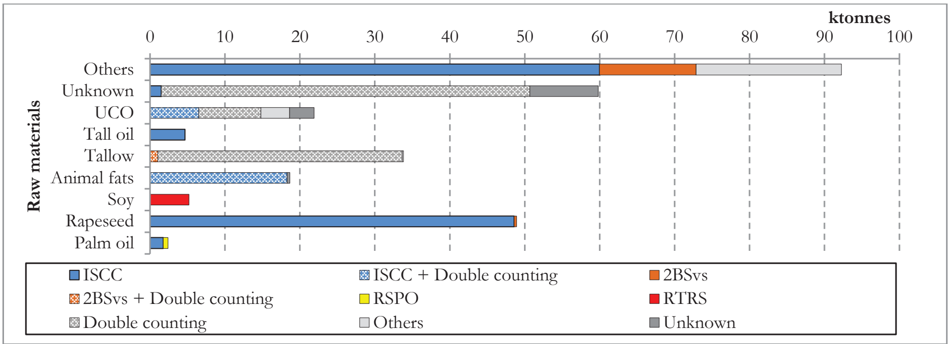

Figure 2-9. Sustainable certified biodiesel consumed in the Netherlands in 2011 by sustainability schemes (Source: NEa 2012a).

Figure 2-9 shows the quantity of sustainable certified biodiesel consumed in the Netherlands in 2011 by sustainability schemes. The total consumption volume amounted to 0.1 MT and 0.29 MT, respectively, in 2010 and 2011. Biofuels consumption in the Netherlands is monitored by NEa. Data for 2010 published by NEa was reported at a highly aggregated level due to a confidentiality agreement with industrial actors (NEa 2011). The nominal share of biodiesel in total Dutch diesel consumption was 4.62% in 2011, but note that this value includes double-counted biodiesel (NEa 2012a). The Dutch biodiesel market relied heavily on double counting, as double-counted biofuels contributed 40% of the compliance with the annual requirement of 4.25% for renewable energy in transportation in 2011. The largest sources of feedstock used were domestic UCO and tallow from Germany. It is unclear whether the 'Unknown' category includes UCO or not, but more than 80% of this category was counted double, and most of the 'Unknown' was reported to have Dutch origin.

Carbohydrates. Carbohydrates are widely used food staples, which can be directly used for food and animal feed, or processed to make food (bread, biscuits), beverages (beer) and feed, or industrial products such as ethanol. In addition to food and feeds, carbohydrates can also be feedstock for textiles, adhesives, and energy. Figure 2-10 illustrates the quantified mass flows of carbohydrates in the Netherlands in 2010 and 2011. Basically the Netherlands was able to self-supply more than half of its total carbohydrates consumption. Other carbohydrates products and sugars (e.g. white sugars) have very little flows. Maize (corn) turned out to be the largest Dutch carbohydrates source. Although the Netherlands produced relatively large amounts of maize, considerable amounts of maize were imported. Potatoes, sugarbeet, and barley were the other important sources of carbohydrates. A significant change in 2011 is that about 1.2 MT of maize and wheat were processed in the Netherlands to produce bioethanol. However, the connection shown in Figure 2-10 was only for indication because the exact feedstock and destination are unknown. Besides bioethanol, it can also be used as feedstock for biogas. About 0.36 MT of maize was fermented into biogas in 2010, but this figure dropped to 0.18 MT in 2011.

Figure 2-11 shows the trend of ethanol trade flows. The major supplying countries were the USA, Brazil, and Guatemala. Net imports from the EU were relatively very low. The import of ethanol under the groups CN 22071000 and CN 22072000 has plummeted since 2008. The main reason lay within the CN code swap of US ethanol. Since 2009, there has been a steep increase in US ethanol entering the EU. These products were found to leave the USA as denatured (CN 22072000) or undenatured ethanol (CN 22071000), but most of those exports entered the EU as chemical compounds (CN 38249097) with lower tariffs. On the EU side (most likely on shore), petrol was added to the ethanol (the percentage of petrol varies between 10 and 15). The problem with CN 38249097 is that it is an 'other' and 'other' category, so the CN code did not clearly state what good was being classified. This means that the ethanol blend might be counted together with other goods. Hence it was difficult to trace back how much ethanol/petrol blends had really entered (NEa 2012a, Vierhout 2013). These operations and imports have happened mainly in the Netherlands, the UK, and Finland. In 2012, these bioethanol blends were reclassified to a higher tariff rate, and trade of ethanol from the USA to Europe slowed dramatically.

However, it was not sure in the long term how this would impact imports from the USA, due to the fact that in 2012 EU domestic production was still insufficient and Brazilian ethanol was more expensive for the EU market (Flach et al. 2012).

For carbohydrates, which differ from woody biomass and oils and fats, there were no specific sustainable certifications over the years, although sustainability schemes were applied to bioethanol derived from carbohydrates. Most carbohydrates consumed in the Netherlands originated from Europe and mostly produced according to the EU's environmental regulations, and therefore the demand for separate sustainability certification was not so strong (the focus was on the other concerns, such as organic food labels). In recent years sustainability has been an important consideration in the Dutch food industry, and included in the procurement policies of many food companies. Companies generally purchased sustainable supplies through bilateral agreements by providing suppliers with a set of rules and criteria to follow. However, in 2012, there were efforts to put sustainability certification on Dutch grains (more precisely on farming practices), namely VVAK and Stichting Veldleeuwerik (NEa 2012b, Veldleeuwerik 2013) It is expected to see some sustainable certified grains in the Dutch market in the near future. For the energy use of carbohydrates, bioethanol derived from carbohydrates was mainly imported. Similar to biodiesel, starting from 2011, only sustainable certified bioethanol enters the Dutch market. In addition to the co-digestion of maize, small-scale biogas production from potatoes was also observed in the Netherlands under the Green Deal, but the involvement of certification schemes is not expected in the near future.

Figure 2-12 illustrates the Dutch bioethanol consumption in 2010 and 2011 by schemes. Differing from biodiesel, which has a diverse source of feedstock and origins, the majority of the bioethanol consumed in the Netherlands originated from US maize. Maize ethanol dominated with about 40% and even 90% of market share in 2010 and 2011, respectively. This was followed by ethanol made from Brazilian sugarcane and French wheat, but in 2011 both streams plummeted drastically. This was mainly because the Brazilian domestic bioethanol market had absorbed most of the Brazilian sugar cane ethanol. Meanwhile the decrease of French wheat ethanol was probably caused by bad harvest in 2011 – feedstock price was high and production of bioethanol from cereal was less attractive (Flach et al. 2012, Knight 2012). The Netherlands may continue to become a hub for biofuels blending and further distribution, as well as production since its large seaports provides easy access to feedstock. Abengoa Bioenergy's bioethanol plant in Rotterdam can produce 480 million liters of bioethanol annually from 1.2 MT of maize or wheat cereal as feedstock. It also produces 0.36 MT of distilled grains and solubles (DGS) which can be used as animal feed (Abengoa Bioenergy 2013). On the other hand, in 2012, Cargill also added 380 million liters of annual starch-based ethanol production capacity to its wheat wet-mill in Bergen op Zoom. The facility can process 0.6 MT of wheat annually (Ethanol Producer Magazine 2012). Unfortunately, it is not publicly known where they source the raw materials and where they supply the bioethanol to.

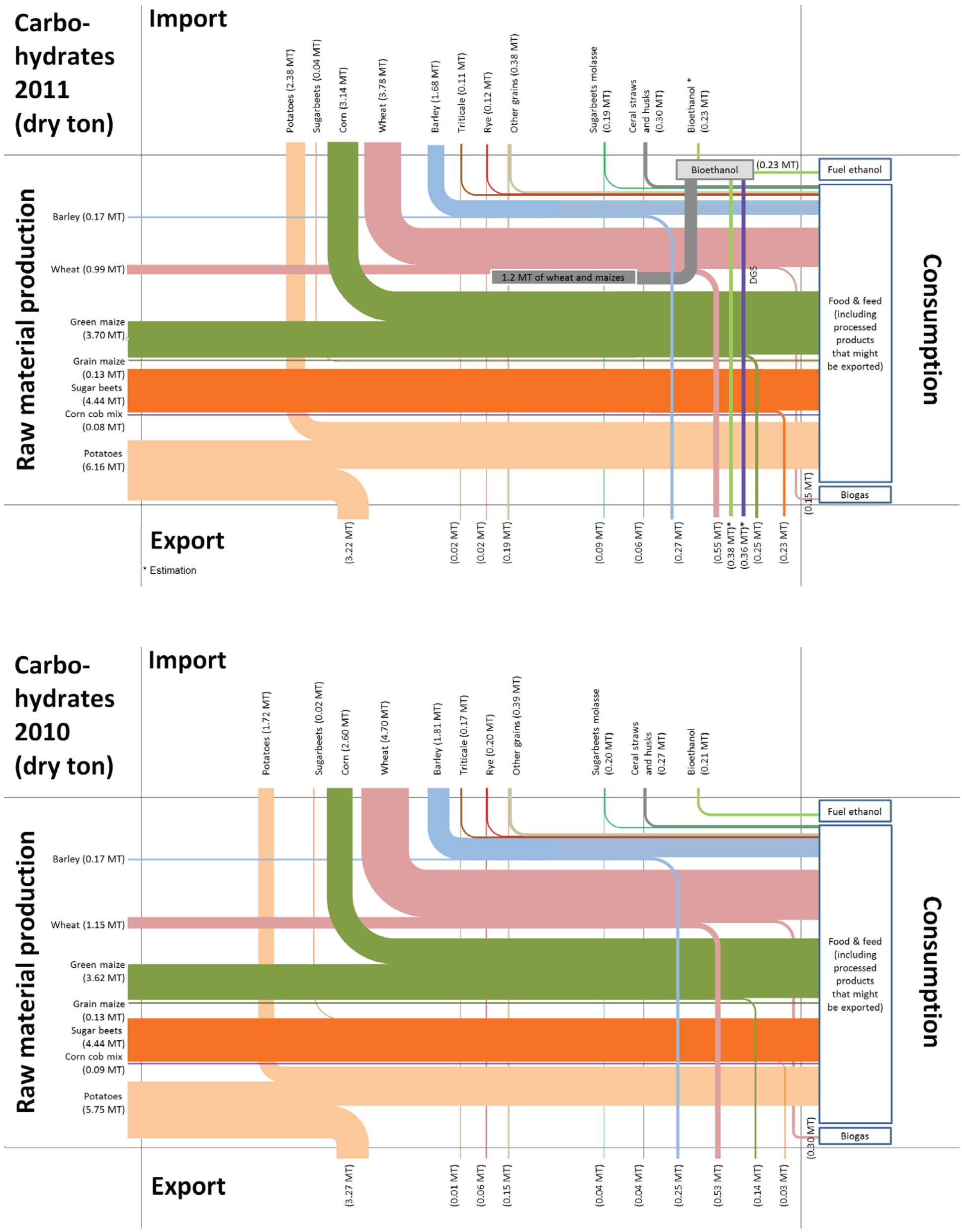

Figure 2-10. Mass flow diagram of carbohydrates in the Netherlands in 2010 and 2011.

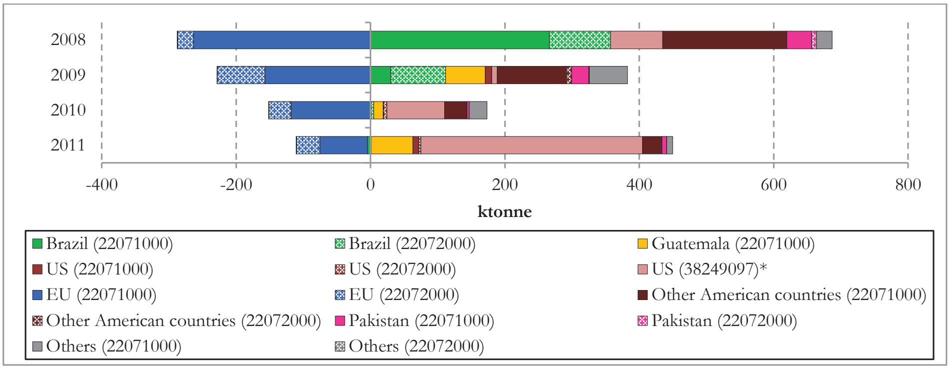

Figure 2-11. Ethanol trade balances (net) of the Netherlands for 2008 – 2011 (Source: CBS 2013).

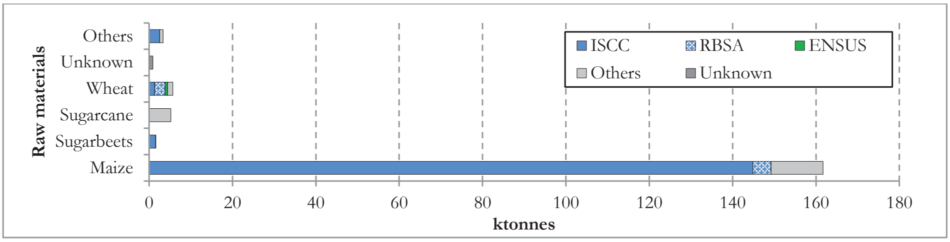

Figure 2-12. Sustainable certified bioethanol consumed in the Netherlands in 2011 by schemes (Source: NEa 2012a).

2.4 DISCUSSION, CONCLUSIONS, AND RECOMMENDATION

2.4.1 Case study summary

Woody biomass. As the use of woody biomass for energy purpose is getting more important in the Netherlands, a number of monitoring activities have been carried out. Among the woody biomass streams, the large-scale use of wood pellets by power companies is easier to monitor due to its large volume and small number of users. Furthermore, starting from 2013, there will be a mandatory reporting system on the sustainability of biomass used for large-scale energy generation through the Green Deal agreement between the government and the power companies (Biobased Economy Magazine 2013). However, it seems more difficult to assess the other streams due to the lack of proper reporting systems (smaller and more complicated flows), especially the waste wood streams. The measurement of municipal waste streams composition is also outdated and less reliable. In terms of sustainability assessment, the share of certified woody biomass for non-energy use is only known for 2008 and 2011, given the fact that the market study performed by Probos is not continuous (Oldenburger et al. 2011). Nevertheless, with the available information, (near to) complete cradle-to-grave (raw wood to combustion) flows of woody biomass can be illustrated.

Oils and fats. The use of oils and fats in the country has been monitored by MVO in the past few years at a relatively high level of detail. Companies in the oils and fats sector have a legal obligation to provide statistical data about their international trade in oils and fats products. The Netherlands has also been actively promoting sustainability certification of vegetable oils through various initiatives such as IDH, and the latest development is available publicly on the website. The biggest challenge at the moment lies within the connection between the administrative biofuels data reported for renewable fuels targets and the feedstock flows. Also, it is not entirely clear how monoalkylester streams recorded in the trade statistics can be linked to the biofuel streams.

Carbohydrates. Due to difficulties in quantifying specific biomass components after secondary processing, assessment of this category was limited to primary feedstock only. Most data can be found on national statistics (CBS) (both general agriculture and trade statistics). The sustainability certification of carbohydrates is still in its infancy, except for specific streams used as feedstock for bioethanol. Similar to oils and fats, the biggest challenge is to link the feedstock streams to the bioethanol streams. There are also some issues with the trade statistics of ethanol (Goh et al. 2013b).

2.4.2 Methodological discussion and conclusions

Seeing the need to understand not only the mass flows but also the share of sustainable certified biomass, five major challenges that need to be addressed were identified through this work:

i. Data definitions: administrative data versus actual physical data

Data collected for administrative purposes do not necessary equal the actual physical flows due to various administrative reasons:

- Definitions used are different from the CN codes
- Definitions differ between organizations
- Definitions differ as the administrative rules change over time
- Delayed or early reporting
- Considerations of indirect trade flows (administratively reporting the origins of goods as either where the goods are produced, or where the goods are imported from through re-export/transhipment)
- Other internal or external considerations

These phenomena are rather prominent for biofuels, reflected in the discrepancies found between data reported by different monitoring bodies. Currently, the reported consumption of liquid biofuels is different from the actual physical situation. First, for administrative purposes, companies are allowed to carry over their physical efforts to later years. Second, companies may administratively allocate a low-blend biofuel to the Dutch market, but physically (part of) this low blend is exported. For comparison, CBS reported biodiesel consumption at 0.11 MT and 0.20 MT (in 2010 and 2011, respectively) (CBS 2013), whereas the monitoring body NEa reported 0.10 MT and 0.29 MT (in 2010 and 2011, respectively) (NEa 2011, 2012a). Sustainability of biomass and bioenergy is important in the context of carbon mitigation policies. This phenomenon causes potential barriers to assessment of GHG emission reduction at sectoral or national level especially when it involves large trade volumes consisting of both sustainable certified and non-certified biomass. The risk of confusion seems very high due to data inconsistency between countries and sectors when different reporting systems are employed.

ii. Lack of coherent cross-sectoral reporting system

Each reporting system usually has a very specific scope and interest in certain biomass or specific products, and seldom covers cross-sectoral flows. Taking liquid biofuels as an example, although the origin of biofuel was reported, it is not known explicitly whether the biofuel was produced domestically using imported feedstock, imported directly from the feedstock-producing country, or imported from a third country. The timing of production and consumption, and their relationship with the feedstock flows remain unclear. This has resulted in the unknown composition of biodiesel flow in Figure 2-4 (shown in grey), because it cannot be matched with data from the oils and fats sector. On top of that, it also causes difficulty to deduct the sustainable share of biomass flows across sectors. Although in the Netherlands some monitoring bodies that cover conventional use of biomass such as MVO (oils and fats) and Probos (woody biomass) have started to include energy use of biomass in their reports, again this is fraught with the same problems as in point (i). Overall, the data consistency of biomass flows still needs improvement, and this requires more alignment between monitoring bodies from different sectors

iii. Reliability of bilateral trade statistics

Significant discrepancies between bilateral trade statistics of biomass reported by exporting and importing countries were noticed, especially for intra-EU trade statistics on the EUROSTAT portal. To ensure that a more consistent set of data is used, data reported by the case study country were given priority to match with other data collected in the country, but this led to different results between country analyses. Vice versa, reconciliation of the bilateral trade statistics may cause inconsistency with other data reported in the country. Besides that, in this study, international trade statistics also show significant discrepancies with other data sources. For the Netherlands, discrepancies were found in the case of wood pellets when comparing Eurostat with own data collection (directly from the industry), showing differences in net trade balance up to 55 ktons per country for the year 2011. The reasons of these discrepancies are multi-fold, but similar to those listed in point (i). The situation is even more complicated in the Netherlands considering the large volume of transhipment and re-export. Various efforts have been made to understand and reconcile the discrepancies in general trade statistics (Wang et al. 2010, Bohatyretz and Santarossa 2005). For bioenergy, a few studies have pointed out that the current CN codes do not differentiate the end-use purposes of the materials between energy use and raw material use. Moreover, more than one product might be included under one CN code. A prominent example is ethanol which is used as transportation fuel and for raw material purposes in the chemical industry. Ethanol is categorized under several different CN codes based on its forms and blending level but not the end uses (Heinimö 2008, Kalt and Kranzl 2012).

iv. Lack of transparency in biomass supply chain

One of the biggest barriers to overcome is the transparency of biomass flows. Currently, the degree of transparency of supply chains is considered low, not only for bioenergy, but also for conventional biomass chains, with only a few companies willing to publicly identify their biomass suppliers (Wilde-Ramsing and Racz 2013). Most of the companies' reports are incomplete, for example revealing only the percentage of sustainable certified vegetable oil consumed by a company in its annual sustainability report, but without giving any concrete information in volumes, origins, destinations, and timing. Companies tend to withhold information (particularly trade information) to protect their business interests. This is further exacerbated when it comes to the question of the sustainability of biomass, which is regarded as a very sensitive issue for private companies. Nevertheless, in the Netherlands, the reporting of liquid biofuels consumption is getting more transparent, as more details were revealed in 2012 compared 2011 (NEa 2011, 2012a). However, the actual situation of liquid biofuels production in the country remains unclear. There is no publicly available knowledge on the actual sources of feedstock (for bioethanol production) and supply destinations (for both bioethanol and biodiesel production), resulting in a few speculative streams in Figure 2-4 and Figure 2-7 (illustrated in grey). On the other hand, solid biofuels users will also have to report annually to the government on the amount of biomass they use and how sustainability is demonstrated via certification or verification systems (Biobased Economy Magazine 2013). However, the level of details of this reporting system will only be revealed when the report is published.

v. Disparity in sustainability requirements

At present, numerous sustainability certification schemes are being developed or implemented by a variety of private and public organisations with different interests, purposes, and target groups. While there are many years of experience for certification of woody biomass with sustainable forestry management schemes, it is worthwhile pointing out that in 2011, the sustainability certification of solid biofuels, liquid biofuels, and vegetable oils for human consumption significantly increased as shown in Figs 2 and 7. However, the systems in this wide range of schemes, developed largely without coordination among the organizations involved, are mostly incompatible in many aspects, especially the measurement of GHG emissions reduction. For example, industrial schemes for wood pellets do take GHG emissions measurement along the supply chain into account, but sustainable forest management schemes do not. Similarly, certification of vegetable oils used for biofuels production does employ the Renewable Energy Directive (RED) criteria but certification of vegetable oils used in food sectors does not. There are also differences between schemes applied in different countries. This disparity in sustainability requirements makes the comparison between supply chains, sectors, and countries very challenging.

To sum up, this work has explored various issues in monitoring biomass flows for a bio-based economy by taking the Netherlands as a case study, and identifying the key challenges. Points (i) to (iii) have to be addressed mainly quantitatively, while point (iv) is a qualitative issue, and point (v) needs to be viewed from both qualitative and quantitative aspects. The case of liquid biofuels in point (i) is considered an administrative issue as it stems mainly from current legislative frameworks. The period between 2010 and 2012 is regarded as a transition period for the use of sustainable certified biofuels in the EU. Improvement in the level of detail was observed. It is recommended that in the future actual physical data should be used for reporting purposes to ensure a sound basis for further analysis. This could be achieved using a track-and-trace system through certification systems. An example is the Renewable Identification Number (RIN) system[4] used in the USA that provides information on the volume of renewable fuel produced in or imported to the United States, allowing tracking of physical flows after going through the distribution system and ownership changes. Addressing point (ii) could be costly at the initial stage because additional efforts have to be made for data collection and compilation. However, with the wider application of sustainability certification, information should be available together with the certificates (if a track-and-trace system is applied), and hence additional efforts in collecting data can be reduced, provided the companies are willing to reveal the information. The methodology framework proposed in this work also shows possibilities in connecting cross-sectoral flows by assembling available data and conducting mass balance deduction. Point (iii) is not a new topic for trade statistics, and has already been discussed at least 30 years ago (Rozanski and Yeats 1994). To ensure consistency for analysis across countries, it is recommended to improve the CN codes for bioenergy, and use a common reconciliation approach on bilateral trade statistics. Point (iv) could be addressed by monitoring bodies or official statistics portals through administrative dimension, such as providing guarantees for the individual business that the confidential information will not be misused in the course of creating aggregate statistics from the original records. On the other hand, social pressure has also been forcing the companies to reveal more information on biomass supply chains. Point (v) is considered the most difficult technical issue at the moment, with dozens of ongoing discussions on sustainability criteria, such as the applicability of universal criteria at local level. Moreover, in a broader scope of bio-based economy, there is also a need for harmonization of criteria regardless of end-uses. As observed in the bioenergy sector, harmonization process could be carried out with both top-down (at regulatory level) and bottom-up approach (at industrial level).

Notwithstanding the issues cited, the results of this work show the opportunity for constructing a monitoring framework at EU level by using the methodology proposed, but the aforementioned challenges have to be addressed adequately to ensure sound assessments.

4 A RIN is a 38-character numeric code that corresponds to a volume of renewable fuel produced in or imported into the United States. RINs remain with the renewable fuel through the distribution system and ownership changes. Once the renewable fuel is blended into a motor vehicle fuel, the RIN is no longer required to remain with the renewable fuel. Instead, the RIN may then be separated from the renewable fuel and used for RFS compliance, held for future compliance, or traded. Available at: http://www.ers.usda.gov/media/138383/bio03.pdf

2.4.3 Recommendations for future research

The present study provides a basic quantification methodological framework of biomass in the broader scope of a bio-based economy. Possible further research activities are recommended below:

Benchmarking of reporting systems: As revealed by this study, there are many shortcomings in the current biomass and biofuels reporting systems. There is a need to further address the issues of data definitions in different systems (e.g. for the case of biofuels), inconsistencies within a system (e.g. trade statistics), as well as transparency in data flows from industries and bilateral agreements, not only at the national level but also at EU level.

Future projection of biomass flows: The impact of altering mass flows in a bio-based economy on existing supply chains is not known. With this methodology, scenarios can be built to display how mass flows will change when certain flows are altered, added, or removed from the big picture, and to provide insights into quantitative impacts from three aspects: cross-border flows, domestic flows, and sustainability certification.

Accounting for GHG emissions associated with biomass flows: At the moment, the substitution effects between sectors due to new demand (e.g. food versus biofuel), particularly the impacts on overall GHG emissions reduction, and are not adequately addressed in quantitative unit. Likewise, the emissions adhered to in the imported/exported biomass are not taken into account in any national emissions reporting. On top of the mass flows, this framework can be further developed to assess allocation of emissions by examining emissions attached to physical biomass flows in two dimensions, i.e. domestic and international flows. This work can also be combined with (ii) to show the impact on national emissions reduction in different scenarios.

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SUPPLEMENTARY MATERIALS

Table S2-1. The Combined Nomenclature (CN) code of relevant biomass streams used by trade statistics.

CN Code	Description
Woody biomass	
CN 44xxxxxx	Wood and articles of wood; wood charcoal
CN 45xxxxxx	Cork and articles of cork
CN 47xxxxxx	Pulp of wood or of other fibrous cellulosic material; recovered (Waste and scrap) paper and paperboard
CN 48xxxxxx	Paper and paperboard; articles of paper pulp, of paper or paperboard
CN 49xxxxxx	Printed books, newspapers, pictures and other products of the printing industry; manuscripts, type scripts and plans
CN 44013020	Sawdust and wood waste and scrap, agglomerated in pellets
CN 94xxxxxx	Furniture (all or partly made of wood)
Oils and fats	
From CN 1201xxxx until CN 1209xxxx	Oil seeds and oleaginous fruits
CN 15xxxxxx **CN 15200000**	Animal or vegetable fats and oils and their cleavage products; prepared animal fats; animal or vegetable waxes Glycerol, crude; glycerol waters and glycerol lyes
CN 23040000	Oil-cake & other solid residues, whether or not ground/in pellets, from extraction of soyabean oil
CN 29054500	Glycerol
CN 382600xx **CN 38249055** **CN 38249091 (used by CBS)**	Biodiesel and mixtures thereof, not containing or containing less than 70% by weight of petroleum oils or oils obtained from bituminous minerals Mixtures of mono-, di- and tri-, fatty acid esters of glycerol (emulsifiers for fats) Monoalkyl esters of fatty acids, with an ester content of 96.5%vol or more esters (FAMAE)
Carbohydrates	
CN 10xxxxxx	Cereals
CN 11xxxxxx	Products of the milling industry; malt; starches; inulin; wheat gluten
CN 121291xx **CN 12129300** **CN 1213xxxx**	Sugar beets Sugar cane Cereal straw and husks, unprepared, whether or not chopped, ground, pressed or in the form of pellets
CN 17xxxxxx	Sugars and sugar confectionery
CN 19xxxxxx	Preparations of cereals, flour, starch or milk
CN 200410xx **CN 200520xx**	Potatoes prepared or preserved otherwise than by vinegar or acetic acid, frozen, other than products of heading 2006: Potatoes prepared or preserved otherwise than by vinegar or acetic acid, not frozen, other than products of heading 2006
CN 22070100 **CN 22070200** **CN 38249097**	Undenatured ethyl alcohol of an alcoholic strength by volume of 80%vol or higher Ethyl alcohol and other spirits, denatured, of any strength Other chemical compounds

Table S2-2. Conversion factors for biomass

	Value	**Unit**
Woody biomass		
Density (Own estimation)	0.7	kg/m^3
Lower heating value (Segers 2013) Wood pellet Wood chips Waste wood and other woods	 17 12 12	 MJ/kg
Economic value (Argus 2013, Index Mundi 2013)	Change with time [d, e]	$/kg
Moisture content (DeWitt 2002)*	12% - 16%	%
Oils and fats		
Density **FAME** (EBTP 2011)	 0.88	 kg/litre
Lower heating value **FAME** (EBTP 2011)	 37.1	 MJ/kg
Economic value (Platts 2012)	Change with time	$/kg
Moisture content	Negligible **	%
Carbohydrates		
Density **Ethanol** (EBTP 2011)	 0.79	 kg/litre
Lower heating value **Ethanol** (EBTP 2011)	 26.7	 MJ/kg
Economic value (Platts 2012)	Change with time	$/kg
Moisture content	Moisture contents for crops are usually high and vary largely with crops, seasons and also reporting sources, usually described together with the data. Moisture contents for other streams are considered negligible.	%

* This range is typical for air-dried exterior wood (DeWitt, 2002), however the moisture content may vary depending on humidity. Furthermore, due to the fact that the range is relatively small (compared to the other errors in data collection, particularly waste wood for which only rough estimation is used), moisture content of woody biomass is neglected in this study.
** UCO and animal fats are assumed to be pretreated before they were traded

Table S2-3. Data sources for each category

Items	Data sources (as in Section 2.1)				
	i	ii	iii	iv	v
(i) Woody biomass					
Data for "Consumed by the utilities (co-firing)" was collected from the utilities directly through surveys, together with the share of certified woody biomass in this stream, and was cross-checked with literature (Essent 2012). As a comparison, data was also available on statistics with CN code CN 44013020 but without the share of sustainable certified biomass.	•				•
Data for "Combustion in BECs" was collected from CBS (Segers 2013, CBS 2012). Biomass Energy Centres (BECs) are stand-alone biomass combustion plants.		•			
Data for "Heat boilers for companies" was taken from CBS (2012), assuming 60% of the biomass used by these heat boilers comes from fresh waste wood, as 60% of the boilers were used in wood processing companies. The rest largely comes from agriculture sector, and therefore is not shown here (Segers 2013).		•			•
Data for "Waste Incineration" was calculated based on direct information from Agentschap NL (2011). with a rough estimation of biogenic components in municipal and household waste streams made in 1995. However, the quantity of recycled paper and cardboard was also provided by Probos (2011, 2012), which was used to complete the recycling loop. Therefore, for paper and cardboard, the incinerated amount was calculated by calculating mass balance based on Probos figures.		•		•	•
Data for "Wood stoves for households" was taken from CBS (2012), assuming 1/6 of wood used was "Waste wood", and the rest were round fuel woods that might originated from forest residues, gardens residues, old fruit trees, public trees from parks and streets (Segers 2013)		•			•
The input streams to "Waste wood (A, B, C wood)" from "Wood products" was derived through mass balance by assuming no export of waste wood. It did not include residues from forests, gardens and parks. Export of "Waste wood (A, B, C wood)" was not shown as data was not available. As a reference, waste wood export in 2007 was 1.16 MT (about 0.76 MT for energy purpose) (Goh et al. 2012).				•	•
Data for "Furniture" was taken from CBS (2013) using selected CN Codes 94036090; 94036010; 94035000; 94016100 ; 94039030; 94016900; 94019080; 94034090			•		
Data for the other streams was taken from Probos (2011, 2012), assuming density of wood = 0.7 tonnes/m^3. It should be noted that Probos's data also relies heavily on CBS trade statistics. Data for the share of certified woody biomass for non-energy use was also taken from Oldenburger et al. (2012). Figures for 2010 were estimated using interpolation of data points, as data for 2008 and 2011 was available.		•	•	•	•
Due to absence of data, both consumption and export streams of paper and cardboard were assumed to have a same percentage of recycled products.					•
(ii) Oils and fats					
Data for most of the oils and fats mass flows was taken from MVO (2011, 2012), unless otherwise stated. This includes production data of the companies which are connected to MVO.		•			
Data for monoalkylesters, oil seeds, oils and fats trade flows by countries was taken from CBS (2013) with CN code listed in Table S2-1. These data are collected by close cooperation between MVO and CBS. Monoalkylesters was assumed to be equivalent to biodiesel.		•	•		•

Table S2-3. (continued)

Items	Data sources (as in Section 2.1)				
	i	ii	iii	iv	v
Data for production of biodiesel (oils and fats used for energy purpose) was collected from MVO (2012) and CBS (2013). MVO data was selected due to the level of details (types of feedstock) and also data consistency across the mass flows of whole category. Instead of 0.29 MT (2010) and 0.55 MT (2011) reported by MVO, CBS reported 0.38 MT (2010) and 0.49 MT (2011).		•	•		
Data for consumption of biodiesel was taken from NEa (NEa 2011, 2012). There were discrepancies between CBS and NEa data for biodiesel: CBS reported physical consumption, whereas NEa published administrative data. Physical data was different from administrative data, because (i) companies were allowed to administratively carry over their physical efforts to later years; (ii) it was still unclear whether book and claim is used for the NEa reports after creating low blends - this implies that companies may create a low blend, administratively allocate this low blend to the Dutch market, whereas physically (part of) this low blend is exported. For comparison, CBS (2013) reported biodiesel consumption of 0.11 MT and 0.20 MT (in 2010 and 2011 respectively), respectively, whereas NEa (2011, 2012) reported 0.10 MT and 0.29 MT (in 2010 and 2011 respectively).		•			
Data for glycerol was taken from CBS (2013) with CN code CN 15200000, 38249055, and 29054500. Also assuming 1 kg of glycerol is produced as by-products of 10 kg of biodiesel production (own estimation).			•		•
Data for sustainable vegetable oils was taken from The Dutch Taskforce Sustainable Palm Oil (2012) for palm oil and RTRS (2013) for soy bean. An assumption was made that all vegetable oils used for biodiesel production in the Netherlands are 100% sustainable certified. Data for certified vegetable oils used for biodiesel production in 2010 is not available. Since there was no mandatory requirement, it is assumed all vegetable oils used for energy purpose was not certified in 2010.		•			•
Trade statistics of monoalkyl esters, oil seeds and oils and fats trade flows (net by regions) for the Netherlands from 2008 – 2011 was collected from CBS (2013).			•		
(iii) Carbohydrates					
Data for all streams other than bioethanol and biogas was taken from CBS (2013) using CN code according to Table S2-1.			•		
Data for biogas was taken from CBS (2012).		•			
Data for all crops produced domestically came with different moisture content. Their moisture content was harmonized to 16%.		•			
Data for consumption of bioethanol was taken from NEa (2011, 2012).		•			
Connection between bioethanol and grains was only a rough estimation. It was not publicly known that where the bioethanol production plant sources the raw materials from and exports the bioethanol and DGS to. NEa reported that 0.18 MT of bio-ethanol was consumed in 2011 and almost all of them was made from materials from foreign countries, but it was unclear where was these bioethanol produced.					•
Connection between secondary products (sugars, flour, glucose) and raw material was unable to establish due to data limitation.					•
Trade statistics of ethanol for 2008 – 2011 were collected from CBS for the EU and EUROSTAT for the others (CBS 2013, EUROSTAT 2013).			•		

CHAPTER 3

Linking carbon stock change from land-use change to consumption of agricultural products (I): A review with Indonesian palm oil as a case study

Authors:
Chun Sheng Goh
Birka Wicke
Judith Verstegen
André Faaij
Martin Junginger

"One morning I shot an elephant *in* my pajamas." --- Groucho Marx

ABSTRACT

Numerous analyses have been performed to quantitatively link carbon stock change caused by land-use change (CSC-LUC) to consumption of agricultural products, but results differ significantly, even for studies focussing on the same region or product. This is due to the different focuses and interpretations of the links between direct drivers and underlying causes of CSC-LUC, which can be translated into differences in key functions, i.e. specific methods, algorithms and parameters embedded in the analysis. Using the example of Indonesian palm oil production (often associated with CSC-LUC), this paper carried out a meta-analysis of 12 existing studies, determined the different settings for the key functions embedded in consumption-based CSC-LUC studies and discussed their implications for policymaking. It identified the underlying reasons of adopting different settings within the eight key functions and their advantages and trade-offs. Examples are the way of determining how deforestation is linked to oil palm, and the inclusion of non-agriculture and non-productive drivers in the accounting to weight their roles in CSC-LUC in comparison to palm oil consumption. Following that, the quantitative results from the selected studies were processed and harmonised in terms of unit, allocation mechanism, allocation key and amortisation period, resulting in ranges of 0.1 - 3.8 and -0.1 - 15.7 tCO_2/t crude palm oil for historical and projection studies, respectively. It was observed that CSC-LUC allocated to palm oil is typically lower when propagating effects and non-agricultural or non-productive drivers were accounted for. Values also greatly differ when marginal and average allocation mechanisms were employed. Conclusively, individual analyses only answer part of the question about CSC-LUC drivers and have their own strengths and weaknesses. Since the context can be very different, using quantitative results from a single study for accounting purposes in policymaking is not recommended. Instead, insights from different studies should be combined, e.g. the relative role of logging and oil palm or the contribution to CSC-LUC in regional and global perspectives.

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Keywords: Land-use change; Carbon stock; International trade; Agricultural production; Consumption; Palm oil.

3.1 INTRODUCTION

Carbon stock change as a consequence of land-use change (CSCLUC) plays a significant role in global greenhouse gas emissions, contributing to 8 - 20% of annual global anthropogenic CO_2 emissions through deforestation, forest degradation and peat emissions (van der Werf et al. 2009). Deforestation as the major source of carbon stock loss has increased substantially in tropical regions, although afforestation, the major carbon stock gain, has increased in other regions like Europe and East Asia (FAOSTAT, 2016).

Many studies have focused on identifying direct drivers (also called proximate causes) of CSC-LUC, e.g. logging and agricultural expansion (e.g. Koh et al. 2011; Wicke et al. 2011). These direct drivers, especially human activities, are closely related to both local and distant underlying causes derived from social, economic, political, cultural and technological processes, e.g. changes in socioeconomic environment, new land-use policies and consumption patterns (Geist and Lambin 2002). Despite efforts to relate these underlying causes to CSC-LUC, it remains a challenge to provide quantitative indications (Azadi et al. 2010; Kissinger et al. 2012; Lambin et al. 2001; Xie et al. 2005). This has become more complicated with the shifts of carbon intensive activities from one region to another (i.e. carbon leakage), particularly in the form of export-oriented agricultural expansion (Ostwald and Henders 2014).

A way to come closer to quantifying underlying causes is associating CSC-LUC with measurable consumption and trade patterns of land-use based products, i.e. consumption-based accounting analyses (Peters, 2008; Larsen and Hertwich, 2009; Davis and Caldeira, 2010). These analyses can be widely categorised as: (i) *historical* studies which examine the historical consumption of agricultural commodities in general and linking this to CSC-LUC (e.g. Yu et al. 2013), and (ii) *projection* studies, which examine potential CSC-LUC impacts of specific causes or drivers, including for example studies on indirect land-use change (ILUC) induced by biofuels (e.g. Laborde 2011).

While both types of studies have different starting points (historical and future perspectives), they both contribute to the discussion of consumption-based land-use accounting. These studies generate a large amount of quantitative indications, but the results vary from one to another significantly. For historical studies, reviews (e.g. Bruckner et al. 2015; Hubacek and Feng, 2016; Schaffartzik et al. 2015; Wiedmann, 2016) have revealed the large discrepancies between quantitative results produced by different studies. For projection studies, reviews on ILUC analyses (e.g. Wicke et al. 2012; Warner et al. 2013; Ahlgren and Di Lucia, 2014) have also found that the land-use emissions projected for biofuels in different studies scattered in a wide range, even for studies that employed similar methods (e.g. computable general equilibrium models). A common finding from these reviews is that the differences in methods, algorithms and parameters are the main reasons for these differences. For communication, these sets of methods, algorithms and parameters may be collectively referred to as methodological ‘functions’, with key examples of such a function being the classification of land and products or the allocation mechanism.

The diversity of settings for these functions may be due to the different focuses and interpretations of the links between direct drivers and complex underlying causes of CSC-LUC, and may involve value judgements (Brandao et al. 2012; Creutzig et al. 2012). For example, while some may allocate CSC-LUC to vegetable oils in general assuming perfect substitutability (where the driver is the increased consumption of vegetable oils in general), the other may consider the differences between oil crops (where the driver is the increased consumption of certain types of vegetable oil). The differences in key functions also affect the compatibility of datasets used for analysis, e.g. when different names and definitions of forest are used (Bruckner et al. 2015; De Rosa et al. 2016).

Indonesian palm oil, a largely export oriented commodity, has received a lot of attention among researchers, civil society and policymakers due to its role in CSC-LUC (Sheil et al. 2009). In 2006-2010, the carbon stock loss in Indonesia has contributed to at least 3% of global anthropogenic CO_2 emissions emission, for which oil palm expansion may be significantly accounted for (Agus et al. 2013; van der Werf et al. 2009). In addition to being an important food source, palm oil is also a major feedstock for chemical products and biofuel production. The role of palm oil in CSC-LUC (and its links to export) has been quantitatively evaluated in various manners through historical and projection approach (e.g. Henders et al. 2015; Laborde 2011). Their quantitative results are often inconsistent, and some are even contradictory in their policy advises. Given that the reasons for discrepancy are not always made clear, this creates confusions among decision makers on both production and consumption side.

Existing literature reviews only examine either historical (e.g. Schaffartzik et al. 2015) or projection studies (e.g. Wicke et al. 2012), but have not compared them in terms of underlying functions and their settings. Strictly speaking, the quantitative results come from these two types of studies cannot be compared directly due to different starting point (similar to the issue of attributional and consequential life cycle analysis, see Creutzig et al. 2012). However, they share similar methodological functions, which can be translated into important policy implications. Comparison of, and possibly exchange between these two types of studies may help to account for arbitrary characters embedded within these key functions, and to explain differences between them. For example, if one wants to know how palm oil performed in the past and will perform in the future, the way of distributing CSC-LUC between palm oil and other drivers (e.g. logging and fire), which could involve arbitrary assumptions, needs to be first understood. Assessing the underlying functions helps to clarify the implications for policymaking, especially when this is done for a specific commodity.

Therefore, the objective of this review is to unravel the different settings for the key methodological functions of the consumption-based CSC-LUC studies, examine the underlying reasons for making the settings, and discuss their implications for policymaking. This is illustrated for the case of Indonesian palm oil as an important example of a product often associated with CSC-LUC.

3.2 MATERIALS AND METHODS

Two types of CSC-LUC approaches were defined. The historical approach (Figure 3-1A) attributes CSC-LUC to consumption (or production) by having the CSC-LUC virtually embodied in consumable products. It does not take into account market dynamics, but it only attributes CSC-LUC to products based on historical trade data. The projection approach (Figure 3-1B) projects the magnitude of CSC-LUC as a consequence of a marginal change in demand for a specific product. It accounts for effects of the new demand on existing markets and consequently on land-uses. This approach has been applied for estimating ILUC from biofuels. It examines trade and market dynamics to project future production and consumption. These two approaches carry different meanings in principle, and therefore their results cannot be directly compared.

Each approach consists of different methodological components on the production side (linking land, land-use and product), consumption side (linking product and consumer) and/or trade (linking both sides) (Figure 3-1). In each component, different methods can be applied. In the historical approach, CSC-LUC is first quantified and allocated to agricultural products, timber and/or other drivers (e.g. fire or urbanisation) on the production side based on either a spatially aggregated (at sub-national, national, regional or global level) or a spatially explicit (at the possible finest scale) method. The destinations of tradable products are then traced through trade analysis. Some studies further expand the system boundaries to conduct extended material and trade flow analysis to trace intermediate traders (i.e. re-export) and/or derivative products (e.g. Fischer-Kowalski et al. 2011; Singh 2014). The key difference between the projection approach and the historical approach is the demonstration of causal effect by expected drivers (the arrows in Figure 3-1B go in the opposite direction compared to Figure 3-1A). The projection of CSC-LUC driven by a new demand, such as the demand for biofuel, is performed on the consumption side using different methods. Economic models (e.g. Searchinger et al. 2008; Laborde 2011) are used to predict the economic response to a change in demand, e.g. effects of biofuel policies on agricultural markets and subsequent impacts on CSC-LUC. Demand can also be forecasted using a causal descriptive method (e.g. Bauen et al. 2010) based on expert opinions with cause and effect logic, or using a simple deterministic method (e.g. Bird et al. 2013) by extrapolating historical trends. The latter studies do not explicitly correlate the trends to market mechanisms.

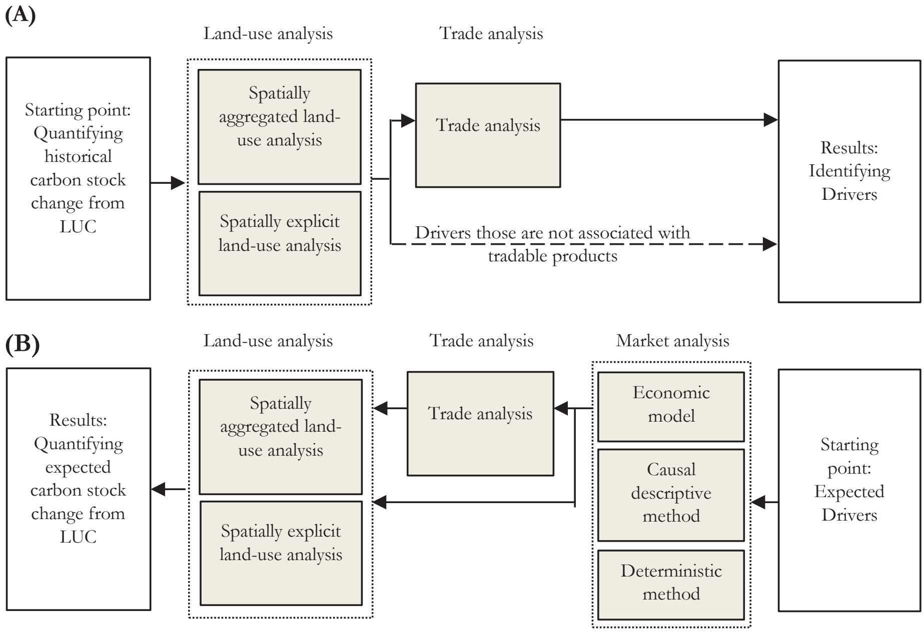

Figure 3-1. Structures of (A) *historical* and (B) *projection* CSC-LUC approach (arrows indicate the direction of the workflow).

3.2.1 Key function

For communication, in this study the term 'function' is used to represent sets of methods, algorithms and parameters embedded in the methodological components (Figure 3-1). Below are the 8 key functions of consumption-based CSC-LUC studies identified based on the findings from existing reviews and studies[5] (see Table S3-1 for full descriptions):

- **Classification of lands and products**: Lands or products within the same class are treated as if they were identical, i.e. a conversion between these lands is not considered as LUC.
- **Interactions between land classes and product classes**: Lands and products from different classes can be convertible or substitutable, depending on a multitude of conditions (e.g. economic incentives or geographical conditions) and involving multiple agents (e.g. small farmers, large plantations, policy makers).

5 Brandao et al. 2012, Broch et al. 2013, Bruckner et al., 2015, Cherubini and Strømman 2011, Cowie et al. 2012, De Rosa et al. 2016, Henders and Ostwald 2014, Hubacek and Feng 2016, Kastner et al. 2014, Kløverpris and Muller 2012, Luo et al. 2009, Meyfroidt et al. 2013, Næss-Schmidt et al. 2011, Seto et al. 2012, Warner et al. 2013, Wicke et al. 2012, Yu et al. 2013.

- **Propagating effects of marginal changes in land and product use**: Two types of propagation were conceptualized. Local propagation occurs when a direct displacement of one land class by another results in the expansion of this displaced land class within the same territory. Distant propagation occurs when the increased consumption and/or reduced production of one product class create a supply gap (and trigger higher crop prices), which then gives incentives to increase production elsewhere in the world (Tipper et al. 2009).
- **Delineation of spatial boundaries**: Spatial boundaries are applied to limit the spatial extent (boundaries around the study area) and spatial scale (boundaries between different territories within the study area, e.g. provinces within Indonesia) of the analyses.
- **Inclusion of non-agricultural and non-productive drivers**: Non-agricultural drivers like logging and fire, as well as expansion and displacement of land classes which do not result in tradable agricultural products (here referred to as non-productive land classes) also play an important role in CSCLUC. Linking these drivers to agricultural activities or not (and to what extent) alters the final quantitative results.
- **Allocation mechanism and allocation key**: This function has two aspects. First, CSC-LUC is linked to land and product classes through different allocation mechanisms depending on the purpose, e.g. to investigate the impact caused by marginal changes in consumption, or to distribute CSC-LUC among all the consumers. Second, these allocation mechanisms also come with the problem of choosing the 'allocation key' (i.e. a common and relevant attribute of the various products over which emissions are allocated).
- **Temporal dynamics**: This function has three aspects: time-step of change (unit of time), temporal extent (period to account for) and temporal distribution mechanism (mechanism to distribute CSC-LUC across time).
- **Extent of trade linkages**: This function determines the extent of tracing product origins and destinations (for both raw materials and derivatives), considering three aspects: spatial boundaries for cross-border trade, re-exports and extension to derivative products.

These key functions were chosen for this review because they consist of many assumptions with significant arbitrariness. Table 3-1 shows their relevance to different methodological components. Based on these functions, the selected studies described in section 3.2.2 were reviewed and compared.

Table 3-1. The relevance of key functions for the three methodological components.

Functions and descriptions	Relevance for methodological components		
	Land-use analysis	Trade analysis	Market analysis
Classification of lands and products	x	x	x
Interactions between land classes and product classes	x	x	x
Propagating effects of marginal changes in land and product use	x		x
Delineation of spatial boundaries	x	x	x
Inclusion of non-agricultural and non-productive drivers	x		
Allocation mechanism and allocation key	x	x	x
Temporal dynamics	x		
Extent of trade linkages:		x	

3.2.2 Selected studies

While a wide range of studies has been performed on CSC-LUC impacts associated with palm oil, 12 studies are chosen for comparison and discussion. The overview of these studies is presented in Table S3-1 (supplementary material). They were chosen because their differences in combinations of methodologies are especially prominent as explained in the following. For the historical approach, consumption-based CSC-LUC analyses with trade linkages were first reviewed. Saikku et al. (2012) presented the simplest method, which directly links CSC-LUC in one country to another in a particular year. In contrast, Persson et al. (2014) and its succession Henders et al. (2015) employed more complex settings with the former attempted to quantify ILUC within the territory (without trade analysis) and the latter focused on trade analysis (without ILUC consideration). Since many existing CSC-LUC studies do not include trade linkages, three of such studies were also selected as illustrative examples. The report of Agus et al. (2013) was chosen to represent spatially explicit analysis in deforestation hotspots because they employed highly disaggregated land classes and have studied the carbon stock values extensively. The study by Abood et al. (2014) and Lee et al. (2013) are two examples of employing alternative ways to link CSC-LUC to the drivers: based on types of concessions granted by government and based on types of management, respectively. For the projection approach, studies were first identified based on different methodologies applied on the consumption side. The work by Laborde (2011) which employs an economic model represents an influential example for the ILUC debates in the biofuel. Two causal descriptive studies were included: the study by Bauen et al. (2010) is spatially aggregated while the study by Harris et al. (2013) is spatially explicit. The study by Overmars et al. (2015) (an updated version of Overmars et al. 2011) was also reviewed because they reported that their results with a simple method are close to that of complex economic modelling. Another example, Fritsche et al. (2010) demonstrated a deterministic method to calculate indirect effect of biofuel considering different types of land conversions in various locations. The last example, Bird et al. (2013), employed also a deterministic method but with globally aggregated calculations.

3.2.3 Harmonisation of CSC-LUC allocated to palm oil

Following the conceptual review, the quantitative differences between the studies were examined. The selected studies have reported various quantitative indicators in different units, so it is impossible to directly compare the values. Therefore, these indicators were further processed so that the final results were converted to the same unit with the key functions harmonised wherever possible (Table 3-2).

First, if the CSC-LUC was already allocated to one unit of crude palm oil (CPO) or palm methyl ester (e.g. in the form of gCO_2/MJ or tC/tCPO), the indicators were further converted into the same unit (tCO2/tCPO). However, for the historical approach, some studies only allocated CSC-LUC to oil palm industry in general. For these studies, the results were further processed by making assumptions and using additional data from the same study or literature, e.g. CPO production in different regions, to produce indicators in the form of tCO2/tCPO.

In terms of allocation mechanism, average allocation was applied for the historical studies. An exception is Agus et al. (2013) for which both average and marginal allocation were applied to test the impacts of changing allocation mechanism. For the projection studies, marginal allocation was used by the ILUC studies. For Harris et al. (2013), which is the only non-ILUC study under this approach, a marginal allocation mechanism was also adopted.

Finally, as amortisation scheme is commonly used by the biofuel ILUC studies, the results were recalculated based on a 20-years amortisation scheme for all studies (20-years was chosen for comparison purpose only). While for most studies the recalculation was simply done by multiplying by the year ratio, the cases of Agus et al. (2013) (marginal) and Harris et al. (2013) have employed different calculation steps (see Figure S3-1 in supplementary material for details).

It was not possible to further harmonise the other functions due to limited access to the actual models and datasets of all selected studies.

3.3 RESULTS AND DISCUSSIONS

3.3.1 Classification of lands and products

Aggregately, the study by Saikku et al. (2012) has regarded all vegetable oils as one land and product class (see the overview of the settings for the eight key functions of the selected historical and projection studies in Table S3-3 and S3-4 in supplementary material). Without distinguishing vegetable oils from different oil crops, the impact from consumers' choices for different types of vegetable oils is not known[6].

Bird et al. (2013) have suggested a method that further aggregates all land and product: all CSC-LUC are directly allocated based on the amount of energy consumed regardless of the types of crops. This setting was proposed as an alternative approach to account for indirect effects. In such a setting, every additional 1 TJ consumed will be assigned to 18 ha of forest loss. However, for oil palm, the crop can produce 1 TJ of vegetable oil on about 6 - 9 ha (assuming 3-5 ton CPO per ha referring to DG Estate Crops 2014). Since palm oil is not substitutable with many other crops like paddy for food purposes, it is questionable if such aggregation is reasonable to estimate the CSC-LUC allocated to additional production of palm oil.

The other ILUC studies also only used few land classes, so it is easier to capture their interactions and propagating effects (see the following sub-sections) at global level. For example, Laborde (2011) only classified land into cropland, savannah, grassland, managed and primary forest by agro-ecological zones. But, it is then not explicitly known, for example, how cropland used for paddy or rubber will respond to the expansion of oil palm (especially when considering land suitability in terms of agro-ecological conditions). Instead, only net changes in total cropland are considered.

In contrast, without covering global indirect effects, Harris et al. (2013) have employed a more detailed classification (with a total of 22 classes) in their spatially explicit analysis. In theory, the more disaggregated the land classification is, the more accurate carbon stock and land-use characteristics can be derived. For example, Agus et al. (2013) demonstrated that peat emissions can be included by distinguishing LUC on swampland. However, in reality, this is largely limited by data availability and technical constraints. For example, the wide range of forest classifications and definitions proposed by different actors result in very different estimates of carbon stock loss[7] (Romijn et al. 2013).

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6 Different oil crops do not necessarily share similar land-use characteristics. For example, they could be permanent (have higher carbon stocks but primarily provide oil, e.g. oil palm) or temporary crops (have insignificant carbon stocks but provide both oil and proteins, e.g. soybean) (Nemecek et al. 2011).

7 While FAO estimated 5 Mha of deforestation in Indonesia, other forest definitions made this estimate to be 18-27% higher.

Table 3-2. Quantitative indicators for CSC-LUC associated with Indonesian palm oil.

Source	Indicators for CSC-LUC associated with Indonesian palm oil	Value	Unit	Methods of derivation and harmonisation
Historical approach				
Saikku et al. 2012	Land-use emission allocated to a ton of CPO in 2007	6.9	tC/tCPO	Direct unit conversion to tCO_2/tCPO. The value was re-amortised to 20 years (divided by 20).
Persson et al. 2014	LUC carbon footprints allocated to a ton of CPO in 2010 (amortised to 10 years)	7.5	tCO_2/tCPO	The value was recalculated with the factor 10/20 to change the amortisation basis from 10 years to 20 years.
Henders et al. 2015	Carbon emissions embodied in exports of palm oil from Indonesia in 2010 (amortised to 10 years)	130.0	$MtCO_2$	These values were divided with the total amount of Indonesian palm oil (including palm kernel oil) in 2000-2011, i.e. 138.7 Mt (for 2011 was 17.8 Mt) based on FAOSTAT (2016). The value was recalculated with the factor 10/20 to change the amortisation basis from 10 years to 20 years.
	Average carbon emissions embodied in exports of palm oil from Indonesia in 2000-2011 (amortised to 10 years)	957.0		
Agus et al. 2013 (Sumatera, Kalimantan, Papua)	Net annual LUC and peat soils emissions associated with oil palm expansion (1990-2000)	58.0	$TgCO_2$	Average allocation: The CSC-LUC allocated to oil palm was allocated to the total production. Based on the same study, it was assumed that the total area were 3.6 Mha, 5.2 Mha and 7.8 Mha respectively for the three periods, and the average yield was 3.7 t/ha for old area and 1.35 t/ha for new area. The values were further amortised to 20 years (divided by 20). Marginal allocation: The CSC-LUC allocated to oil palm was allocated to the marginal production (new area in that period only). Based on the same study, it was assumed that the new area were 2.4 Mha, 1.6 Mha and 2.6 Mha respectively for the three periods, and the average yield was 1.35 t/ha. The values were further amortised to 20 years (divided by 2 for 1990-2000, divided by 4 for 2001-2005 and 2006-2010) (Figure S3-1).
	Net annual LUC and peat soils emissions associated with oil palm expansion (2001-2005)	65.0		
	Net annual LUC and peat soils emissions associated with oil palm expansion (2006-2010)	125.0		

Table 3-2. (continued)

Source	Indicators for CSC-LUC associated with Indonesian palm oil	Value	Unit	Methods of derivation and harmonisation
Abood et al. 2015	Gross carbon dioxide emission from forest loss within industrial concessions in 2000-2010 (low)	1,306.0	$MtCO_2$	These values were divided by the production of palm oil in 2000-2010 in Indonesia, which was amounted to 152 Mt (FAOSTAT 2016). The value was amortised to 20 years (divided by 20).
	Gross carbon dioxide emission from forest loss within industrial concessions in 2000-2010 (high)	2,345.0		
Lee et al. 2014 (State-owned plantations are not included due to its relatively small contribution, i.e. ~0.5%)	Gross carbon dioxide emissions from deforestation in Sumatra within oil palm sectorial boundary of private enterprises in 2000–2010 with burning for land clearance	956.0	$MtCO_2$	First, mean values were calculated for the case with burning and without burning. These values were then divided by the production of palm oil in 2000-2010 in Sumatera by either private enterprise or smallholdings. National average yield of private enterprises and smallholdings for each year in 2000-2010 were taken from DG Estate Crops (2014). To obtain the amount of CPO production, these yield values were multiplied by area of cultivation by private enterprises and smallholdings in Sumatra in 2000-2010 (reported in the same study), respectively. The value was amortised to 20 years (divided by 20).
	Gross carbon dioxide emissions from deforestation in Sumatra within oil palm sectorial boundary of private enterprises in 2000–2010 without burning for land clearance	685.0		
	Gross carbon dioxide emissions from deforestation in Sumatra within oil palm sectorial boundary of smallholdings in 2000–2010 with burning for land clearance	83.0		
	Gross carbon dioxide emissions from deforestation in Sumatra within oil palm sectorial boundary of smallholdings in 2000–2010 without burning for land clearance	67.0		
Projection approach				
Laborde 2011	LUC emission associated with 1 MJ of palm-based biofuel (amortised to 20 years)	54.0	gCO_2eq / $MJ_{biofuel}$	Direct unit conversion to tCO_2/tCPO. The energy content of biodiesel was assumed at 37 MJ/kg, and 1 kg of biodiesel was produced from 1 kg of palm oil. For the case of Bauen et al. (2010), the value was recalculated with the factor 30/20 to change the amortisation basis from 30 years to 20 years.
Bauen et al. (2010)	ILUC factor associated with 1 MJ of palm-based biofuel (scenario with the lowest value) (amortised to 30 years)	8.0	gCO_2eq/MJ	
	ILUC factor associated with 1 MJ of palm-based biofuel (scenario with the highest value) (amortised to 30 years)	82.0		

Table 3-2. (continued)

Source	Indicators for CSC-LUC associated with Indonesian palm oil	Value	Unit	Methods of derivation and harmonisation
Harris et al. 2013 (Sumatera, Kalimantan, Papua)	Cumulative emission 2010 - 2050 expected to be caused by oil palm expansion (BAU)*	9.5	$PgCO_2$	The CSC-LUC allocated to oil palm was allocated to the marginal production (new area in that period only). Based on the same study, it was assumed that the new area of oil palm cultivation will be 8.2 Mha, 5.3 Mha and 5.3 Mha respectively for the BAU, MRT and RET scenarios, and the average yield will be 1.35 t/ha. For amortisation, CSC-LUC allocated to new area in a particular year was distributed to total CPO production on that particular area in the next 20 years (see Figure S3-1).
	Cumulative emission 2010 - 2050 expected to be caused by oil palm expansion (MRT)*	5.5		
	Cumulative emission 2010 - 2050 expected to be caused by oil palm expansion (RET)*	4.0		
Fritsche et al. 2010	Land-use emission including ILUC (50%) on grassland associated with 1 MJ of palm-based biofuel	48.0	gCO_2eq / $MJ_{biofuel}$	Direct unit conversion to tCO_2/tCPO. The energy content of biodiesel was assumed at 37 MJ/kg, and 1 kg of biodiesel was produced from 1 kg of palm oil. For Fritsche et al. (2010) the values were further amortised to 20 years (divided by 20).
	Land-use emission including ILUC (50%) on degraded land associated with 1 MJ of palm-based biofuel	-55.0		
	Land-use emission including ILUC (50%) on forest associated with 1 MJ of palm-based biofuel	213.0		
Overmars et al. 2015	Best-estimate ILUC emissions over 20 years by RED method (emission factor from IMAGE)	207.0	gCO_2 / $MJ_{biofuel}$	
	Best-estimate ILUC emissions over 20 years by RED method (emission factor from CSAM)	249.0		
Bird et al. 2013	Deforestation allocated to additional 1 TJ of CPO consumed	18.0	ha/TJ	The deforestation allocated was multiplied by carbon stock of forest (109.2 tC/ha) and food energy value for oil crop (25.9 MJ/kg) (these values were taken from the same study). The final CSC-LUC was further amortised to 20 years (divided by 20).

* Business as usual (BAU), Moratorium on peat (MRT), Restoration of peat (RET).

Land classification can also be done alternatively departing from the producer perspectives. Abood et al. (2015) classified land based on concessions granted by government, while Lee et al. (2014) further classified oil palm cultivation by ways of management to distinguish the role of industrial players and smallholders in CSC-LUC. This rationale can be supported by the finding of Davis et al. (2013) that the overall performance of a production system is determined by different ways of management rather than species.

For product classification, traded products from oil palm are often distinguished as palm oil and palm kernel oil, but sometimes meals are also captured on trade statistics portals (FAOSTAT 2016). With the introduction of sustainability certification, certified palm oil can be further distinguished in the trade flows (Goh et al. 2013). Such a distinction reveals more insights into how the behaviour of consumers is related to CSC-LUC in the producing regions. Nevertheless, traded palm oil is not explicitly distinguished by type of producers (i.e. industry or smallholders).

Overall, different ways of disaggregation will add more information in certain aspects. But as results are sensitive to classification, relative contribution, i.e. ratio of CSC-LUC allocated to classes instead of absolute values may be more suitable to be employed for decision making. As such, modifying the classification in different aspects and comparing the outcomes will help to provide more insights into the relative roles of different drivers in multiple contexts.

3.3.2 Interactions between land classes and product classes

The interactions between land classes can be captured or modelled by either spatially explicit or aggregated land-use analysis. For the former, direct LUC is often accounted for by inspecting changes in land cover, e.g. Agus et al. (2013). Another spatially explicit study by Abood et al. (2015) took a different approach in linking drivers to CSC-LUC in Indonesia by assuming that CSC-LUC within oil palm concessions should be allocated to oil palm, and similarly for other types of concessions like mining and logging. Given that the starting point is to link local policy drivers to deforestation, the results deviate from the actual LUC because some of the deforested land within the oil palm concessions was not planted with oil palm at the moment (and may not be necessarily planted later) while there is also oil palm expansion that occurred outside these concessions (GRAIN 2014, Goh et al. 2016c). One of the projection studies, Harris et al. (2013) predicted the interactions spatially explicitly employing factors such as agro-ecological suitability, economic factors and logistic constraints. But, the uncertainty is also high because the number of parameters has increased (Verstegen et al. 2015).

Spatially aggregated methods only account for the net area changes of land classes (although expansion and displacement could happen at the same time in different locations). For example, Persson et al. (2014) and Henders et al. (2015) have employed the ratio of net area changes as factors to allocate historical CSC-LUC to different crops. Projection studies have also explored ways to explain the future response of land-use to multiple factors (e.g. economic, logistic or policy factors) at spatially aggregated level (e.g. Bauen et al. 2010, Bird et al. 2013, Fritsche et al. 2010, Laborde 2011). For example, Laborde 2011 used a ratio to aggregately account for the area displaced by oil palm in the future (25% of net total cropland expansion in the region where 30% of that happens on peatland).

The interactions between product classes are modelled differently in the projection studies. Technically, palm oil may be considered highly substitutable with other vegetable oils, but they may have different degrees of market access depending on e.g. changing prices, logistics, trade policies and consumer behaviour. For economic models, modelling the substitution elasticity between palm oil and other vegetable oils faces great uncertainty, considering factors like institutional interventions (e.g. anti-dumping measure imposed by the EU on Indonesian biodiesel, see European Commission 2013) or market changes (e.g. changes in vegetable oil prices) that greatly alter the product flows (Villoria and Hertel 2011). For causal descriptive and simple deterministic methods, the definition of interaction is more straightforward – basically, they rely on expert opinions and extrapolation of historical data rather than developing complex algorithms to relate the changes. For example, Bauen et al. (2010) implicitly projected prices based on historical trends and expert opinion, meanwhile Overmars et al. (2015) assumed that increasing demand would increase yield and area at the same proportions as happened historically.

Due to the complexity and uncertainty in recognising interactions between land and product classes, this function is often interpreted quite differently by individual studies. For land class interaction, studies tend to generalise the dynamics of oil palm which vary significantly from one case to another. In reality, the linkages between CSC-LUC and oil palm can be much more complex than can be detected from remote sensing or predicted with bio-physical models. Further assessing land-use dynamics at smaller administrative unit with the incorporation of both agro-ecological and socio-economic aspects will help to identify the underlying causes of CSC-LUC more precisely (see e.g. Potter 2011). For product class interaction, since it is not possible to accurately predict the future, it is necessary to perform more tests on the outcome by adjusting this setting and investigating ways to achieve the best outcome scenario.

3.3.3 Propagating effects of marginal changes in land and product use

Propagating effect is the underlying concept of the ILUC studies using the projection approach. However, it can also be applied within the historical studies, e.g. Persson et al. (2014). It has two components: local propagation which occurs within the spatial boundaries, and distant propagation which occurs beyond the spatial boundaries.

For local propagating effects, it can be resolved spatially aggregated land-use analysis by considering the net change in total area of land classes, offsetting expansion and displacement within the same land class (e.g. Persson et al. 2014, Bauen et al. 2010, Zaks et al. 2009). The disadvantages are that it does not reflect the causal relationship nor the actual spatial changes of individual land classes. Local propagation within the spatial boundaries can also be traced or projected in spatially explicit analysis based on factors such as land suitability for oil palm (e.g. Harris et al. 2013).

For distant propagation effects, economic models were employed to investigate the transmission of distant propagation through price changes. However, they also add further uncertainties to the final results as they cannot be validated empirically, such as the price elasticity employed by economic models (Plevin et al. 2014). Causal descriptive (Bauen et al. 2010) and simple deterministic methods (Fritsche et al. 2010) do not model such propagation in a complex way, but rather employ expert opinions and historical trends. One different example is that Bird et al. (2013) resolve the distant propagating effect by directly correlating the net changes in consumption to total deforestation at global level.

Using more aggregated land and product classification, as well as larger spatial boundaries, the uncertainty in modelling the propagating effect can be reduced (as there will be less interactions between classes), but details are also masked. In policy context, tracing propagating effect with aggregation at a relevant administration scale could be more meaningful. For example, tracking the propagating effects on a regency scale in Indonesia could identify some key policy implications because the regencies are the most influential authorities in land-use planning. This may provide more details (compared to national scale) for practical implementation of policies.

3.3.4 Delineation of spatial boundaries

Most analyses take national or supra-national (e.g. EU) administrative boundaries as the spatial limits (e.g. Fritsche et al. 2010, Saikku et al. 2012). Boundaries are also established for regions which to some extent share characteristics in terms of culture or agro-ecological zoning, such as sub-national (e.g. Harris et al. 2013, Laborde 2011, Lee et al. 2014) or (sub-)continents (e.g. Bauen et al. 2011). A global approach treats all lands as global assets without any boundaries (Bird et al. 2013).

For spatially aggregated analysis like Saikku et al. (2012) or Persson et al. (2014), the choice of spatial boundaries has a substantial impact on the results as it greatly affects the pattern and extent of interactions between land classes and product classes. For example, paddy may experience a substantial expansion in a province, but zooming out to national level, the total expansion could be negligible if there is also an equally substantial area reduction of paddy field in other provinces. Switching to a spatially explicit analysis, e.g. Agus et al. (2013), provides additional information on the spatial extent, pattern and continuity of land-use dynamics (Olson et al. 2004). Still, some aspects can only be investigated aggregately on certain spatial scale, e.g. socio-economic environment like labour availability.

Up- or down-scaling of spatial boundaries provides different perspectives on LUC patterns to re-examine policies and sustainability considerations that are usually restricted by spatial boundaries. From a global perspective, high afforestation rates in Europe and East Asia are offset by high deforestation rates in

Indonesia when the viewpoint is lifted from regional to global level, and thus consumption that happens anywhere will in any case lead to deforestation (e.g. Bird et al. 2013). Conversely, shifting the perspective to a finer spatial scale gives a better insight into local problems. For the case of Indonesia, disaggregating the analysis to regency level, which is the most influential unit in land-use decisions (Thorburn 2004), may improve the representation of local policy interventions. But this has not been done so far – most of the existing studies on Indonesia apply either a national or island scale.

3.3.5 Inclusion of non-agricultural and non-productive drivers

Most selected studies did not explicitly allocate CSC-LUC to non-agricultural or non-productive drivers, except Abood et al. (2015) (logging, timber plantation and mining industries), Agus et al. (2013) (logging and wild fire), Bauen et al. (2010) (allocation to logging) and Henders et al. (2015) (timber products) using different weighing methods. For example, Agus et al. (2013) showed that a large area of forest in Kalimantan was replaced by shrub, which could be the result of logging, wildfire and land clearing for shifting cultivation. Parts of these shrub land were then cultivated with oil palm a few years later. Distributing CSC-LUC to these drivers alter the allocation of CSC-LUC to palm oil consumption. There are also a number of quantitative and qualitative studies looking at single non-agricultural drivers, such as forest fire in Indonesia (Siegert and Hoffmann 2000). While there could be links between these drivers and increasing export-oriented agricultural activities, such links are not well examined yet by the existing consumption-based CSC-LUC studies.

Neglecting logging and non-productive drivers in consumption-based CSC-LUC analysis may overestimate the impact caused by product consumption. For example, the dynamics of logging, (temporarily) land abandonment and oil palm expansion in Indonesia are not modelled well in consumption-based driver analysis. Given the wealth of land-use analyses on this topic in the literature (e.g. Gunarso et al. 2013), there is a need to reconcile the findings and incorporate them in CSC-LUC analysis to more accurately estimate the impact of distant consumption (see e.g. Goh et al. 2016b).

3.3.6 Allocation mechanism and allocation key

The first aspect in this function is how CSC-LUC can be linked to consumption. Four common allocation mechanisms are summarised in Table 3-3. For allocation among land classes, mechanism (1) used by Saikku et al. (2012) distributes CSC-LUC based on the total land area used by individual crops but not the impact in terms of the degree of expansion. The rapid expansion of oil palm may be overlooked as it occupies a much smaller area than other crops like paddy. Meanwhile, mechanism (3) used for direct LUC (e.g. Abood et al. 2015, Agus et al. 2013, Lee et al. 2014) does not recognize the propagating effect, and mechanism (4) (used by the projection approaches) largely depends on the baseline selected. Persson et al. (2014) has employed mechanism (2), which is somewhat between the others, as it considers the land area expanded as a factor for allocation instead of total area occupied, and recognizes propagating effect (representing by the net change in area of each land class).

Table 3-3. Basic mechanisms to allocate CSC-LUC to consumption.

#	By land class	By product class	Full equation	Applications
1	$\frac{A_x}{A_{total}}$		$\bar{a}_x = a.\frac{A_x}{A_{total}}.\frac{1}{P_x}$	Used by some historical spatially aggregated studies (e.g. Saikku et al. 2012) based on share of land occupied.
2	$\frac{\Delta A_x}{\sum \Delta A_x}$	$\frac{1}{P_x}$	$\bar{a}_x = a.\frac{\Delta A_x}{A_{total\ expansion}}.\frac{1}{P_x}$	Used by some historical spatially aggregated studies (e.g. indirect LUC factor in Persson et al. 2014 and Cuypers et al. 2013) based on contribution to land expansion.
3	-		$\bar{a}_x = \frac{a}{P_x}$	Can be applied on some historical spatially explicit studies (e.g. Agus et al. 2013) for estimating direct CSC-LUC.
4	-	$\frac{1}{P_x - P_{x,baseline}}$	$\bar{a}_x = \frac{a - a_{baseline}}{P_x - P_{x,baseline}}$	Used by projection studies.

Note:
x = the product(s) of interest;
$\bar{a}_x$ = CSC-LUC embodied in one unit of x (g C / unit product x);
a = CSC-LUC in the territory or spatial unit (g C);
$a_{baseline}$ = CSC-LUC within the territory or spatial unit in the baseline (reference) scenario (g C);
A_x = land area used to produce x;
ΔA_x = marginal increase in land area used to produce x;
A_{total} = total land area of the territory;
$\sum \Delta A_x$ = sum of all marginal increase in land area for land classes that have experienced expansion;
P_x = production of x after LUC (unit product x) which is usually assumed to be equivalent to consumption neglecting stock changes;
$P_{x,baseline}$ = P_x in the baseline scenario (unit product x)

For allocation among products, mechanism (1), (2) and (3) allocate the CSC-LUC to all product consumption, implying that all consumers share the same liability whether they are existing or new consumers. For example, the developed nations with small or no additional consumption (but maintaining high volume of consumption as usual) have to share the CSC-LUC from the expansion of food crops with the developing nations with new additional consumption (with poor level of consumption in the past). Such allocation may mask the actual driver (i.e. the increasing demand in the developing nations), but it provides a mean to re-examine the level of consumption between different consumers. In contrast, in mechanism (4) the LUC impacts are only allocated to the marginal increase in consumption. It is exclusively designed for projection analyses that investigate the impact of changes in a specific consumption, e.g. additional demand for biofuel. The impact of the allocation mechanism (average vs marginal) is very high as indicated by taking the results derived based on Agus et al. (2013)

as a prominent example (see section 3.3.9): marginal allocation could result in emissions 14 times higher than emissions based on average allocation.

The second aspect to be examined is the allocation key for dealing with by-products. For palm oil, this is less an issue because it has relatively small number of by-products (but could be significant for other commodities, e.g. soy and beef, see Blonk et al. 2008). Overmars et al. (2015) demonstrated that the CSC-LUC allocated to Indonesian palm oil may be ~4% higher if the allocation key is switched from energy to economic value.

It is crucial to point out that outcomes of different allocation mechanism and allocation key carry different meanings (e.g. marginal change versus average) and cannot be equivalently compared or combined. Lack of such awareness often causes confusion for the decision-makers when they require quantitative indicators for analysis and decision-making, for example when determining (dis)incentives for biofuels from different feedstock based on their GHG performance (Tipper et al. 2009).

3.3.7 Temporal dynamics

Three aspects are covered under this function: (i) time-step of change, (ii) temporal extent and (iii) temporal distribution mechanism. The first problem is the choice of time-step: the intermediate LUC might be overlooked if the time-step is big, e.g. five or ten years, often due to data limitation even for a LUC hotspot like Indonesia. For example, interpretation of satellite images for spatially explicit analysis is very costly and only performed for selected images with a larger time-step (e.g. Agus et al. 2013). Alternatively, ground surveys could be used but are too costly to be performed on an annual basis (Hosonuma et al. 2012). While the other studies included in this review have employed a time-step of one year, they often involved interpolation because not all data are available annually, e.g. forest area statistics on FAOSTAT (2016).

The second and third aspects are interlinked: Differences of studies may come from the selection of temporal extent for distribution and the design of distribution mechanism along the time-steps. In many analyses, CSC-LUC is amortized over a period of time instead of attributing it to a single year. The first consideration is the selection of the temporal extent – the number of years for tracing backward or distributing forward. In ILUC calculation for biofuels, CSC-LUC are typically annualized over 20 (e.g. Laborde 2011) or 30 years (e.g. Bauen et al. 2011) but the rationale behind these choices is debatable (Edwards et al. 2010). The choice of amortisation schemes adds further arbitrariness: the carbon stock loss can be distributed over the years equally or by a certain ratio based on a subjective decision (Zaks et al. 2009). When performing amortisation, one prominent question for palm oil is how to divide CSC-LUC between timber products from forest clearing and future agricultural activities on the deforested land which occur in different time steps. Agus et al. (2013) revealed that in many cases forest was not directly converted to another use, but instead was deforested and unused for several years. Parts of this unused land were converted to oil palm, while the rest remained unused or used for other purposes although they fall in oil palm concessions. The resulting CSC-LUC may either be distributed to oil palm or different land classes using arbitrary distributing factors. For example, Henders et al. (2015) assumed that 80% of deforestation associated with oil palm should be linked to logging prior to full conversion. Such assumptions are arbitrary and often not (fully) discussed in the studies.

While it involves arbitrary choices, currently, there is still no consensus on how to deal with the temporal dynamics of CSC-LUC. It largely depends on policy perspectives, but data availability to enable smaller time-steps is also a key limitation. It is challenging to justify the temporal extent to link CSC-LUC in different periods, facing questions such as whether new land-use should bear the CSC-LUC caused by previous land-use. One crucial aspect for future work is improving the coverage of CSC-LUC monitoring in terms of frequency and minimizing time lag to reduce the uncertainties in framing of land-use and carbon dynamics. Since land-use dynamics vary significantly from one place to another, location-based temporal accounting is more appropriate than regional generalisation.

3.3.8 Extent of trade linkages

Trade linkages for consumption-based CSC-LUC analyses are basically determined in three aspects: (i) spatial boundaries for cross-border trade, (ii) re-exports and (iii) extension to derivative products.

First, spatial boundaries dictate whether the products are considered traded or consumed domestically. This is a common issue in trade analysis (e.g. Wilting and Vringer 2009). Spatial boundaries are drawn in most consumption-based studies to predict trade patterns, while these boundaries were omitted in Bird et al. (2013) in their global approach.

Second, trade flows can also occur at multiple orders - imported agricultural products may be re-exported. It is difficult to explicitly distinguish whether domestic products or imported products are (re-) exported. For example, Malaysia is not only a palm oil producer and exporter but also an importer (from Indonesia), processor and consumer (FAOSTAT 2016). It is not clearly known how much domestically produced and imported palm oil is exported, unless a track-and-trace instrument is applied (Goh et al. 2014). To address this issue, Henders et al. (2015) assumed that part of the imported products are re-exported again and the rest are consumed/stored domestically, using the same ratio of total export to total domestic consumption.

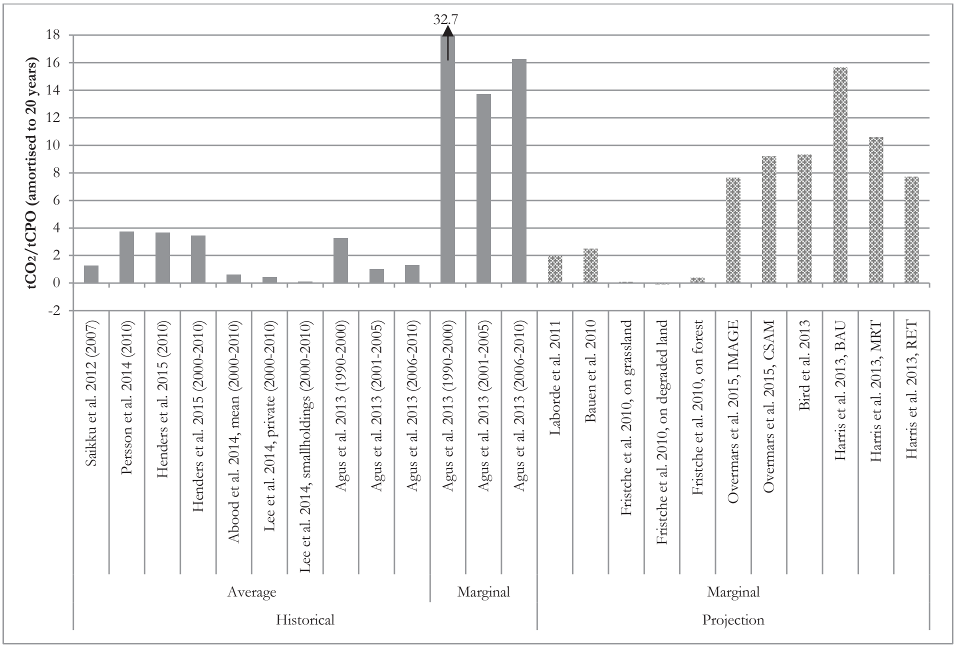
Third, the trade flows become even more complicated if links are extended to derivative products (e.g. palm oil to biofuels). CSC-LUC is often only allocated to one specific group of consumers, i.e. either the primary product users (e.g. biofuel producer using imported palm oil like the Netherlands) or the final consumers (e.g. other European countries that consume biofuels) (Goh et al. 2013, 2014). Most biofuel studies employ the latter case for national accounting. The distribution of responsibility among processors and consumers are not discussed, not to mention if this includes secondary processors and traders.

Allocating CSC-LUC via extended trade flows with the considerations of different spatial boundaries, re-export and derivatives adds further complexity, and it remains debatable how to distribute CSC-LUC to the actors along the supply chains (e.g. distributed by added values kept by producers and processors, or fully allocated to final consumers). Furthermore, before such allocations can be performed, a prerequisite is a reliable (cross-sectorial) biomass flows monitoring framework. However, covering the whole supply chain for individual crops (e.g. from crude palm oil to its derivatives) is challenging in terms of data acquisition. Only some specific products like biofuels have received so much attention and incentives to conduct a full track-and-trace assessment (Goh et al. 2014).

3.3.9 Comparison of quantitative indicators for palm oil

Following the conceptual review, in this section the results of the selected studies on Indonesian palm oil were harmonised to (i) same unit (tCO_2/tCPO) and (ii) consistent amortised years (20 years) (Figure 3-2). For historical studies, an average allocation mechanism was employed, with Agus et al. (2013) as an exception for both average and marginal allocation were used to test the difference caused by choices in allocation mechanism. In contrast, all of the projection studies employ marginal allocation mechanism. Overall, the CSC-LUC values were found to be scattered in a range from 0.1 to 3.8 tCO_2/tCPO and -0.1 to 15.7 tCO_2/tCPO for historical studies (with average allocation) and projection studies, respectively. The set of values obtained from the historical studies (using average allocation) has a mean value of 1.9 and a standard deviation of 1.5.For the projection studies, the mean value and standard deviation are 5.9 and 5.2, respectively. Although the individual impact of variation in each of the key functions between studies is impossible to be quantitatively distinguished in the final results, the impacts of several functions can still be observed:

Propagating effects of marginal changes in land and product use: While Harris et al. (2013) do not include indirect effects outside Indonesia, their results (except in the optimistic RET scenario where peatland will be restored) are generally higher compared to the other projection studies that specifically quantify global ILUC. It seems that the impact of oil palm has been reduced with the consideration of propagating effects, which is probably attributable to its higher oil yield compared to other oil crops (thus less land is required for the same demand). A similar point was also made by Villoria et al. (2013) who suggested that increasing oil palm yields in Southeast Asia could result in an overall net reduction of CSC-LUC at global level with international trade, particularly through land saving in countries like Brazil.



Note: To visually distinguish the two approaches, projection studies are represented by shaded bars.

Figure 3-2. Harmonised CSC-LUC values for Indonesian palm oil from selected studies.

Inclusion of non-agricultural and non-productive drivers: A possible comparison can be made between Henders et al. (2015) and Agus et al. (2013) (average) for 2000-2010. Henders et al. (2015) have distributed CSC-LUC among timber and palm oil but not to the other non-productive drivers, whereas Agus et al. (2013) have also allocated a large part of the CSC-LUC to logging and wild fire, thus leading to values that are about three times lower.

Allocation mechanism: This function can have a large impact to the overall result. For example, the values derived based on Agus et al. (2013) show that marginal CSC-LUC can be 10 to 14 times larger than average CSC-LUC using a 20-years amortisation scheme.

The various studies using the historical approach show that Indonesian palm oil is associated with direct deforestation to different degrees. This is often due to the location of expansion (formerly forest or peatlands) and its association with logging and improper practices like land clearing with fire. Distinguishing the impacts caused by non-agricultural and non-productive drivers reduces the CSC-LUC allocated to palm oil. These drivers were documented to be mostly location specific (Geist and Lambin 2002). This implies that using a single/universal method to evaluate the CSC-LUC impacts of palm oil from a consumer or policymaking perspective is in principle not possible.

By comparing among the studies using the projection approach, the impact of oil palm seems to be smaller if propagating effects is accounted for at global level. This is due to the relatively small area occupied by oil palm compared to other oil crops. Theoretically, these suggest that establishing new oil palm cultivation on low carbon land and avoiding association with logging and fire may minimize the potential carbon stock loss and can in some cases even lead to carbon sequestration (e.g. referring to the scenarios reported by Wicke et al. 2008), especially when global indirect effects are taken into account. While this strategy has already been suggested by a number of studies, there remains a strong economic push towards using forested land for conversion to oil palms. Thus, the marginal allocation mechanism is essential to monitor the future development of oil palm (e.g. the difference due to choice of land is also demonstrated by Fritsche et al. 2010). However, individual CSC-LUC results should not be used to generalise the performance of all palm oil in the market, especially when the magnitude of CSC-LUC can vary strongly between marginal and average allocation.

3.4 CONCLUSIONS

Overall, the selected studies were found to vary greatly in terms of level of details. The on-going debates have been pushing for more depth in CSC-LUC accounting analysis, such as identifying and establishing links to account for indirect effects across boundaries and markets. However, it is doubtful whether increasing complexity of a study will necessarily lead to increased accuracy and reliability. The inspection of key functions in this study shows that uncertainties may grow enormously with complexity because more (arbitrary) assumptions and choices (sometimes based on value judgement) have to be made. At the same time, more forms of interactions, especially interacting decisions of many actors and institutions at different geographical level, are still not well formulated and therefore cannot be accurately incorporated in the analysis.

Furthermore, as the major actors in driving the development of consumption-based CSC-LUC accounting are among the consumer countries (e.g. the development of default GHG values in the EU biofuel policies), the land-use dynamics involving non-agricultural and non-productive drivers (e.g. improper land-use practices like uncontrolled fire typically being the most important ones) are generally not adequately addressed in current studies. The interactions with these drivers are documented to be mostly region specific, which means that designing universal mitigation policy solely from consumption side is not conceivable (Geist and Lambin 2002). This implies that rather than having continuous debates only from the consumer perspective, future international or regional policy interventions require more connection to locally distinct dynamics of CSC-LUC. This may further reveal new opportunities to overcome non-productive carbon stock loss by shifting future agricultural expansion onto under-utilised and degraded land with sustainable practices.

This review concluded that individual consumption-based CSC-LUC studies (i) only answer part of the question about CSC-LUC drivers, and (ii) have unique strengths and weaknesses, depending on the objectives and perspectives. They provide different insights into the subject, e.g. the relative role of logging and oil palm expansion, or the contribution to CSC-LUC in regional and global perspectives. Since the context can be very different, using quantitative results from a single study for accounting purposes in policymaking is not recommended. Instead, by comparing the different studies, this paper managed to draw some implications for the case of Indonesian palm oil. To improve such a comparison and generate more useful information from the studies, three aspects for further research are proposed:

i. To improve the understanding of the relative role of different underlying causes in different contexts and to test the sensitivity of the results to these contexts, the settings of each function can be adjusted to inspect the quantitative changes in the final results. For example, in the case of Indonesian palm oil, the priority is to conduct and compare analysis at both national and regency level which are the most relevant administrative units for land-use policies, with the consideration of various non-agricultural and non-productive drivers.
ii. To determine causes of differences between studies and to link findings from different studies, the key functions and the underlying datasets need to be harmonised (to the extent that it is possible). The case of Indonesian palm oil in this work shows only partial harmonisation due to limitation in access to the underlying methods and datasets.
iii. To shed light on uncertainties, studies can be complemented by Monte Carlo analyses to assess the influence of uncertainty in a specific component and the propagation of all potential errors to the final output, in order to help identify the most important sources of uncertainty and therefore the highest priority for improvement (Verstegen et al. 2015, Plevin et al.2015).

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SUPPLEMENTARY MATERIALS

Table S3-1. Brief description of eight key functions and their relevance for the three methodological components.

Functions and descriptions	Relevance for methodological components		
	Land-use analysis	Trade analysis	Market analysis
Classification of lands and products: Lands or products within the same class are treated as if they were identical. If two crops are grouped as one class, i.e. a displacement of one of these crops by the other will not considered as LUC. The criteria used to classify lands and products not only vary with the objectives of a particular study, but are also limited by data availability when secondary data from other sources are adapted (De Rosa et al. 2015, Henders and Ostwald 2014, Næss-Schmidt et al. 2011, Seto et al. 2012, Warner et al. 2013, Yu et al. 2013).	x	x	x
Interactions between land classes and product classes: Lands and products from different classes can be convertible or substitutable, depending on a multitude of conditions (e.g. economic incentives or geographical conditions) and involving multiple agents (e.g. small farmers, large plantations, policy makers). Determining the way they interact with each other is the key for explaining past and projecting future CSC-LUC, but this varies greatly between studies with different interpretation of historical and future trends (Broch et al. 2013, Henders and Ostwald 2014, Meyfroidt et al. 2013, Næss-Schmidt et al. 2011, Seto et al. 2012, Warner et al. 2013, Wicke et al. 2012).	x	x	x
Propagating effects of marginal changes in land and product use: Two types of propagation were conceptualized. Local propagation occurs when a direct displacement of one land class by another results in the expansion of this displaced land class within the same territory. The same effect may then propagate by displacement of other land classes. For example, in a case in Brazil, pastures are displaced by soybean cultivation and in turn displace forests (Barona et al. 2010). Distant propagation occurs when the increased consumption and/or reduced production of one product class create a supply gap (and trigger higher crop prices), which then gives incentives to increase production elsewhere in the world (Tipper et al. 2009). This effect may propagate from one region to another as long as there are direct or indirect trade linkages. Such distant propagation can be more complex to determine than local propagation. It is often interpreted differently due to lack of empirical studies, leading to discrepancies in CSC-LUC allocation (Meyfroidt et al. 2013, Næss-Schmidt et al. 2011, Seto et al. 2012).	x		x
Delineation of spatial boundaries: Spatial boundaries are applied to limit the spatial extent (boundaries around the study area) and spatial scale (boundaries between different territories within the study area, e.g. provinces within Indonesia) of the analyses. For example, displacement and expansion of land class A in two different territories are regarded as two separate events in land-use analysis. Changing boundaries will have significant effect to quantitative results (Seto et al. 2012, Warner et al. 2013).	x	x	x

Inclusion of non-agricultural and non-productive drivers: Non-agricultural drivers like logging and fire, as well as expansion and displacement of land classes which do not result in tradable agricultural products (here referred to as non-productive land classes) also play an important role in CSC-LUC. Examples of these non-productive land classes include unused arable land, shrub land, temporary grassland, desert and others. The expansion of these land classes can be linked to various underlying causes, which could be human interventions (e.g. land abandonment) or natural processes (e.g. wild fire) (Hosonuma et al. 2012). Linking these drivers to agricultural activities or not (and to what extent) alters the final quantitative results (Bruckner et al. 2015, Cowie et al. 2012, Warner et al. 2013).	x		
Allocation mechanism and allocation key: This function has two aspects. First, CSC-LUC is linked to land and product classes through different allocation mechanisms depending on the purpose, e.g. to investigate the impact caused by marginal changes in consumption, or to distribute CSC-LUC among all the consumers. Second, these allocation mechanisms also come with the problem of choosing the 'allocation key' (i.e. a common and relevant attribute of the various products over which emissions are allocated) that has been extensively discussed in LCA (Luo et al. 2009, Cherubini and Strømman 2011) as well as consumption-based CSC-LUC studies (e.g. monetary vs physical flows discussed by Kastner et al. 2014). The divergence in final results may grow larger depending on the consideration of by- or co-products as well as the extent of trade linkages to be traced.	x	x	x
Temporal dynamics: This function consists of three aspects: time-step of change (unit of time), temporal extent (period to account for) and temporal distribution mechanism (mechanism to distribute CSC-LUC across time). As a piece of land can be productive for many years, CSC-LUC occurring at the initial conversion stage is often amortized over several years (Broch et al. 2013). However, LUC is also a dynamic process where a piece of land may be converted multiple times for multiple purposes during or beyond the course of the amortisation period. The underlying causes of such process may be interwoven and the causal relationship could be complex when it involves transitional land classes (Brandão et al. 2013, Cowie et al. 2012, Kløverpris and Muller 2013, Seto et al. 2012, Warner et al. 2013). Attributing CSC-LUC to such multiple land-uses depends on all the three settings.	x		
Extent of trade linkages: The core idea of consumption-based analysis is linking CSC-LUC in one territory to consumers in another territory via trade. With rapid globalization, a substantial share of agricultural products is increasingly traded internationally in much more complex patterns. Palm oil as a commodity, together with its derivatives, is cross-traded between producers, processors and consumers (Goh et al. 2013; 2014). This function determines the extent of tracing product origins and destinations (for both raw materials and derivatives), considering three aspects: spatial boundaries, re-exports and extension to derivative products. Adjusting these establishes different quantitative links between CSC-LUC and distant consumption (Bruckner et al. 2015, Henders and Ostwald 2014, Hubacek and Feng 2016).		x	

Table S3-2. Overview of selected studies on CSC-LUC for Indonesian palm oil

Studies	Objectives (quoted from the original publications)	Geographical scope	Land-use analysis	Trade analysis	Market analysis	Main findings (adapted from the original publications)
Historical approach (to quantify CSC-LUC caused by oil palm in the past)						
Saikku et al. 2012	*"…develop a robust and transparent method to avoid emission leakage by considering CO_2 emissions from deforestation using end-use responsibility as a principle."*	Brazil and Indonesia (producers)	Spatially aggregated	Direct allocation to primary importer based on bilateral trade	-	Approximately 32% and 15% of the total agricultural land harvested and LUC emissions in Brazil and Indonesia respectively were due to exports. For Brazilian ethanol produced from sugar cane, the carbon lost calculated was 0.36 tC/t product. For palm oil produced in Indonesia, the corresponding figure was 6.86 tC/t product.
Persson et al. 2014	*"…propose a new methodology for calculating land-use change carbon footprints for agricultural commodities and illustrate this methodology by applying it to three of the most prominent agricultural commodities driving tropical deforestation."*	Brazil and Indonesia (producers)	Spatially aggregated and explicit	-	-	Land-use change carbon footprints in 2010 are estimated to be 66 tCO_2/t meat (carcass weight) for Brazilian beef, 0.89 tCO_2/t for Brazilian soybeans, and 7.5 tCO_2/t for Indonesian palm oil.
Henders et al. 2015	*"…quantify tropical deforestation area and carbon emissions from LUC induced by the production and the export of four commodities (beef, soybeans, palm oil, and wood products)…"*	A number of tropical countries including Indonesia (producers)	Spatially aggregated and explicit	Allocation to apparent consumption by making assumption on re-export	-	For Southeast Asia, embodied emission flows are dominated by exports of palm oil and wood products to consumers in China, India and the rest of Asia, as well as to the European Union. In 2011, oil palm was the second largest source of embodied emissions (327±73 $MtCO_2$).
Agus et al. 2013	*"…provide estimates of the greenhouse gas (GHG) emissions linked to other productive sectors and place the emissions directly linked to palm oil in the broader context of land cover and land use change."*	Malaysia, Sumatra, Kalimantan, Papua and Papua New Guinea (producers)	Spatially explicit	-	-	Oil palm is estimated to be responsible for approximately 13% of the total emissions from aboveground carbon due to LUC and peat oxidation between 2000 and 2005, and 18% between 2006 and 2009/2010. Emissions from logging and wildfire were estimated at 39% between 2000 and 2005 and 36% between 2006 and 2009/2010.

Abood et al. 2015	*"…compare the magnitudes of forest and carbon loss, and forest and carbon stocks remaining within oil palm plantation, logging, fiber plantation (pulp and paper), and coal mining concessions in Indonesia."*	Indonesia (producer)	Spatially explicit	-	-	Oil palm industry was ranked third in terms of deforestation (~1 Mha), and second in terms of carbon dioxide emissions (~1,300-2,350 Mt CO_2).
Lee et al. 2014	*"…compare the magnitude of forest and carbon loss attributable to smallholdings, private enterprises, and state-owned oil palm plantations in Sumatra."*	Sumatra (producer)	Spatially explicit	-	-	Oil palm-driven deforestation in Sumatra resulted in 756–1,043 Mt of total gross carbon dioxide emissions, of which ~90% and ~9% can be attributed to private enterprises and smallholdings, respectively.
Projection approach (to estimate expected CSC-LUC caused by future oil palm expansion)						
Laborde 2011	*"…analyse the impact of the EU biofuels mandate, and possible changes in EU biofuels trade policies, on global agricultural production and the environmental performance of the EU biofuel policy as concretised in the RED."*	Global, with special focuses on big producers and consumers	Spatially aggregated	Direct allocation to biofuel consumer	Economic model	Sunflower and palm oil are the only biodiesel feedstocks that generate (small) net emission savings for biodiesel (4 to 6 $grCO_2eq/MJ$, <6% of the fossil fuel comparator). LUC emission of palm oil in 2020 with methane capture at mill associated with 1 MJ of palm-based biofuel is 54 g $CO_2eq/MJ_{biofuel}$ (55 with trade liberation).
Bauen et al. 2010	*"…develop an understanding of the chain of causes and effects that lead from an increased demand for biofuel feedstock to indirect land use change (ILUC), and provides a framework for capturing and quantifying those relationships."*	Global, with special focuses on big producers and consumers	Spatially aggregated	Direct allocation to biofuel consumer	Causal descriptive	For palm biodiesel, the 'ILUC factor' ranges from 5.9 to 82 gCO_2e/MJ, followed by soy (8.7 to 66 gCO_2e/MJ) and rapeseed (15 to 35 gCO_2e/MJ). For wheat ethanol, its 'ILUC factor' ranges from -53 to -5.1 gCO_2e/MJ, while that of sugarcane ethanol ranges from 7.8 to 27 gCO_2e/MJ.

Harris et al. 2013	*"…simulate future scenarios of oil palm expansion until the year 2050" and "…quantify the potential extent and location of future oil palm expansion and resulting net carbon emissions."*	Malaysia, Sumatra, Kalimantan, Papua, Papua New Guinea (producers)	Spatially explicit	-	Causal descriptive	Net cumulative carbon emissions under Business As Usual (BAU) are estimated to be 15.2 Pg CO_2 by 2050; ~77% of these emissions would originate from the continuous drainage of peat. Halting expansion into peat areas and shifting it to lower biomass areas can potentially reduce total net cumulative emissions by more than 50%. Restoration of peat would lead to annual emissions near zero for a mature stable oil palm sector covering approximately 21 Mha of plantations.
Fritsche et al. 2010	*"…introduces a deterministic approach … giving an outlook to the range of possible future iLUC factor values from 2010 to 2030."*	Global	Spatially aggregated	Direct allocation to biofuel consumer	Deterministic	For the 50% iLUC factor, greenhouse gas emissions of palm oil are estimated to be -55, 48, 213 g $CO_2eq/MJ_{biofuel}$, for the case of converting degraded land, grassland and forest, respectively.
Overmars et al. 2015	*"…understand how much crop expansion (and hence ILUC) would be attributed to 1 megajoule of biofuel if the crop had been used for that purpose."*	Global	Spatially aggregated	Direct allocation to biofuel consumer	Deterministic	ILUC emissions calculated by a methodology using historical data are generally in line with those of economic models, showing a lower impact of cereals and sugar crops compared to vegetable oils. Best-estimates ILUC emissions for Indonesian palm oil range from 207 to 249 gCO_2/MJ.
Bird et al. 2013	*"…identify the amount and type of land use change required to satisfy increased food energy demand and so can be used to estimate indirect land use change if agricultural crops are used to the production of biomass for energy."*	Global	Spatially aggregated	Assuming perfect material flows across the whole world	Deterministic	The model suggests that: (i) for every increase of 1 TJ of food energy demand there is 18 ha of deforestation worldwide. (ii) if the current trend continues then the EU Renewable Energy Directive and the US Ethanol Program will cause 28-53 Mha and 20-38 Mha of deforestation; (iii) the deforestation caused by the conversion of a hectare of food-producing land to biofuel production depends on the amount of food energy that the land produced.

Table S3-3. Overview of the settings for the eight key functions of the selected historical studies.

Studies / Functions	Saikku et al. 2012	Persson et al. 2014	Henders et al. 2015	Agus et al. 2013	Abood et al. 2015	Lee et al. 2014
Classification of lands and products	6 land classes with each class having one product class.	Land: Not applicable (based on results of other land-use analyses) Product: Palm oil for the Indonesian case.	Land: Not applicable (based on results of other land-use analyses) Product: Palm oil and timber for the Indonesian case.	Land: 22 land classes. Product: Not specified.	Land: 5 forest classes were examined for their losses. Other areas were classified based on concession boundaries (logging, fibre, oil palm and mining) regardless of the land cover.	Land: 4 forest classes were examined for their losses. Oil palm area was classified based on concession boundaries (private enterprise, small-holdings or state-owned) regardless of the land cover.
Interactions between land and product classes	Not considered.	Land: Based on literature (both spatially aggregated and explicit land-use analyses). Product: Not considered.	Land: Based on literature (both spatially aggregated and explicit land-use analyses). Product: Not considered.	Land: Direct LUC was accounted for using spatially explicit method. Product: Not considered.	Land: Direct LUC was accounted for using spatially explicit method. Product: Not considered.	Land: Direct LUC was accounted for using spatially explicit method. Product: Not considered.
Propagating effects of marginal changes in land and product use	Not considered.	Local propagating effect (within the spatial boundary) was estimated through spatially aggregated approach by considering only the net area changes of each land class.	Not considered.	Not considered.	Assumed that all deforestation occur within an industrial concession was related to that particular industry.	Assumed that all deforestation occur within an oil palm sectorial boundaries was related to that particular type of ownership.
Delineation of spatial boundaries	National boundaries were used.	For Indonesia, national boundary was used.	National boundaries were used.	Sub-national boundaries were used (outer islands).	Sub-national boundaries were used (outer islands).	Sub-national boundaries were used (outer islands).

Inclusion of non-agricultural and non-productive drivers	Not considered.	CSC-LUC was partly allocated to logging using preset ratio based on literature findings and own assumptions, but non-productive drivers were not taken into account.	CSC-LUC was partly allocated to timber using preset ratio based on literature findings and own assumptions, but non-productive drivers are not taken into account.	CSC-LUC was allocated to oil palm, logging and wildfire.	In addition to oil palm, CSC-LUC was allocated to different industries, i.e. logging, fibre and mining. Non-productive drivers (e.g. uncontrolled fire) are not isolated.	Not considered.
Allocation mechanism and allocation key	CSC-LUC was allocated to product classes proportional to land area used by each product class. Then, CSC-LUC is distributed averagely among the products in the same class by weight.	Direct CSC-LUC was allocated to land class based on spatially explicit analysis. The indirect allocation factor was calculated by dividing annual changes in area devoted to produce a given commodity by the total change in agricultural area for all commodities exhibiting an increase in area. Then, CSC-LUC was distributed averagely to products based on revenues received.	CSC-LUC was allocated to palm oil based on pre-set values derived from literature findings and own assumptions on weight basis.	CSC-LUC was allocated to land class based on spatially explicit analysis but not to single unit of palm oil.	CSC-LUC occurred within an industrial concessions (e.g. oil palm or mining) was allocated to that particular industry, regardless of the actual outcome (i.e. whether the CSC-LUC resulted in actual oil palm establishment or not).	CSC-LUC occurred within oil palm sectorial boundaries was allocated to that particular sector (private enterprise, smallholdings or state-owned).
Temporal dynamics	Time step is one year. No amortisation.	Time step is one year. CSC-LUC is amortised to 10 years.	Time step is one year. For palm oil, CSC-LUC is amortised to 10 years.	Time steps are 10 years (for 1990-2000) and 5 years (for 2001-2010). No amortisation.	Time step is 10 years (2000-2010).	Time step is 10 years (2000-2010).

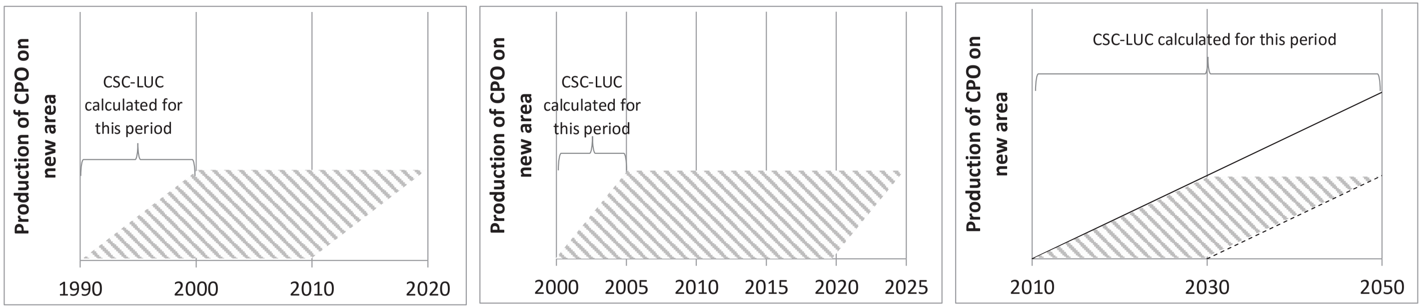
Extent of trade linkages	Bilateral trade of primary products was considered.	Not considered.	Bilateral trade of primary products was considered, assuming that the imported products were partly re-exported again and the rest were consumed or stored domestically, in the same ratio of total export to total domestic consumption.	Not considered.	Not considered.	Not considered.

Table S3-4. Overview of the settings for the eight key functions of the selected projection studies.

Studies / Functions	**Laborde 2011**	**Bauen et al. 2010**	**Harris et al. 2013**	**Fritsche et al. 2010**	**Overmars et al. 2015**	**Bird et al. 2013**
Classification of lands and products	Land: Classified into cropland, savannah, grassland, managed and primary forest by agro-ecological zones. Product: Four oil crops were considered. Co-product classes were examined.	Land: 7 non-agricultural land classes for all cases and different crop land classes were examined in each case. Product: Breakdowns of substitutable product and co-product were examined.	Land: 22 land classes. Product: Not specified.	Land: Three land classes were defined as potential candidates for oil palm conversions. Product: Three oil crops were investigated.	Land: Followed the FAO classification. Product: 12 main product classes (feedstock for biofuel) but by-products are also distinguished.	Land: Not relevant. Product: Not relevant.

Interactions between land and product classes	Land: Used a ratio to aggregately account for area displaced by oil palm in the future (25% of net total cropland expansion where 30% of that happens on peatland). Product: A range of parameters that represent elasticity of substitution were employed.	Land: Calculated yield and area changes in the future according to change in demand based on historical relationships. Product: Supply-demand relationships were implicitly projected based on historical trends and expert opinion.	Land: Used varied assumptions about where expansion is allowed to occur based on land suitability, hypothetical policies and programs to promote climate change mitigation in three different scenarios. Product: Not considered.	Land: Proposed that three types of conversion can happen, i.e. conversion of grassland, degraded land and forest to oil palm. Product: Not considered.	Land: Emission factors allocated to specific land classes were adopted from IMAGE and CSAM models. Product: Not considered.	Land: Assumed historical deforestation rate will remain the same in the future. Product: Assumed all product classes are fully substitutable on calorific basis.
Propagating effects of marginal changes in land and product use	Indirect effects were accounted using a complex economic model with various algorithms that represent interactions between product classes (e.g. substitution).	Local propagating effect (within the spatial boundary used to quantify land classes) was estimated through spatially aggregated approach by considering only the net area changes of each land class. These net area changes qwre determined by changes in demand and prices which propagate across borders through pre-defined supply-demand elasticity considering different bilateral trade specifications.	Not considered.	The ‘world mix’ was used as a proxy for the average pattern of all displaced land.	Two approaches were used: For the ‘local approach’, it was assumed that extra crop production takes place in the region where crop was diverted to biofuel. For the ‘export region’ approach, the extra crop production was assumed to occur in the world regions that export that crop group, no matter where the biofuel was actually produced.	Global aggregated approach was used to estimate global propagating effect by considering the net changes in global consumption and CSC-LUC.

Delineation of spatial boundaries	National and supra-national.	National and supra-national.	National and sub-national.	National and supra-national.	National and supra-national.	Global.
Inclusion of non-agricultural and non-productive drivers	Not considered.	Logging.	Not considered.	Not considered.	Not considered.	Not considered.
Allocation mechanism and allocation key	Net CSC-LUC compared to baseline scenario was assigned to biofuels on energy basis.	CSC-LUC was allocated to land classes by other land classes they displaced, and combined with indirectly avoided or triggered emission by other crops. Then, it was distributed averagely among the products in the same class by energy content.	Net CSC-LUC compared to baseline scenario was assigned to oil palm expansion but not to single unit of palm oil.	Per ha ILUC emission was assumed to be certain % of the CO_2 emission from per ha LUC associated with the average 'world mix'. It was then assigned to palm oil biodiesel on energy basis.	CSC-LUC for land classes was directly borrowed from IMAGE and CSAM, and further distributed among (by-) products from the same land class. Two allocation keys were used for comparison: mass and economic values.	Linearly correlated global CSC-LUC with net food energy consumption. Allocation key used is energy.
Temporal dynamics	Time step is one year. CSC-LUC is amortised to 20 years.	Time step is one year. CSC-LUC is amortised to 30 years, but also to 100 years in a scenario of palm oil. Projection is made until 2020.	Time step is 10 years. No amortisation. Projection is made until 2050.	Time step is one year. No amortisation.	Time step is four years for cancelling annual variations. CSC-LUC is amortised to 20 years.	Time step is one year. No amortisation.
Extent of trade linkages	Two trade scenarios were analysed: status quo and free trade.	Bilateral trade specifications were considered, covering direct trade of both primary products and co-products, and projected based on expert opinions.	Not considered.	Not considered.	Not considered.	All products were assumed freely accessible across the world.



(a) (b) (c)

(a) Illustrated for Agus et al. (2013) for 10 years analysis (1990-2000)
(b) Illustrated for Agus et al. (2013) for 5 years analysis (2001-2005; 2006-2010)
(c) Illustrated for Harris et al. (2013) for 40 years analysis (2010-2050)

Notes: Each year after the starting year, some new area has been established. The key assumption is that both the expansion rate and amount of new CPO produced follow a linear trend. The shaded part represents CPO production from area established between the years analysed. The lower right is excluded because a 20-year scheme is adopted. As such, the amount of CPO represented by the shaded part can be simply derived by (a) multiplying the total production in 1990-2000 by 4, (b) multiplying the total production in 2000-2005 by 8, and (c) halving the total production in 2010-2050.
To calculate CSC-LUC for 20-year-amortisation, for case (a) and (b), we divide the total CSC-LUC in the years analysed with the total production represented by the shaded part to obtain a value at tCO_2/tCPO. For case (c) we divide the total CSC-LUC in 2010-2050 to half (thus 20 years), and this amount of CSC-LUC is further divided to the production represented by the shaded part to obtain a value at tCO_2/tCPO.

Figure S3-1. Illustrations for simplified amortisation schemes used for Agus et al. (2013) and Harris et al. (2013)

3

CHAPTER 4

Linking carbon stock change from land-use change to consumption of agricultural products (II): Alternative perspectives

Authors

Chun Sheng Goh

Birka Wicke

André Faaij

David Neil Bird

Hannes Schwaiger

Martin Junginger

"With four parameters I can *fit* an elephant, and with five I can make him wiggle his trunk." --- John von Neumann

ABSTRACT

Agricultural expansion driven by growing demand has been a key driver for carbon stock change as a consequence of land-use change (CSC-LUC). However, its relative role compared to non-agricultural and non-productive drivers, as well as propagating effects were not clearly addressed. This study contributed to this subject by providing alternative perspectives in addressing these missing links. A method was developed to allocate historical CSC-LUC to agricultural expansions by land classes (products), trade, and end use. The analysis for 1995-2010 leads to three key trends: (i) agricultural land degradation and abandonment is found to be a major (albeit indirect) driver for CSC-LUC, (ii) CSC-LUC is spurred by the growth of cross-border trade, (iii) non-food use (excluding liquid biofuels) has emerged as a significant contributor of CSC-LUC in the 2000's. In addition, the study demonstrated that exact values of CSC-LUC at a single spatio-temporal point may change significantly with different methodological settings. For example, CSC-LUC allocated to 'permanent oil crops' changed from 0.53 Pg C (billion tonne C) of carbon stock gain to 0.11 Pg C of carbon stock loss when spatial boundaries were changed from global to regional. Instead of comparing exact values for accounting purpose, key messages for policymaking were drawn from the main trends. Firstly, climate change mitigation efforts pursued through a territorial perspective may ignore indirect effects elsewhere triggered through trade linkages. Policies targeting specific commodities or types of consumption are also unable to quantitatively address indirect CSC-LUC effects because the quantification changes with different arbitrary methodological settings. Instead, it is recommended that mobilising non-productive or under-utilised lands for productive use should be targeted as a key solution to avoid direct and indirect CSC-LUC.

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Keywords: Land-use change; Carbon stock; International trade; Consumption; Biofuel; Palm oil.

4.1 INTRODUCTION

Over the past decades, carbon stock change as a consequence of land-use change (CSC-LUC) has contributed significantly to annual global anthropogenic CO_2 emissions, amounted to 8-20% as a result of deforestation, forest degradation and peat emissions (van der Werf et al. 2009). A major driver is the rapid agricultural expansion driven by both growing domestic and international demand for agricultural commodities (DeFries et al. 2010). A number of studies have sought to assess the relative magnitude of historical CSC-LUC triggered by consumption by quantitatively allocating land-use change (LUC) or CSC-LUC to consumers via bilateral international trade linkages (e.g. Karstensen et al. 2013, Persson et al. 2014, Saikku et al. 2012).

Most of these consumption-based studies, however, do not clearly distinguish between the impacts caused by agricultural expansion and non-productive drivers (i.e. causes of CSC-LUC not yielding tradable agricultural products, such as uncontrolled fire and land abandonment). This is despite evidence showing that non-productive drivers have played important roles in global CSC-LUC (Hosonuma et al. 2012). For example, improper land use practices that have caused uncontrolled fires in Indonesia are among the main reasons for massive CSC-LUC (van der Werf et al. 2008). The non-productive drivers may also indirectly exacerbate deforestation rate, as degradation and loss of arable land potentially drives further agricultural expansion elsewhere to fill the production gap. For example, in Brazil, pasture degradation due to inefficient land use followed by land abandonment has driven further pasture expansion into forests (Hondwald et al. 2010, Spera et al. 2014). Thus, not accounting for non-productive drivers and allocating CSC-LUC solely to consumption likely leads to an over-estimation of the impact caused by increasing demand and masks underlying poor land use practices. Recognising and quantifying the magnitude of non-productive drivers helps to identify the underlying causes of CSC-LUC on the producer side and allows designing policies that can target the underlying causes more specifically.

Also, bilateral trade analyses used to link historical CSC-LUC to consumers do not account for indirect effects propagating across spatial boundaries. Concerns over indirect land-use change (ILUC) have been raised in the context of increasing demand for bioenergy (e.g. Searchinger et al. 2008). ILUC occurs when existing agricultural land is converted for biofuel production, leading to agriculture expansion elsewhere to fill the demand gap in the global market through market-mediated effects (Wicke et al. 2012). This is also applicable for demand for food crops – a country with growing consumption will drain the global supply and (in)directly drive further agricultural expansion on a global scale, even if it only imports from countries with no large-scale deforestation. For the case of biofuel, various projection methods (e.g. economic equilibrium models) have been employed to address ILUC, but they are in principle not suitable for distinguishing the effect of different drivers of historical CSC-LUC and are typically subject to high uncertainties (De Rosa et al. 2015, Wicke et al. 2012, Verstegen et al. 2015). Some studies have attempted to cover such propagating effect when accounting for historical CSC-LUC, e.g. Persson et al. (2014) have demonstrated a method to account for ILUC effects within a territory, but the study did not cover global propagating effects.

This work aims to quantify historical CSC-LUC linked to consumptions in different regions, in connection to cross-boundary trades of agricultural products and their end markets while also considering non-productive drivers and indirect effects. The idea is to supply alternative perspectives in viewing the drivers of CSC-LUC from both producer and consumer sides by examining the patterns and trends, particularly when the methodological settings are adjusted, instead of emphasizing the exact magnitude for accounting purpose.

4.2 MATERIALS AND METHODS

This analysis consists of five major steps with three extensions with the workflows shown in Figure 4-1. The method was explained by eight key 'functions' (in italic), i.e. sets of methods, algorithms and parameters embedded in methodologies (see also the previous work Goh et al. 2016a for more details). First, the effects of **delineation of spatial boundary** were taken into account by repeating the analysis with regional and global setting (section 4.2.1). Then, by determining the **classification of lands and products** and considering the **inclusion of non-agricultural and non-productive drivers**, a spatially aggregated analysis was performed to determine carbon stock change of individual land classes (section 4.2.2). This was followed by identifying and capturing direct and indirect CSC-LUC through defining the **interactions between land and product classes**, **propagating effects of marginal changes in land and product use**, and **allocation mechanism and allocation key** (section 4.2.3). The CSC-LUC was then distributed across time based on a pre-defined **temporal dynamics** (section 4.2.4). In the last step, a mechanism was proposed for defining the **extent of trade linkages** so that the calculated CSC-LUC can be allocated to local and distant consumption as well as non-productive drivers (section 4.2.5). In addition, three extensions were designed for wood products, palm oil and soy-beef chain to further explore the impact of adjusting the setting, i.e. employing different ways to address specific issues related to them (section 4.2.6-4.2.8). The data collection and processing was described in the Box S4-1 (supplementary materials), especially the assumptions made to compromise with data shortage. A key assumption is that only living biomass (i.e. above and below ground carbon stock) was accounted, but not soil carbon and dead organic matter due to high data uncertainty (see the last paragraph of Box S4-1). For comparison, the method was tested with the inclusion of peat emission in section 4.2.7.

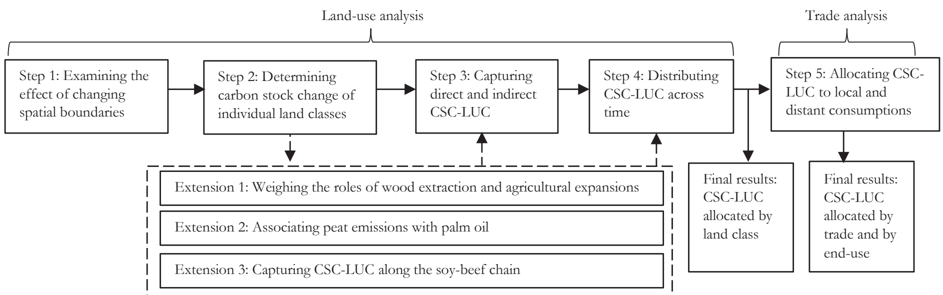


Figure 4-1. Work flow of this study to allocate historical CSC-LUC to different drivers.

4.2.1 Examining the effect of changing spatial aggregation

The first step was **delineation of spatial boundary**, i.e. setting the boundaries between different territories within the study area. Two spatial settings, i.e. on a global and a regional scale, were employed to evaluate the effect of changing spatial aggregation on the results. In the global setting, all lands and forests were treated as global assets, and therefore all consumption regardless of geographical regions share the same liability without trade analysis. This setting aimed to inspect overall trends of CSC-LUC by resolving all indirect effect through aggregating all changes (i.e. only the net changes on global level were inspected). In the regional setting, regions were treated as individual closed territories that were linked via trade. This provided more details on different developments in each region. Table S4-1 shows the aggregation of spatial boundaries (continental and sub-continental) for the regional setting. The analysis was first performed with a global setting using step 2 to 4, and repeated with a regional setting using step 2 to 5 and three extensions, generating two separate sets of results.

4.2.2 Determining carbon stock changes of individual land classes

This step aimed to calculate the total carbon stock stored in individual land classes and its changes over time (e.g. how much carbon is stored in the land class 'fruits' in this year compared to last year – this depends on the total area and average carbon stock of the land class in a particular year). To begin with, lands were divided into several classes. Most of these land classes were linked to different product classes, but some do not result in agricultural products (i.e. non-productive land classes).

Two key functions were involved in this step. First, **classification of lands and products** was performed according to Table S4-2 (supplementary materials) largely based on FAOSTAT (2014) definition. Lands or products within the same class were treated as if they were identical. If two crops were grouped as one class, a displacement of one of these crops by the other was not considered as LUC. FAOSTAT definitions were used because they have distinctive land-use characteristics and connecting product classes used in consumption and trade statistics. 'Permanent crops' and 'temporary crops' were separated as they have significantly different amount of carbon stock.

The role of improper land-use practices was investigated through the **inclusion of non-agricultural and non-productive drivers** by identifying non-productive land classes. First, the remaining arable lands that are not cultivated were grouped as 'unused arable land'. Then, one feature of this study was the introduction of the land class 'unused deforested land' (UDL). UDL represents cleared forested land that has not (yet) been used for agricultural activities in the next time-step. The reason for distinguishing this land class is to track step-wise LUC after deforestation, a phenomenon which does occur widely in deforestation hotspots (Gunarso et al. 2013). A piece of land considered as UDL if it was deforested last year but is not being used this year. The advantage of this setting is that it accounts for new expansion step-wise conversions with a small time delay. This is often not clearly addressed in the other studies

(Goh et al. 2016a). 'Desert' (including tundra) is another unproductive land class, but unfortunately, data as a time series is not available. Thus, the effect of desertification was excluded in the current study. Finally, the remaining lands that do not belong to any land classes were considered to be 'others'. This land class may be a transitional land class that occurs temporarily as the result of a natural disturbance or human activities, e.g. slow regeneration of deforested land, in the form of shrub, temporary meadows and pasture and other lands with sparse vegetation, including human settlements and infrastructure. However, changes in the area of human settlements is insignificant on a global scale, considering that only about 0.5 – 1.5 % of 'non-productive lands' were occupied (Potere and Schneider 2009). While some of the changes of these non-productive land classes may be closely linked to agricultural drivers (e.g. fire to prepare land for oil palm which has gone uncontrolled), they were distinguished and the related CSC-LUC were allocated to the producer regions rather than to the consumers because demand can be fulfilled without involving these drivers, e.g. uncontrolled fire, if sustainable agricultural practices are adopted.

For the actual calculations, land area changes of all other land classes were first calculated by distinguishing the changes as expansion or displacement with a time-step of one year as shown in Eq. 1:

Let

$$\Delta A_{x,t} = A_{x,t} - A_{x,t-1}$$

If

$$\Delta A_{x,t} > 0$$

$$\Delta A_{exp,x,t} = \Delta A_{x,t}$$

$$\Delta A_{dis,x,t} = 0$$

Else

$$\Delta A_{exp,x,t} = 0$$

$$\Delta A_{dis,x,t} = |\Delta A_{x,t}| \quad (1)$$

where
x is the land class;
t is the time-step (year);
$A_{x,t}$ is the land area of x at time t (ha);
$\Delta A_{x,t}$ is the change of land area of x at time t compared to $t-1$ (ha);
$\Delta A_{exp,x,t}$ is the land area of x expanded to other land covers at time t compared to $t-1$ (ha);
$\Delta A_{dis,x,t}$ is the land area of x displaced by other land covers at time t compared to $t-1$ (ha).

The change of area of UDL was derived using Eq. 2. UDL has a lifespan of one year. At the starting of a year, on the one hand, existing UDL was excluded from the UDL land class (converted to other land classes); on the other hand, new UDL area was added to the land class.

4

Let

$\Delta A_{deforestation,t} = \Delta A_{dis,F,t}$

$\Delta A_{agri-expansion,t} = \sum_x^X \Delta A_{exp,x,t} - \Delta A_{exp,F,t} - \Delta A_{exp,D,t} - \Delta A_{exp,OTH,t}$

If

$\Delta A_{deforestation,t} > \Delta A_{agri-expansion,t}$

$\Delta A_{exp,UDL,t} = \Delta A_{deforestation,t} - \Delta A_{agri-expansion,t} - A_{UDL,t-1}$

$\Delta A_{dis,UDL,t} = 0$

Else

$\Delta A_{exp,UDL,t} = 0$

$\Delta A_{dis,UDL,t} = A_{UDL,t-1}$ (2)

where

X is the set of land classes;
'F' is 'forest'; 'D' is 'desert'; 'OTH' is 'others' (see also Table S4-2).

It is important to point out that this UDL area is only an estimate, it may either under- or over-estimate the actual amount of UDL: (i) under-estimation may occur when agricultural expansion happens on existing non-forested land, which means there are more recently deforested lands not being used; (ii) over-estimation may occur when UDL is used for non-agricultural use, such as human settlement, which could not be distinguished here. However, it is still regarded as a reasonable estimation that can be used to account for 'step-wise' expansion.

For x = 'others', its change of area was derived as a remainder, assuming that no creation or loss of total land area:

$\sum_x \Delta A_{x,t} = 0$ (3)

Finally, carbon stock change of an individual land class in a time step are calculated with Eq. 4. Specifically in this study, only forest has a changing $\bar{C}_{x,t}$ every year to account for forest degradation.

Let

$$C_{change,x,t} = A_{x,t}.\bar{C}_{x,t} - A_{x,t-1}.\bar{C}_{x,t-1}$$

If

$$C_{change,x,t} > 0$$

$$C_{gain,x,t} = A_{x,t}.\bar{C}_{x,t} - A_{x,t-1}.\bar{C}_{x,t-1}$$

$$C_{loss,x,t} = 0$$

Else

$$C_{gain,x,t} = 0$$

$$C_{loss,x,t} = A_{x,t-1}.\bar{C}_{x,t-1} - A_{x,t}.\bar{C}_{x,t} \quad (4)$$

where
$C_{change,x,t}$ is the change in total carbon stock of land class x (ktC);
$C_{gain,x,t}$ is the gain in total carbon stock of land class x (ktC);
$C_{loss,x,t}$ is the loss in total carbon stock of land class x (ktC);
$\bar{C}_{x,t}$ is the average value of all carbon stock on one ha of x in a particular year (ktC/ha).

4.2.3 Capturing direct and indirect CSC-LUC

This step distributed carbon stock loss to individual land classes and their products, involving three key functions. First, the **interactions between land and product classes** were determined. Although they might be classified differently, lands and products from different classes can be convertible or substitutable. It is possible to switch from one land-use (or product) to another, depending on a multitude of conditions, e.g. economic incentives or geographical conditions. As reviewed in the previous work, the uncertainty and arbitrariness in capturing these interactions is large (Goh et al. 2016a). To avoid making more arbitrary choices (e.g. how much land class A is displaced by B or C based on different methods and assumptions), only the net changes in total area of individual land classes at spatially aggregated level were accounted for (i.e. we do not distinguish whether land class A is actually displaced by land class B or C). This avoids the uncertainties from making numerous assumptions which cannot be calibrated with empirical evidence especially in the global context, yet incorporating propagating effects within the spatial boundaries.

Then, **propagating effects of marginal changes in land and product use** were incorporated. Change of land-use in one place can also trigger local and distant propagation effects (Wicke et al. 2012). Local propagation occurs when a direct displacement of one land class by another results in the expansion of this displaced land class within the same territory, while distant propagation occurs when the increased consumption and/or reduced production of one product class create a supply gap in the global market (and trigger higher crop prices), which then gives incentives to expand the cultivation of this product class elsewhere in the world (Tipper et al. 2009). Two key assumptions employed to account for these effects were (i) perfect substitutability within a product or land class and (ii) perfect free trade conditions between territories. For local propagation, all land expansions shared the liability proportionate to the expanded area regardless of what land classes they displace, considering the multiple orders of propagating effect after expansion and displacement within the pre-set spatial boundaries (see Figure S4-1). Based on perfect substitutability, if 1 ha of 'cereals' field with Y amount of yield has been displaced, correspondingly some new 'cereals' fields will be established elsewhere to produce Y amount of 'cereals' to maintain the consumption level. However, there was no data on the actual yields on both displaced and new fields at global and regional level as time series. One potential risk for this assumption is that the new field has a lower yield than the displaced field, and a larger area is required to fill the demand gap. However, a high yield field is less likely to be displaced. Also, the global average yield has been increasing (FAOSTAT 2014). Thus, the risk of under-estimating the propagating effect is low at a higher spatially aggregated level. For distant propagation via international trade, the 'market pool' concept was employed (as described in section 4.2.5) based on assumption (ii). The advantage is that the market pool concept captures all the indirect effects globally. It is assumed that if one type of 'cereals' is less attractive in terms of price or other reasons, other types of 'cereals' are perfectly substitutable for the consumers (assumed they are one aggregated group).

The next key function was **allocation mechanism and allocation key**, i.e. how CSC-LUC was linked to land and product classes and what 'allocation key' (i.e. a common and relevant attribute of the various products over which emissions are allocated) was used. CSC-LUC was first allocated to land class using the 'relative role in total land expansion' as the allocation factor: i.e. expansion area of a land class per total expansion area of all land classes (see Eq. 6). This mechanism shares the basic allocation concept with Cuypers et al. (2013) and Persson et al. (2014) (only for the part of indirect effects). Persson et al. (2014) described that this allocation method includes also ILUC. However, Cuypers et al. (2013) do not treat all expansion equally, as deforestation is always first allocated to agricultural expansion. In this study, carbon stock loss was equally distributed to all land classes, except for UDL. Since UDL is a direct result of deforestation, respective carbon stock change was first directly allocated to UDL (Eq. 5). In terms of allocation to products, the average allocation mechanism was employed, implying that all existing and new consumers share the same liability. For example, developed nations with small or no additional consumption (but maintaining high volume of consumption as usual) have to share the LUC impacts from the expansion of food crops with developing nations with new additional consumption (with poor level of consumption in the past). In terms of allocation key, energy content was employed instead of mass, based on the trend that global deforestation is linearly correlated to the amount of crops consumed in energy terms (Bird et al. 2013).

Regarding the actual calculation, we first calculate the CSC-LUC allocated to UDL with Eq. 5:

$$\Delta C_{exp,UDL,t} = \Delta A_{exp,UDL,t} . \bar{C}_{F,t} \quad (5)$$

where

$\Delta C_{exp,UDL,t}$ is the carbon stock change caused by expansion of UDL (ktC).

For the other land classes, a denominator $\Delta A_{exp,x,t} / \Delta A_{converted,t}$ was derived to represent the 'relative role in total land expansion' to distribute the remaining carbon stock loss using Eq. 6:

Let

$$\Delta A_{converted,t} = \sum_{x} \Delta A_{exp,x,t} - \Delta A_{exp,UDL,t}$$

$$\Delta C_{exp,x,t} = C_{gain,x,t} - \frac{\Delta A_{exp,x,t}}{\Delta A_{converted,t}} . \left(\sum_x C_{loss,x,t} - \Delta C_{exp,UDL,t} \right) \quad (6)$$

where

$\Delta A_{converted,t}$ is the land area converted excluding UDL (ha);
$\Delta C_{exp,x,t}$ is the CSC-LUC caused by $\Delta A_{exp,x,t}$ (ktC).

4.2.4 Distributing CSC-LUC across time

The key function, **temporal dynamics**, consists of three important aspects: (i) time-step of change (unit of time), (ii) temporal extent (period to account for) and (iii) temporal distribution mechanism (mechanism to distribute CSC-LUC across time). For (i), one year was usually employed as a time-step based on data availability from FAOSTAT (2014). For (ii), different studies have employed different years (e.g. 10 years by Persson et al. 2014, 20 years by Laborde 2011, and 30 years by Bauen et al. 2010) for different reasons. These are arbitrary choices, i.e. there is no single 'correct' period. For example, three years can also be employed for the case of Indonesia, where deforested land is legally allowed to be left unused for maximum three years before conversion to oil palm (Fairhurst et al. 2010). For (iii), CSC-LUC can either be equally distributed for each time-step or using various distribution mechanisms (see also Zaks et al. 2009). This is important in allocating CSC-LUC to different land classes because a piece of land may be converted several times to different classes in multiple time-steps. For example, forest might be first logged and abandoned for a few years, and then converted to annual crops and subsequently to permanent crops (Gunarso et al. 2013, Colchester et al. 2013, Purnomo et al. 2015).

In this method, the CSC-LUC was amortised to the land classes expanded in the next three years, with a distribution factor h, as illustrated with examples in Table 4-1. These land classes carry the CSC-LUC for a period of time until they were displaced. By then, the remaining amortised CSC-LUC was transferred to the newly expanded land classes. Such a mechanism provides a way to address 'step-wise' conversion.

For the actual calculation, total historical carbon stock change passed down by a land class was calculated as below:

$$\Delta C_{total\ historical,x,t} = \sum_{n}^{N} \left(\Delta C_{exp,x,t-n} . h_{t-n}\right) \quad (7)$$

where
$\Delta C_{total\ historical,x,t}$ is the total historical carbon stock changes of x passed down from previous years (ktC).
n is the number of past years that the carbon stock change will be amortised to current year;
N is the maximum number of past years that the carbon stock change will be amortised to current year;
h is the factor that distributes the carbon stock change across different years.

To distribute more CSC-LUC to the first year of the expansion, and gradually decrease the allocation, as a demonstration the following conditions were added to Eq. 7:

$N = 2$;
$h_{t-1} = 0.30$;
$h_{t-2} = 0.20$

This set of conditions attribute 30% of carbon stock change a year ago and 20% of carbon stock change two years ago to the current year; which means that 50% of carbon stock change is allocated to the year of expansion. The key assumption is that a typical 'step-wise' expansion will occur in less than three years-time.

Table 4-1. Examples of amortisation mechanism of CSC-LUC using a 3-years amortisation.

	Year 1	Year 2	Year 3
Case 1			
Event	*Deforestation*	*Nothing happens*	*Nothing happens*
Unused deforested land	$a_1 \times h_1$	$a_1 \times h_2$	$a_1 \times h_3$
Land class A	-	-	-
Land class B	-	-	-
Case 2			
Event	*Deforestation*	*Expansion of land class A*	*Nothing happens*
Unused deforested land	$a_1 \times h_1$	-	-
Land class A	-	$a_1 \times h_2$	$a_1 \times h_3$
Land class B	-	-	-
Case 3			
Event	*Deforestation*	*Expansion of land class A*	*Expansion of land class B*
Unused deforested land	$a_1 \times h_1$	-	-
Land class A	-	$a_1 \times h_2$	-
Land class B	-	-	$a_1 \times h_3$

a_t : CSC-LUC (g C) in year *t*; h_t: Amortisation factor, where *t* = year

Then, Eq.8 was employed to determine how much will be inherited by checking the area of individual land class. If the area is less than last year, then only a proportion will be inherited. The rest of the historical CSC-LUC will go into a 'historical pool' which will be accounted for later. The $A_{x,t-1} \neq 0$ condition is used to avoid zero division error, which will happen when that particular land class has diminished in the particular year, e.g. UDL which is a temporary land class. The key assumption is that a typical 'step-wise' expansion will occur in less than three years-time.

If

$$A_{x,t-1} \neq 0$$

$$\Delta C_{direct\ historical,x,t} = \frac{A_{x,t-1} - \Delta A_{dis,x,t}}{A_{x,t-1}} . \Delta C_{total\ historical,x,t}$$

Else

$$\Delta C_{direct\ historical,x,t} = 0 \qquad (8)$$

where

$\Delta C_{direct\ historical,x,t}$ is the direct historical carbon stock changes inherited by x (ktC);

The CSC-LUC which is not distributed through Eq. 8 is gathered in a 'historical pool' as shown in Eq. 9, and will be re-distributed to other expanded land class in Eq. 10 as indirect historical CSC-LUC, again using also the relative role in total land expansion.

$$\Delta C_{historical\ pool} = \sum_x \left[\Delta C_{total\ historical,x,t} - \Delta C_{direct\ historical,x,t}\right] \quad (9)$$

$$\Delta C_{indirect\ historical,x,t} = \frac{\Delta A_{exp,x,t}}{\Delta A_{converted,t}} . \Delta C_{historical\ pool}$$

(10)

where
$\Delta C_{historical\ pool}$ is the historical CSC-LUC that has not been directly inherited by x (ktC);
$\Delta C_{indirect\ historical,x,t}$ is the indirect historical CSC-LUC inherited by x (ktC).

Lastly, final CSC-LUC is allocated to product by a summation of current and historical carbon stock change distributed among the products based on energetic value in Eq. 11 and eq. 12:

$$\Delta C_{combined,x,t} = \Delta C_{exp,x,t} . h_0 + \Delta C_{direct\ historical,x,t} + \Delta C_{indirect\ historical,x,t} \quad (11)$$

$$\overline{\Delta C}_{combined,x,t} = \frac{\Delta C_{combined,x,t}}{P_{x,t}}$$

(12)

where
$\Delta C_{combined,x,t}$ is the CSC-LUC caused by $\Delta A_{exp,x,t}$ using temporal distribution factor h (ktC);
$h_0 = 0.50$;
$P_{x,t}$ is the production of tradable primary product x in energetic value of petajoule (PJ);
$\overline{\Delta C}_{combined,x,t}$ is the average change CSC-LUC caused by $\Delta A_{exp,x,t}$ using temporal distribution factor h per unit of tradable primary product (ktC/PJ).

4.2.5 Allocating to local and distant consumption

The key function, **extent of trade linkages**, has three aspects: (i) spatial boundaries, (ii) extent of countries' re-export and (iii) extent of product chain. For (i), this step was applicable using the regional setting but not for the global setting. For (ii), CSC-LUC was allocated to distant consumption via the 'market pool' concept to fully cover all indirect effects. It assumed that the global market is fully (directly or indirectly) accessible by all producers and consumers, and all substitutable products share the same opportunity value. Figure S4-2 shows how the concept works. Both territory P and Q produced product x, and both territory R and S imported product x. Product x from territory P was allocated with more CSC-LUC than product x from territory Q. However, after they entered the market pool, the embodied CSC-LUC of all product x in the market was averaged. Both territory R and S share the CSC-LUC based on proportion of consumption of product x, but not by the actual origins of products imported. The setting assumed that if territory R does not import from territory Q, territory S will take over the import from territory Q, and vice versa. In this setting, only net import and net export were considered. Such a setting allows including indirect effects (i.e. carbon leakage) and minimizes uncertainties from complex trade flows (i.e. resolving complex re-exports). Naturally, one trade-off of this setting is its inability to monitor selective purchase by the consumers since indirect effects were taken into account. For land class without products, the assigned CSC-LUC was directly allocated to region where the CSC-LUC occurred.

For (iii), a compromise was made due to data availability, i.e. CSC-LUC was only allocated to primary products (without processing or only with preliminary processing). In other words, only the consumers of primary products (who could be processors but not necessarily the final end consumers) were accounted for. For example, the consumption of soybean, soy oil and soymeal was included under temporary oil crops, but the linkages to secondary products (e.g. processed food) or products linked via feed (soymeal) to animals (e.g. beef) are not traced (this was further investigated in section 4.3.6). Crop-based liquid biofuel was an exception: biofuel was identified as a separate end-use (see Table S4-3), and was directly linked to final consumers instead of the processors of primary materials as how it was done for all the other products. However, this only included biofuel made of raw materials that were considered as main or co-products but not waste, as they were purposely produced for fuel use. Liquid biofuels made of waste streams, e.g. biodiesel from used cooking oil was not linked to land-use and thus not included here.

Allocation for domestic and distant consumption was performed as in Eq. 13 and 14, respectively:

$$\Delta C_{combined\_domestic,x,t} = \overline{\Delta C}_{combined,x,t} . D_{x,t} \quad (13)$$

$$\Delta C_{combined\_import,x,t} = \frac{\sum_r \Delta C_{combined,x,r,t} . E_{x,r,t}}{\sum_r E_{x,r,t}} . I_{x,t} \quad (14)$$

where

$\Delta C_{combined\_domestic,x,t}$ is the is the carbon stock change allocated to the consumption of domestic products;

$D_{x,t}$ is the consumption of product x from domestic source in energetic value (PJ);
$\Delta C_{combined\_import,x,t}$ is the is the carbon stock change allocated to the consumption of imported products;

$E_{x,r,t}$ is the product x exported by territory r in energetic value (*PJ*);
r is the territory where the product is being produced and exported;
$I_{x,t}$ is the consumption of primary product x from domestic source in energetic value (PJ).

To further distinguish CSC-LUC by end-use (see Table S4-3), Eq. 13 and Eq. 14 were combined as Eq. 15:

$$\Delta C_{combined\_end\_use,u,t} = \sum_x^X \overline{\Delta C}_{combined,x,u,t} \cdot D_{x,u,t} + \sum_x^X \left(\frac{\sum_r \overline{\Delta C}_{combined,x,r,t} \cdot E_{x,r,t}}{\sum_r E_{x,r,t}} \cdot I_{x,u,t} \right) \quad (15)$$

where

$\Delta C_{combined\_end\_use,x,t}$ is the is the carbon stock change allocated to the consumption for end-use u; u is the end-use.

4

4.2.6 Extension 1: Weighing the roles of wood extraction and agricultural expansions

Wood extraction is a key driver of deforestation, especially in Southeast Asia (Sasaki et al. 2009, Abood et al. 2014). However, the method described earlier did not allocate CSC-LUC to wood harvested from forest. Here, two methods were tested for how to distribute CSC-LUC between forestry and agricultural activities, taking Southeast Asia which has experienced massive logging as well as agricultural expansion as an example. This was performed cumulatively for 1995-2010.

Method 1 ('Direct carbon calculation'): The amount of carbon embodied in all roundwood harvested was calculated based on the conversion factor in IPCC (2006, Table 12.4). This amount of CSC-LUC was then fully allocated to wood products (i.e. paper and paperboard, sawn wood, total fibre furnish, wood-based panels, chips and particles, wood charcoal, wood residues) consumption and export, and the remaining carbon stock loss was allocated to agricultural products or non-productive drivers in proportional as in the previous method. Since soil carbon was not included in this study (see Box S4-1), and roundwood data from FAOSTAT (2014) already includes logging losses, it was assumed that there was no further carbon stock loss during logging.

Method 2 ('Priority for agriculture'): It was assumed that 95% of CSC-LUC allocated to non-productive driver in Southeast Asia was attributable to wood products, based on Hosonuma et al. (2012) (~85% to timber products, ~10% to fuel wood, and the rest to uncontrolled fire or grazing). This method assumes that agricultural activities should be held responsible for all CSC-LUC if deforestation and agricultural expansion happened in the same year (i.e. no transition to non-productive land class).

4.2.7 Extension 2: Associating peat emission with palm oil

CSC-LUC from peat degradation has been a serious problem in Southeast Asia (Agus et al. 2013). Carbon loss through peat fire and oxidation of peat soil are the major sources of carbon stock loss. Agus et al. (2013) reported that the annual peat emissions are about 0.19 billion tC/year for 2000-2005 and 0.22 billion tC/year for 2006-2010 in Malaysia, Indonesia and Papua New Guinea. However, the estimation of this CSC-LUC highly uncertain (Agus et al. 2013, Gunarso et al. 2013, Ramdani and Hino 2013). Peat loss is often associated with agricultural activities, especially oil palm cultivation. Two scenarios were made to examine the role of oil palm in peat loss. this. In the scenario ‘Default setting with peat’, peat emission (taken from Agus et al. 2013) was added to the total CSC-LUC, but the default allocation mechanism was employed for all land classes. In the scenario ‘Pre-allocation to permanent oil crops’, based on Agus et al. (2013), 13% (for 2000-2005) and 18% (for 2006-2010) of the peat emission was allocated to ‘permanent oil crops’ and the rest was distributed to the other land classes by using the default allocation mechanism.

4.2.8 Extension 3: Capturing CSC-LUC along the soy-beef chain

A limitation of this method is that it only accounts for the consumption of primary materials. While inspecting the relationship between distant consumption and production, the question arises is: should CSC-LUC also be allocated to ‘derivative products’ (e.g. processed food, rubber products, clothes etc.) if the added values are kept in the processor countries? A following question is how we define ‘derivative products’? A typical example for discussion is the soy-beef chain in South America. In the current setting of this methodology, soymeal and soy oil are regarded as ‘primary products’ although they are products of crushing soybean. The two main reasons are because the trade and consumption of these two products can be captured on FAOSTAT (2014), and there are no additives (i.e. no incorporation of other raw materials) in them compared to other derivatives. Thus, especially significant for the case of South America, when locally produced soymeal consumed by local cattle to produce beef (partially for export) later, the CSC-LUC embodied in soymeal was allocated to the producing territory, i.e. South America, instead of the ultimate beef consumers. The changes in results were tested if the portion of CSC-LUC embodied in feed consumption was transferred to animal products, simply by adding this amount of CSC-LUC on animal products (which was a good presentative for beef), and recalculating the CSC-LUC embodied in products exported or consumed domestically.

4.3 RESULTS

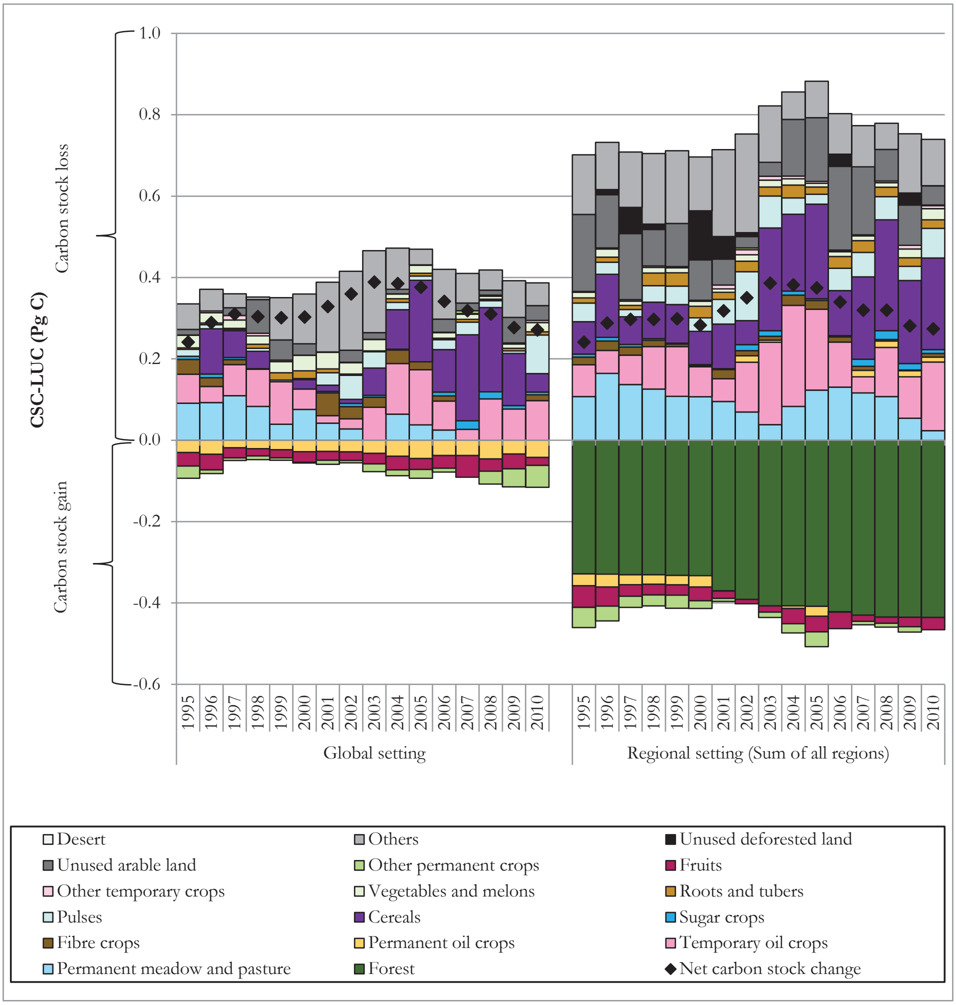
4.3.1 Allocation by land class

Figure 4-2 compares the CSC-LUC allocated to different land classes in 1995-2010 using the global and regional settings. Generally, both settings show that ‘cereals’, ‘temporary oil crops’ and ‘permanent meadow and pasture’ were the major agricultural drivers for CSC-LUC, but there were several differences between the two settings.

For the global setting, as the inputs were spatially aggregated to only one territory, there was no carbon stock gain by afforestation because the net total global forested area had been declining. It highlights that 'permanent oil crops', 'fruits' and 'other permanent crops' had emerged as drivers of carbon stock gain in 1995-2010. This was largely attributable to accounting for indirect land-use savings, considering the lesser demand on land and higher carbon sequestration potential of permanent crops compared to annual crops. Although certain individual plots of 'permanent oil crops' (particularly oil palm plantations in Southeast Asia) were undoubtedly directly associated with carbon stock loss through forest conversion, from a global perspective on CSC-LUC they outcompeted the other lesser productive, more land extensive and without carbon sequestration 'temporary oil crops' (which contribute to more direct and indirect CSC-LUC) such as soybean. Despite that 'permanent oil crops' do not produce protein, they directly compete with 'temporary oil crops' in vegetable oil market and affect each other's supply-demand dynamics. This responds to the findings of Villoria et al. (2013) which suggest that increasing oil palm yields in Southeast Asia would result in an overall net reduction of CSC-LUC at global level with international trade.

Contrarily, with regional setting, substantial carbon stock gains but also higher carbon stock losses were noticed. The carbon stock gain of 'permanent oil crops' seen in the global setting had diminished in many years, because the expansions mainly occurred in regions with high carbon stock loss, particularly Southeast Asia (Figure 4-3). Also, the expansion of 'unused arable land', which represents land abandonment or degradation, had turned out to be an obvious driver with the regional setting (Figure 4-2); they were in total (for 1995-2010) about 4 times larger than in the global setting. This suggests that in certain regions more arable land had lost their productivity, while in other regions more lands had come under agricultural production. The global setting masks such regional variation since no significant net change to the total agricultural land area had occurred. Additionally, a significant amount of carbon stock loss also stemmed from 'unused deforested land', where forests were logged and land was left without any productive activities. This could be linked to step-wise agricultural conversion (where agricultural activities only appear >1 year after deforestation).

Figure 4-3 depicts the trends in each region in 1995-2010. Global carbon stock loss concentrated in three regions: South America, Africa and Southeast Asia. For South America, 'others' and 'unused arable land' were the major drivers of carbon stock loss, together with the major agricultural drivers 'permanent meadow and pasture', 'temporary oil crops' and 'cereals'. This large expansion of 'others' and 'unused arable land' could be a result of massive pasture degradation and abandonment, especially in Brazil (Barona et al. 2010). This implies that there had been expansion of new arable land, but in the meantime some arable land was also abandoned. A research on Mato Grosso (Brazil) revealed that recent expanded lands were more likely to be abandoned because the quality of these lands was lower (high quality land had been exploited much earlier) (Spera et al. 2014). While in Africa the agricultural drivers of CSC-LUC were more diverse: 'unused arable land' was in most years the leading contributor, followed by 'cereals' and 'permanent meadow and pasture'. Land degradation was a key driver for abandoning existing arable land in search of new areas (Barbier 2000). Southeast Asia was the third largest global source of carbon stock loss after South America and Africa, mainly due to rising deforestation since 2002 which was largely caused by the expansion of 'unused arable land' and 'others' in 2003-2005, followed by a sizable expansion of 'cereals'. 'Permanent oil crops' had played an important role in Southeast Asia's CSC-LUC, but this time as a contributor to carbon stock loss in contrast to its role with the global setting. This is because its advantage in indirect effects is limited by the regional boundaries. Meanwhile, within the regional boundaries, Europe had gained the largest carbon stock over the past two decades, followed by East Asia and North America. Overall, it seems that there was a 'virtual shift' of agricultural lands from these regions to South America, Africa and Southeast Asia, and a 'virtual shift' of forests in the reverse direction through reforestation and afforestation initiatives. The other regions were rather smaller actors in global CSC-LUC.



Note: '+' and '-' represents carbon stock loss and gain respectively

Figure 4-2. Time trend (1995-2010) of CSC-LUC allocated to land classes based on their expansion rates using the global and regional setting.

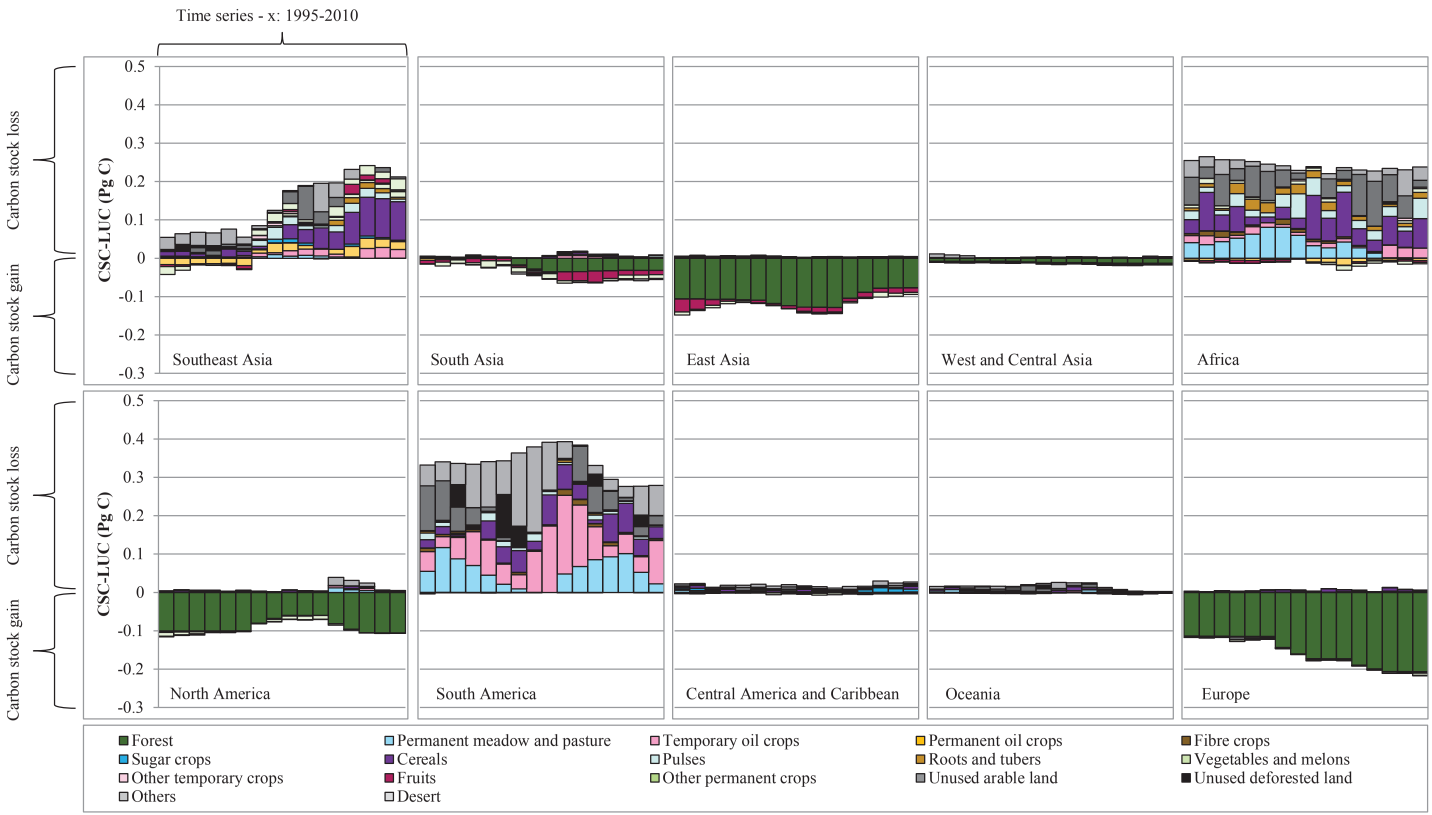


Figure 4-3. Time trends (1995-2010) of CSC-LUC (y: Pg C) allocated to land classes based on their expansion rates using the regional setting.

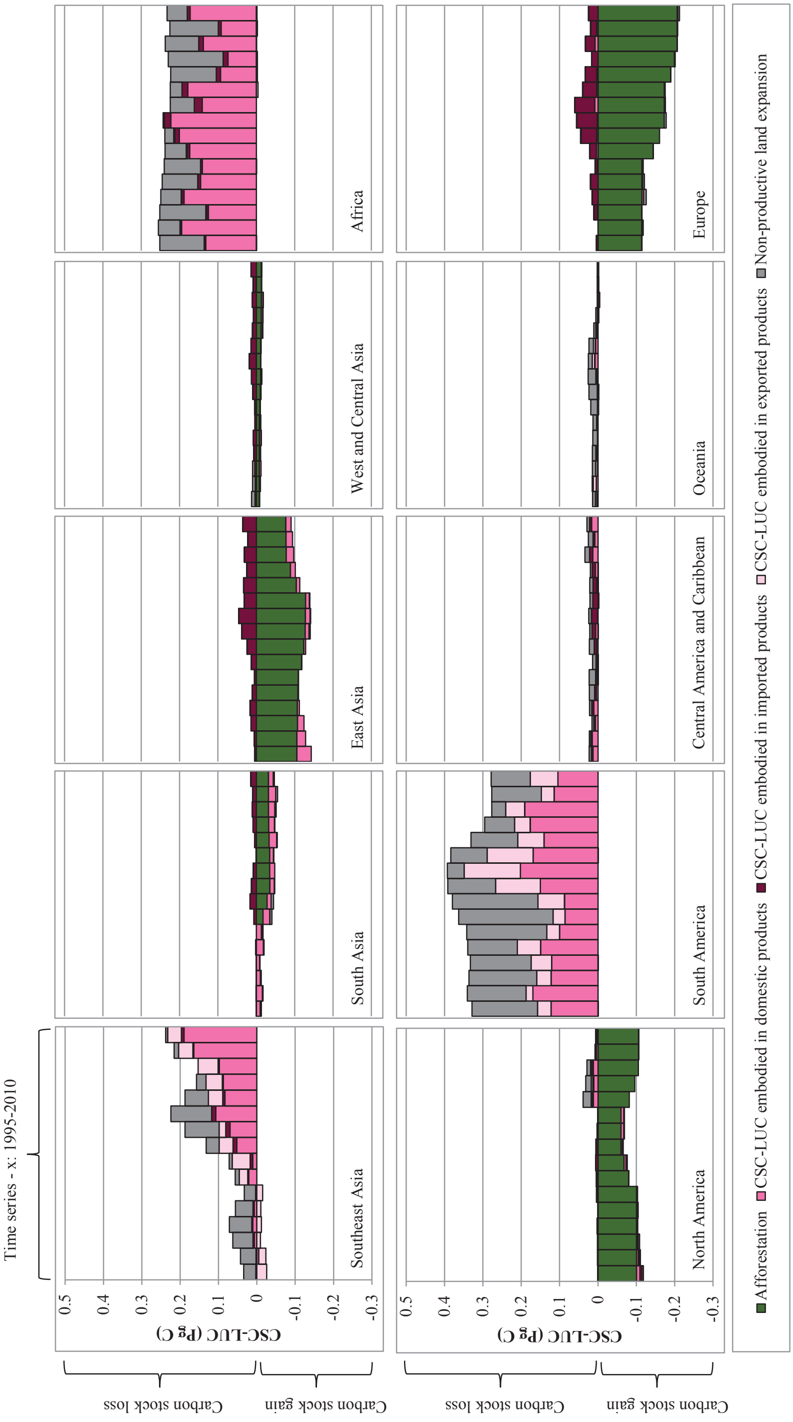


Figure 4-4. Time trend (1995-2010) of CSC-LUC (y: Pg C) allocated to regional consumption with cross-border trade using the regional setting.

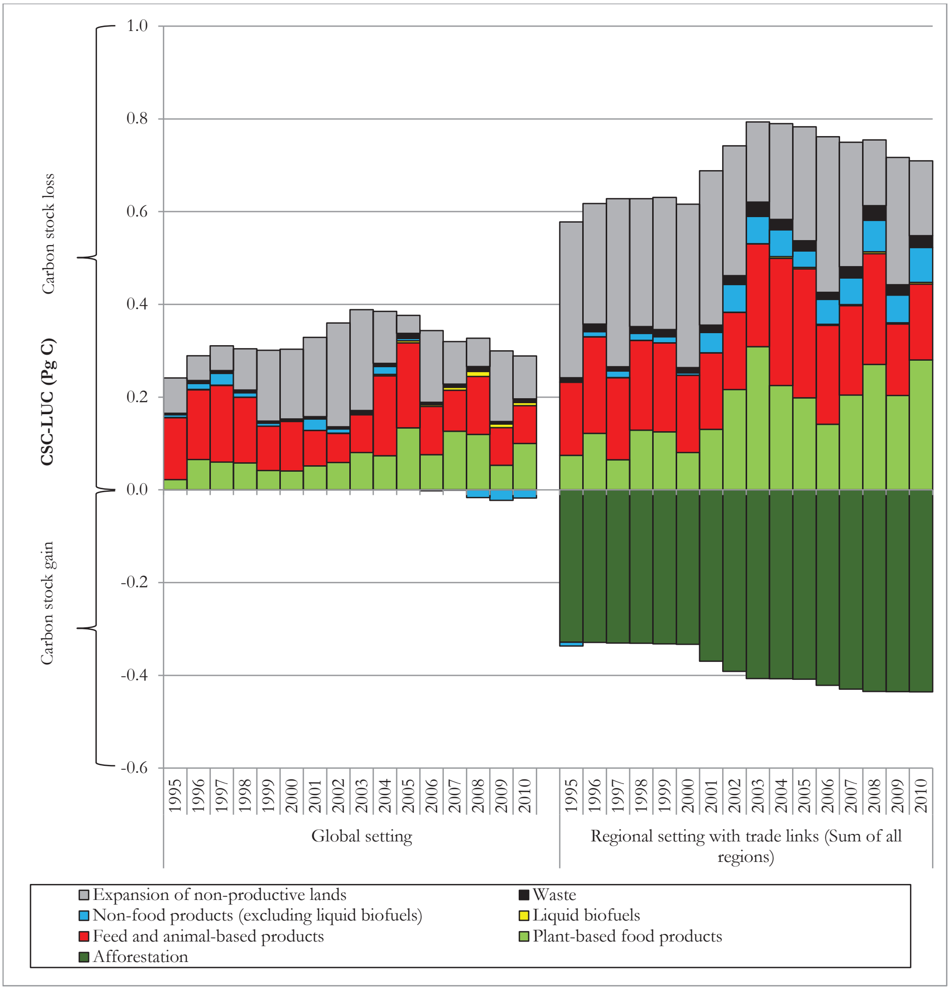


Figure 4-5. Time trend (1995-2010) of CSC-LUC by regions and end-uses using the regional setting.

4.3.2 Allocation by trade

Figure 4-4 illustrates the distribution of regional CSC-LUC linked to cross-region trade flows. In total for all regions, the average gross carbon stock loss exported per annum had increased significantly from <10% of total CSC LUC before 2000 to 8-21% since 2001. This suggests that the role of extra-territorial demand for imported agricultural products had become increasingly important as a driver for CSC-LUC. Amongst the different regions, South America had been the largest source and also the largest 'exporter' of CSC-LUC. Southeast Asia had followed a similar trend since 2000, with about one fifth of its CSC-LUC exported in the form of tradable agricultural products. In contrast, CSC-LUC in Africa, the region with the second largest carbon stock losses, especially in East African countries (FAOSTAT 2014), was driven largely by agricultural production for local rather than international markets (reported also by DeFries et al. 2010), most likely due to increasing population growth (Brink and Eva 2009). Meanwhile, Europe and East Asia were the largest importers of agricultural products with embodied CSC-LUC. Despite large export volumes, North America on aggregate was not associated with exporting carbon stock loss since these were offset by gains from reforestation and afforestation within the region.

4.3.3 Allocation by end-use

Figure 4-5 illustrates the CSC-LUC allocated to different end-uses. For both global and regional settings, 'feed and animal-based products' was the main driver causing carbon stock loss since the beginning, but 'plant-based products' have been catching up throughout the years. For 'non-food products (excluding liquid biofuels)', it appeared to be different in the two settings: it had emerged as a key contributor to carbon stock loss in the regional setting but carbon stock gain in the global setting. This is probably because a large amount of these products came from 'permanent oil crops' in Southeast Asia (see section 4.3.1). In 2010, 'liquid biofuels' production contributed to about 2.5% of annual global carbon stock loss in the global setting and 1.4% in the regional setting, which were both relatively small. This carbon stock loss can primarily be attributed to biofuels derived from temporary crops that have experienced stable annual expansion (e.g. maize, soybean, and rapeseed). A large amount of carbon stock loss had been allocated to the expansion of 'non-productive lands'. This implies that if some agricultural lands were abandoned or become unproductive in one region, it may have caused a shortage of global food supply and generated new incentives for agricultural expansion elsewhere inside or outside the territory. But causal links cannot be traced here, which means that it could also happen in the opposite way, i.e. land is abandoned because production elsewhere is more economically attractive.

Figure 4-6 (global) sketches the average annual carbon stock losses allocated to consumers from different regions using the global setting for 1995-2010 in order to illustrate their relative roles in CSC-LUC in a global context. Note that this study only accounted for consumption of primary feedstock except for biofuel. From a global perspective, North America had triggered the highest per capita carbon stock losses because of the highest per capita consumption rate. In contrast, Southeast Asia had the lowest per capita carbon stock loss, since its per capita calorific consumption was only about one-third of North American consumption.

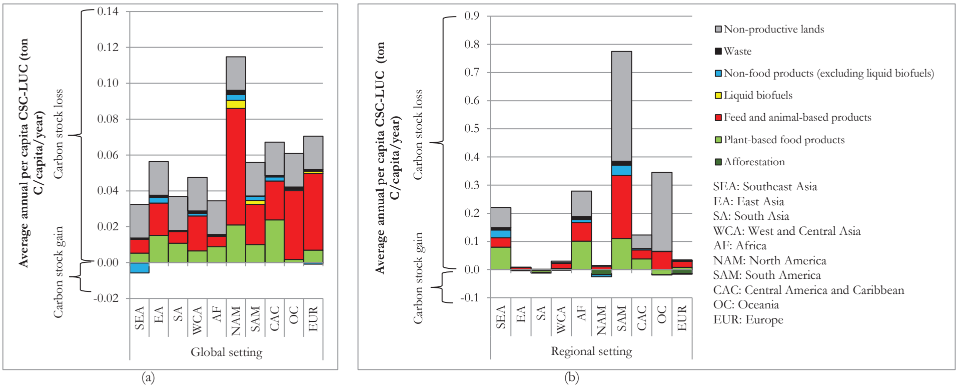
By using the regional setting as shown in Figure 4-6 (regional), South America had the highest per capita carbon stock loss, mainly due to the expansion of non-productive lands and also agricultural land to produce 'feed and animal products'. The expansion of non-productive lands, mainly due to land abandonment, was likely to be linked to unsustainable agriculture activities that have caused land degradation (Hohnwald et al. 2010). Also, it should be noted that carbon stock loss associated with feed was not further linked to animal products. For example, South America exported approximately 10% of the animal-based products that may involve the consumption of feed produced locally (e.g. soymeal). If the CSC-LUC associated with feed was to be transferred to animal-based products, part of the carbon stock loss allocated to South Americans (for feed consumption) would be transferred to the meat importers, such as Europe (one of the biggest importers of beef). The impact of this link was tested in section 4.3.6.

Oceania had recorded the second highest, probably due to its low population density and large land area. This was followed by Africa and Southeast Asia which had the third and fourth highest per capita carbon stock loss. Although per capita consumption rates in North America and Europe were comparatively high, local production was generally 'free' from CSC-LUC based on the regional setting (as there was net afforestation). Nevertheless, they still had imported products from other regions and therefore recorded some carbon stock loss. Also, CSC-LUC associated with biofuels had disappeared in the regional setting. This was because in North America and Europe, the carbon stock loss had been offset by large afforestation, meanwhile in South America and Southeast Asia the CSC-LUC allocated to biofuel was too small to be seen in the Figure 4-6.

4.3.4 Extension 1: Allocation to wood products for the case of Southeast Asia

Figure 4-7 shows the results after re-adjustment of CSC-LUC using the two methods described in section 4.2.6. In both methods, the CSC-LUC allocated to exported wood products was relatively small because a large percentage of wood products were recorded to be consumed domestically as wood fuels on FAOSTAT (2014). This is contradictory with the findings from Hosonuma et al. (2012) which attributed only 10% of deforestation to fuelwood for the case of Asia. Furthermore, it was unclear how illegal logging is addressed in data collection. On average, the values of CSC-LUC embodied in wood exports were 9 Mt C/year and 3 Mt C/year for method 1 and 2, respectively. In comparison, Henders et al. (2015) allocated about 20-90 Mt C/year to timber exported from Indonesia in 2000-2010, but it was not explained how they distributed the carbon stock loss among the large volume of local wood fuel consumption and exported timber.

The allocation to wood products remained highly uncertain because (too) many arbitrary assumptions were required, and may either largely under-estimate (method 1) or over-estimate (method 2) the role of agriculture. The two aforementioned methods were of course also based on arbitrary choices that remain debatable, and only used for exploratory purpose. Leaving out wood products from the accounting resulted in overestimated CSC-LUC caused by agricultural products. But, even with the re-distribution of total CSC-LUC to wood products, the *proportion* between different agricultural consumption still remained the same. Since the aim was to inspect the trend rather than to produce exact values, it was decided not to incorporate allocation to wood products into the full analysis.



Note 1: '+' and '-' represents carbon stock loss and gain respectively.
Note 2: The carbon stock gain in some cases indicates that the production of the products is associated with carbon stock gain (e.g. the cultivation of permanent crops with higher carbon stock like rubber trees).

Figure 4-6. Average annual per capita CSC-LUC by regions and end-uses using the global and regional setting for 1995-2010.

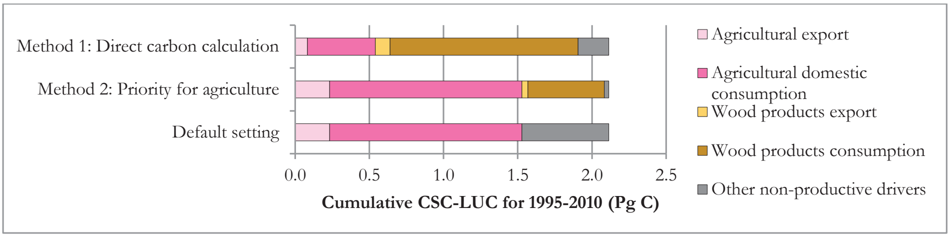
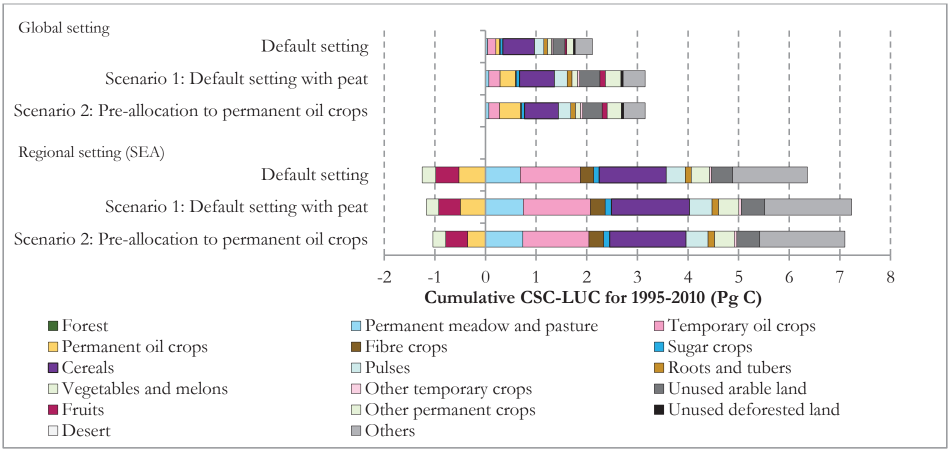


Figure 4-7. Cumulative CSC-LUC re-allocated to agricultural product and wood products for the case of Southeast Asia in 1995-2010.

4.3.5 Extension 2: Allocation peat emission to permanent oil crops in Southeast Asia

Figure 4-8 illustrates how the addition of peat emission changed the results for 1995-2010. A top-up of about 50% of the CSC-LUC allocated to land classes was observed when peat emission is included. For the first scenario, the CSC-LUC had increased by proportion allocated to each land class. For the second scenario, the CSC-LUC allocated to ‘permanent oil crops’ had become about 30% larger than the previous case. With the regional setting, the carbon stock loss allocated to ‘permanent oil crops’ had increased 4 and 5.5 times with default setting with peat and pre-allocation of peat emission, respectively. If the boundaries were omitted at global level, the previous advantage in terms of carbon stock gain of ‘permanent oil crops’ had shrunk significantly if peat loss was specifically pre-allocated to this land class, i.e. the carbon stock gain was 28% and 33% less compared to the value obtained from default setting with and without peat, respectively. This confirms that employing different ways to link CSC-LUC to product will lead to significant differences in final results.



Note: ‘+’ and ‘-’ represents carbon stock loss and gain respectively.

Figure 4-8. Cumulative CSC-LUC allocated to different land classes in Southeast Asia adjusted with peat emissions for 1995-2010.

4.3.6 Extension 3: Allocation from soy to beef

The result of re-allocation of emissions along the soy-beef chain in South America cumulatively for 1995-2010 is shown in Figure S4-3. After adjustment, the total CSC-LUC embodied in exported animal products had become 1.5 times larger compared to the default setting. This investigation illustrated that adjusting the boundaries of tracing trade linkages can have significant impacts on final results. Nevertheless, for this case, since the majority of the animal products (largely beef, in calorific terms) were consumed within South America, a large portion of CSC-LUC embodied in feed was assigned to domestic consumption of animal products. The results show that, even with the association of feed, distant consumers of animal products (beef) play a lesser role compared to consumers of temporary oil crops (soy) in a ratio of 13:87 in terms of CSC-LUC (in this setting the CSC-LUC associated with the export of these two classes contributed to 14% of total CSC-LUC in South America). This is quite different from the study of Karstensen et al. (2013) which reported that 30% of the Brazilian deforestation was attributable to exported beef and soybean in a ratio of 71:29. The main reason of this disparity was probably our use of 'relative role in total land expansion' as the allocation factor (see section 4.2.3) which provides another way of looking at the problem when indirect effect was taken into account. No matter how, one finding that should hold true in different methodological setting was that the impact of domestic consumers was much higher than the distant consumers due to the fact that relatively large amount of animal products were consumed domestically.

4.4 DISCUSSIONS

4.4.1 Methodological implications and limitations

As described by Goh et al. (2016a), each CSC-LUC analysis carries different implications and must be interpreted carefully by inspecting their methodological settings in the key functions. The rationales of making the settings in this study were discussed here.

Delineation of spatial boundary: As this method limits the accounting of propagating effect within the pre-determined territory, the results changed significantly if the spatial boundaries were adjusted (regional and global). By performing the analysis at different geographical levels, territorial distortions were examined. For example, with the regional setting, Europe had experienced a positive carbon stock change due to expansion of forests (driven by political and economic decisions) despite its relatively high per capita consumption rate (roughly double of the per capita rates of Asia and Africa). However, the global setting suggests that this carbon stock gain was more than offset by extra-territorial CSC-LUC associated with consumption (particularly in South America and Southeast Asia where crops were exported to Europe). This indicates that territorially confined mitigation programs such as local afforestation do not necessarily contribute positively to global CSC-LUC. Another prominent example is 'permanent oil crops' which seemed to play a positive role looking at the global picture, but appeared to be a contributor to carbon stock loss when zooming into individual regions. This was particularly evident by the case of oil palm in Southeast Asia. Palm oil was exported all over the world and thus alleviates pressure on land for oil crop production elsewhere which required much larger land areas. But, certain individual plantations held accountable for substantial carbon stock losses through direct LUC. This implies that certain crops like oil palm were theoretically beneficial for CSC-LUC in a global context due to their high yield and carbon storage characteristics, but in reality the situation can be bad due to the ways human manage the expansion, such as converting forests and peatlands for oil palm.

Classification of lands and products: This study gives priority to the consumption perspective (i.e. substitutability of products for consumers) in classification. The results cannot be explained from producer perspective, e.g. management of individual land parcels, because the average characteristics or performance was used to represent the whole land class. For example, all ‘temporary oil crops’ were regarded identical from a consumption perspective (producing oils and proteins). One important point is that ‘permanent oil crops’ were classified differently, because they do not produce protein as ‘temporary oil crops’ plus they also have different land-use characteristics. But, both classes compete directly on the vegetable oil market. Such competition was emphasized when they were classified differently, as the expansion and displacement of both land classes were accounted for separately in the allocation of CSC-LUC.

Inclusion of non-agricultural and non-productive drivers: This method shows that the expansion of non-productive land classes (e.g. unused arable land) had been a noticeable driver of CSC-LUC in 1995-2010, particularly in the three main deforestation hotspots, i.e. South America, Africa and Southeast Asia. The underlying causes behind these drivers were complex, involving socio-economic, political and environmental factors at multiple scales. These drivers may have close links to agricultural drivers, but in principle they can be avoided with more sustainable land management while not affecting the agriculture output (e.g. the uncontrolled fire in Southeast Asia was an unintended consequence which could be avoided while maintaining the production). This suggests that mitigation programs should not be generalised, e.g. not blaming a single crop or a single type of consumption, but a more locally focused approach should be employed to address the actual underlying causes of CSC-LUC.

Interactions between land and product classes: This method simplifies interactions between land and product classes. It does not ‘reward’ a land class that did not directly replace high carbon stock area, but ‘punishes’ a land class that had expanded regardless on high or low carbon stock area. For example, in Southeast Asia, the land class ‘cereals’ had been expanding rapidly due to increasing domestic food demand. For economic reason, export-oriented crops like oil palm (in the land class ‘permanent oil crops’) had also been massively developed in the region. This methodological setting did not give priority for domestic food demand or export-oriented expansion, i.e. it treats the expansion of all land classes equally, and allocate CSC-LUC to respective land class based on their relative roles in expansion (i.e. its expansion per total expansion occurred). The results can be interpreted from a macro land-use perspective, i.e. in what proportion land within a territory can be designed for different uses to fit the future need of the territory, e.g. producing more food, diversifying food production, or generating income from exports, in view of the overall CSC-LUC performance.

Propagating effects of marginal changes in land and product use: This is defined based on the land area expanded. If one land class does not experience net expansion, it is considered free from CSC-LUC. However, the causal relationship may be missing from the results. For example, in Brazil, the degraded pasture was cultivated with soybean while forest was converted to new pasture, but the cause -effect relationship between these two types of conversion was complex (Barona et al. 2010). Based on the method in this study, if the net total area of pasture does not increase, no CSC-LUC will be allocated to it. Nevertheless, the 'final receiver' of CSC-LUC, i.e. soybean, was identified. Additional work is still required to investigate such complex causal relationships at local level. In terms of propagating effects of product use, the 'market pool' concept employed in this study averages CSC-LUC of products come from and go to different regions. This provides an alternative perspective in viewing CSC-LUC based on consumption volume, i.e. the more one consumes, the more CSC-LUC one gets, assuming that any amount consumed will in any way trigger CSC-LUC in a global context regardless of the source of product.

Allocation mechanism and allocation key: This study allocated CSC-LUC averagely to both new and existing consumers. For example, the developed regions with small or no additional consumption (but maintaining high volume of consumption as in the past) have to share the CSC-LUC from the expansion of food crops with the developing regions (which had poor level of consumption in the past) with growing consumption. Such allocation may mask the actual driver (i.e. the increasing demand in the developing regions), but it provides a mean to re-examine the impact on CSC-LUC caused by different consumers by their level of consumption. In terms of allocation key, energy content was employed based on the trend reported by Bird et al. (2013), where total amount of food consumed on energy basis was directly proportional to deforestation in the past decades. The choice of allocation key has significant impacts to land class which have many products, but not so much for land class which mainly produce one type of product. To better understand the underlying causes from different perspectives, both allocation mechanism and allocation key can be further varied using the same method.

Temporal dynamics: The method demonstrated that step-wise conversion can be accounted for if transitional land classes were included in the calculations. Nevertheless, a principal question is how much historical CSC-LUC should be brought forward to current agricultural activities? New cultivation and previous deforestation may be related (e.g. operated by the same company) or may be regarded as independent events. It is difficult to define and distinguish deliberate (planned) step-wise conversion. This involves socio-political reasoning and is impossible to be generalized at aggregated level. A temporal extent of three years was employed in this study based on the conditions in Indonesia (see section 4.2.7), but this may not be valid for the other parts of the world: the choice of time period depends on specific case characteristics and stakeholder views.

Extent of trade linkages: The results in this study shows only CSC-LUC allocated to the consumers or processors of primary products, except for the case of biofuels. The question remained is how to distribute

CSC-LUC among the players on the supply chain (e.g. by added values kept in the territory). For example, cocoa produced in Southeast Asia may be processed in Europe, and the final products may be consumed in East Asia. Based on the current methodological setting, CSC-LUC resulted from the expansion of cocoa in Southeast Asia was allocated to Europe only. This question cannot be solved without further analysis including extended trade flows, but again this will naturally involve more arbitrary assumptions.

4.4.2 Data uncertainty

Data uncertainty is a major limitation for CSC-LUC studies. Ideally, data should be collected for methodological needs. But in practice, data availability, quality and compatibility actually play the decisive role in shaping CSC-LUC analysis.

Firstly, most CSC-LUC analyses employ secondary data which were collected for various purposes, e.g. FAOSTAT. Data availability has limited the setting of functions (e.g. land classification) or the choice of methods (e.g. spatially aggregated or spatially explicit). In this study, 'forests' was not further disaggregated into different types of forests because of lack of data. If data for different types of forests, e.g. based on level of degradation, is available, the dynamics in CSC-LUC can be better understood. For example, the above ground carbon stock values of different 'forest' land classes in Southeast Asia are reported in a range of 27 – 399 tC/ha (Agus et al. 2013); but this variation remains unnoticed at aggregated level, since only one land class (i.e. 'forest') and the average carbon stock values were used.

Secondly, uneven quality of data may undermine the reliability of the results. This is, for example, reflected in the carbon stock values collected from various sources. There is a range of techniques to measure carbon stock and the outcome could be significantly different (Quereshi et al. 2012, Yuen et al. 2013, Ziegler et al. 2012). In addition, human errors during collection and compilation of data could also be enormous, especially in developing countries, not to mention deliberate falsification for political or economic reasons (Caviglia-Harris and Harris 2005, Judge and Schechter 2007, Luzar et al. 2011).

Lastly, connecting datasets from different sources represents a big challenge because they are usually less compatible, and harmonising of incompatible datasets requires assumptions (Goh et al. 2014). The common problem is how to harmonise land-use datasets collected based on different classification (Romijn et al. 2013, Agus et al. 2013). This is the reason why this study mainly adapts data from FAOSTAT (2014) to avoid such an issue.

4.5 CONCLUSIONS AND RECOMMENDATIONS

This study aimed to allocate historical CSC-LUC to agricultural expansions with the consideration of non-productive drivers and indirect effects. A method was developed and CSC-LUC was quantified and allocated by land class, trade and end-use. By land class, it was demonstrated that about one third of the gross carbon stock loss can be attributed to the expansion of non-productive land classes, implying that agricultural land degradation and abandonment was a major (albeit indirect) driver for CSC-LUC. By trade, the increase in CSC-LUC embedded in cross-border traded products was observed, implying that CSC-LUC was also greatly spurred by the growth of cross-border trade. By end-use, 'non-food products (excluding liquid biofuels)' was found emerging as a significant contributor to CSC-LUC in the 2000's in the regional setting, as a large amount of 'permanent oil crops' in Southeast Asia were used for this end-use.

While this study has revealed key trends in CSC-LUC, it did not aim for providing exact values for accounting purposes. In fact, findings of this study reiterated the outcome of the previous review (Goh et al. 2016a), concluding that comparing drivers by exact values of CSC-LUC (e.g. in tonne C) at a single spatio-temporal point is highly uncertain, because they may change significantly with the methodological settings if different arguments or assumptions were employed. For example, CSC-LUC allocated to 'permanent oil crops' changed from 0.53 Pg C (billion tonne C) of carbon stock gain to 0.11 Pg C of carbon stock loss when spatial boundaries were changed from global to regional. In other words, policies targeting specific commodities or types of consumption within specific territories, as can be seen in the ILUC debate in the liquid biofuel arena, may overlook the complex underlying causes in shaping the CSC-LUC trends.

Instead of having continuous debates only from the consumer perspective, more detailed understanding of locally distinct land-use dynamics in the producing regions, especially the underlying causes of CSC-LUC which are not directly linked to increasing demand e.g. land abandonment and uncontrolled fire, may reveal more meaningful solution to fulfil growing demand while preventing further carbon stock loss. As shown in this study, by distinguishing non-productive drivers, a large amount of CSC-LUC was not being directly triggered by demand but rather improper land-use practices. This means that a large amount carbon stock loss can be avoided while maintaining agricultural production if better land-use practices are adopted, such as mobilising non-productive or under-utilised lands for productive use with sustainable practices. This could be accompanied by forging synergies with rural development (e.g. providing education, capital and techniques) that potentially help to prevent further inefficient expansion (which then resulted in a large area of non-productive lands).

ACKNOWLEDGEMENT

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SUPPLEMENTARY MATERIALS

Box S4-1. Data sources

For 'geographical region', 'land class' and 'end-use', definitions from FAOSTAT (2014) were adapted (Table S4-1 – S4-4). Annual data of land class area, production, consumption, trade flows, population and carbon stock values were collected from different sources (Table S4-5). FAOSTAT (2014) was used as the major source because it provides most of the required data using (i) consistent definitions, (ii) consistent geographical setting, and (iii) harmonised trade balance and consumption volume across different sectors. One key issue is that the area for temporary crops reported by FAOSTAT (2014) is harvested area instead of physical area under cultivation in a year. The harvested area can be equal to the total physical area for the case like North America for which Borchers et al. (2014) reported that only 2% of total cropland of US has undergone double cropping, but not for the other cases like East Asia, e.g. Qiu et al. (2003) has reported that 30% of the cropland in China was double-cropped. For the deforestation hotspot, Southeast Asia, the cropping intensity of the main crop, i.e. paddy, can be as high as 1.83 in Vietnam (i.e. 1 ha of land is harvested for 1.83 times on average), but also can be as low as 1.07 in Thailand (Xiao et al. 2006). For another deforestation hotspot, South America, reports on increase in cropping intensity has been found for several cases, e.g. double cropping (mainly soy-cotton and soy-corn) in Mato Grosso has increased from only 6% in 2001 to 50% in 2011 (Spera et al. 2014). However, there was a wide range of values reported for different cases and they are largely inconsistent (e.g. Arvor et al. 2014, Galford et al. 2008). Applying cropping intensity in the method will help to bring the results closer to reality, but consistent data in time series is missing. To compromise for the short of data, an average cropping intensity of 1.38 was assumed for 'cereals' in Southeast Asia for all years (using average paddy intensity weighted with paddy cultivation area, based on data reported by Xiao et al. 2006). Since there are no consistent values that can be used for the other cases, the cropping intensity was assumed to be 1.0 for all the other crops and regions as Bruinsma (2009) reported that the average cropping intensity in developing countries is close to 1.0.

In terms of carbon stock, only living biomass (above- and below-ground biomass) was covered. The Tier-1 method in IPCC (2006) was used for all to ensure consistency and equality in comparison (Tubiello et al. 2013). Data for living biomass for each land class was collected from various sources and presented in Table S4-5. FRA (2010) (CountrySTAT 2010) reported carbon stock of living biomass in forests in different geographical regions using the Tier-1 method in IPCC (2006). For the other land classes, data compiled by Ruesch and Gibbs (2008) was chosen as the main source as the biome-wide biomass carbon datasets were derived with consistent methodologies across ecosystems that include living biomass of non-forest ecosystems based on the Tier-1 default values (IPCC 2006) and global land cover map. Soil carbon changes were excluded due to constraints in data availability. As peat loss was a major type of carbon stock loss, particularly related to oil palm expansion, it was further investigated in section 4.2.7. For dead organic matter, the net stock changes of this pool were assumed to be zero based on the Tier-1 method in IPCC (2006).

Table S4-1. Classification of geographical area based on FAOSTAT (2014).

Geographical area	Code
Southeast Asia	SEA
South Asia	SA
East Asia	EA
West and Central Asia	WCA
Africa	AF
North America	NAM
South America	SAM
Central America and Caribbean	CAC
Oceania	OC
Europe	EUR

Table S4-2. Land classes and definitions.

Types	Land classes	Code	Definition (Source: FAOSTAT 2014; FAO 2011)	Product groups as in FAOSTAT
Forest		F	Forest area is the land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ.	-
Temporary crops	**Cereals**	TC	Annual plants, generally of the gramineous family, yielding grains used for food, feed, seed and industrial end-uses, e.g., ethanol.	Cereals, corn oil and ricebran oil
	Fibre crops	TF	Annual crops yielding vegetable fibres, mostly soft fibres, which are utilized by the textile industry to produce first thread and yarn, and, from these, innumerable fabrics or manufactures.	Cotton lint, cottonseed, cottonseed oil, jute, jute like fibres, soft-fibres (others), hard-fibres (others), cottonseed oil cakes
	Sugar crops	TS	Crops cultivated primarily for the manufacture of sugar, secondarily for the production of alcohol (food and non-food) and ethanol.	Sugar crops, sugar & sweeteners
	Temporary oil crops	TOC	Annual plants whose seeds are used mainly for extraction of culinary and industrial oils, excluding essential oils.	Oil crops: other than those in permanent oil crops
	Pulses	TP	Annual leguminous crops yielding grains or seeds used for food, feed and sowing end-uses.	Pulses
	Roots and tubers	TRT	Annual crops and yield roots, tubers, rhizomes, corms and stems which are used largely for human food, either as such or in processed form, but also for animal feed.	Starchy roots

Temporary crops	**Vegetable & melons**	TVM	Plants cultivated both as field crops and garden crops, both in the open and under glass.	Vegetable
	Other temporary crops	TO	Tobacco and other remainder temporary crops	Tobacco
Permanent crops	**Fruits and berries**	PFB	Those yielding fruits and berries which generally are characterized by their sweet taste and their high content of organic acid and pectin.	Fruits excluding wine
	Permanent oil crops	POC	Perennial plants whose seeds (kapok), fruits or mesocarp (olives) and nuts (coconuts) are used mainly for extraction of culinary or industrial oils and fats.	Oil crops: palm kernel oil, palm oil, coconut oil, olive oil, palm kernel, palm kernel oil cakes, copra oil cakes
	Other permanent crops	PO	Nuts, hops, coffee, cocoa, tea, spices, rubber and others	Treenuts, stimulants, spices, rubber
Permanent meadow and pasture		PMP	Land used permanently (five years or more) to grow herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land). Data are expressed in 1000 hectares.	Meat, eggs, milk, wools
Non-productive lands	**Unused arable land**	NAL	Arable land excluding temporary crops.	-
	Unused deforested land	UDL	Deforested land that has not been converted to agricultural land. It will lose this status after 1 time-step.	-
	Desert	D	Permanent non-productive lands	-
	Others	OTH	The remainder of the above mentioned land.	-

Table S4-3. End-uses and data sources

End-uses	Data sources
Plant-based food products	FAOSTAT Food balance sheet: Food, Seed, Food Manufacture (exclude animal products)
Feed and Animal-based products	FAOSTAT Food balance sheet: Food, Seed, Food Manufacture (only animal products, but aquatic animal products are excluded), and all Feed. FAOSTAT Commodity balance sheet: Oilcakes
Liquid biofuel	USDA GAIN Reports (2013), US DOE (2014)
Non-food products	FAOSTAT Food and Commodity balance sheet: Other utilizations

Waste	FAOSTAT Food and Commodity balance sheet: Waste According to FAOSTAT (2014): Amount of the commodity in question lost through wastage (waste) during the year at all stages between the level at which production is recorded and the household, i.e. storage and transportation. Losses occurring before and during harvest are excluded. Waste from both edible and inedible parts of the commodity occurring in the household is also excluded. Quantities lost during the transformation of primary commodities into processed products are taken into account in the assessment of respective extraction/conversion rates. Distribution wastes tend to be considerable in countries with hot humid climate, difficult transportation and inadequate storage or processing facilities. This applies to the more perishable foodstuffs, and especially to those which have to be transported or stored for a long time in a tropical climate. Waste is often estimated as a fixed percentage of availability, the latter being defined as production plus imports plus stock withdrawals.
Non-productive lands	Carbon stock change from non-productive lands classes, i.e. "unused arable land", "unused deforested land", "desert" and "others". This land class have no tradable products, so the entire carbon stock loss is allocated to its home country or region (assumed its expansion is caused by the action of the people in this geographical boundary).

Table S4-4. Sources of statistical data inputs

Data inputs	Source
Land class area	FAOSTAT (2014) – Resources, Own calculation
Trade	FAOSTAT (2014) – Food balance and Commodity balance
Production and consumption	FAOSTAT (2014) – Food balance
Production and consumption: Biofuels	USDA GAIN (2013), US DOE (2014)
Population	FAOSTAT (2014) – Population

Table S4-5. Carbon stock values (above- and below-ground) used in the study

Land class	Region	Carbon stock (ton C/ha)	Sources	Assumptions / Remarks
Forest	South-Eastern Asia	102.7 - 111.0	Country STAT (2010)	Carbon stock value (Mg C/ha) = Total forest carbon stock in living biomass in the region / Total forest area
	Southern Asia	46.4 - 49.5		
	Eastern Asia	31.5 - 34.5		
	West and Central Asia	35.1 - 38.2		
	Africa	81.1 - 82.6		
	Northern America	49.4 - 51.9		
	South America	105.7 - 107.9		
	Central America & Caribbean	81.5 - 83.3		

Forest	Oceania	53.6 - 55.1	Country STAT (2010)	Carbon stock value (Mg C/ha) = Total forest carbon stock in living biomass in the region / Total forest area
	Europe	42.4- 44.8		
Temporary crops	Global	0	Ruesch &Gibbs (2008)	According to IPCC (2006), this should remain zero
Permanent crops	South-Eastern Asia	71.4	Ruesch &Gibbs (2008)	Assume agroforestry system (Average of Forest / Cropland Mosaic, i.e. GLC2000 Class 17)
	Southern Asia	50.6		
	Eastern Asia	43.4		
	West and Central Asia	43.4		
	Africa	52.9		
	Northern America	57.0		
	South America	52.5		
	Central America & Caribbean	52.5		
	Oceania	64.6		
	Europe	24.6		
Permanent meadow and pasture	South-Eastern Asia	2.0	Ruesch &Gibbs (2008)	Take the lowest among grasslands: Sparse Grassland and Grassland Mosaic (GLC2000 Classes 14 & 18)
	Southern Asia	2.0		
	Eastern Asia	1.5		
	West and Central Asia	1.5		
	Africa	2.0		
	Northern America	1.5		
	South America	2.0		
	Central America & Caribbean	2.0		
	Oceania	1.5		
	Europe	1.5		
Unused arable land; Unused deforested land; Others	South-Eastern Asia	2.0	Own estimates	Assume its carbon stock equals to 'Permanent meadow and pasture'
	Southern Asia	2.0		
	Eastern Asia	1.5		
	West and Central Asia	1.5		
	Africa	2.0		
	Northern America	1.5		
	South America	2.0		
	Central America & Caribbean	2.0		
	Oceania	1.5		
	Europe	1.5		
Desert	World and all regions	0	Own estimates	Assume it has negligible carbon stock

Table S4-6. Overview of cumulative gross carbon stock loss allocated to different land classes for 1995-2010.

Spatial scale	Global	Regional
Gross carbon stock loss* (Pg C)	6.4	12.1
Proportion (%)		
Forest	0	-51
Permanent meadow and pasture	11	13
Temporary oil crops	19	15
Permanent oil crops	-8	-1
Fibre crops	4	2
Sugar crops	2	1
Cereals	21	20
Pulses	6	7
Roots and tubers	2	3
Vegetable and melons	6	2
Other temporary crops	1	1
Fruits	-7	-4
Other permanent crops	-4	-2
Unused arable land	6	15
Unused deforested land	0	3
Desert	0	0
Others	23	18

Note: '+' and '-' represents carbon stock loss and gain respectively
* 'Gross carbon stock loss' is the amount without deduction of all gains.

Table S4-7. Overview of cumulative carbon stock loss distinguished by cross-border trade for 1995-2010.

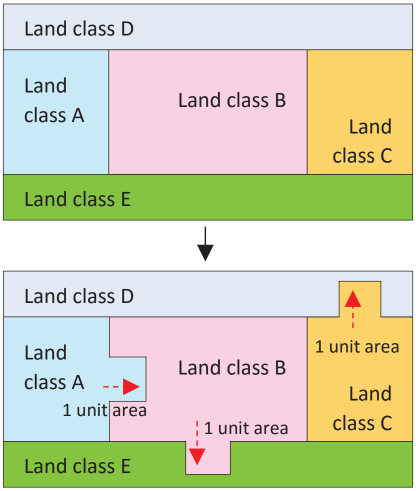
Spatial scale	Regional
Gross carbon stock loss* (Pg C)	11.5
Proportion (%)	
Afforestation	-53
Consumption of domestic products	50
Consumption of imported products	12
Non-productive drivers	38

Note: '+' and '-' represents carbon stock loss and gain respectively
* 'Gross carbon stock loss' is the amount without deduction of gains.

Table S4-8. Overview of cumulative carbon stock loss allocated to different end-uses for 1995-2010.

Spatial scale	**Global**	**Regional**
Gross carbon stock loss* (Pg C)	5.2	11.2
Proportion (%)		
Afforestation	0	-55
Plant-based food products	22	25
Feed and animal-based products	36	28
Liquid biofuel	1	0
Non-food products	1	6
Waste	2	3
Non-productive lands	37	38

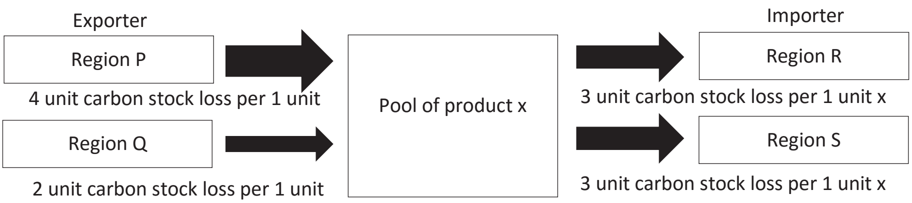
Note: '+' and '-' represents carbon stock loss and gain respectively
* 'Gross carbon stock loss' is the amount without deduction of gains.



Land-use change: (i) both land class A and C have experienced net expansion of 1 unit area, (ii) land class B has zero net expansion, and (iii) land class D and E have been displaced for 1 unit area each.

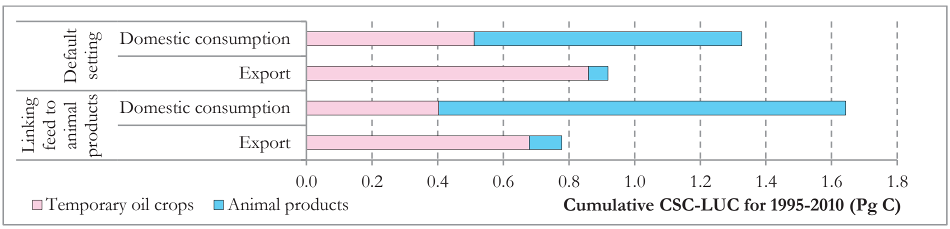
Liability is shared based on the expansion rate: (i) both land class A and C share the total carbon stock loss proportionate to their expansion area, (ii) land class B will not be attributed to any carbon stock loss, however, (iii) land class D and E will not get any credit for being displaced.

Figure S4-1. A simple scenario to show how CSC-LUC is distributed among land classes.



Note: Arrows represent total CSC-LUC embedded in the trade flows

Figure S4-2. An example to illustrate the 'market pool' concept.



Note: '+' and '-' represent carbon stock loss and gain respectively.

Figure S4-3. Cumulative CSC-LUC allocated to domestic and exported animal products from South America in 1995-2010 with and without addition of CSC-LUC from feed.

CHAPTER 5

Exploring under-utilised low carbon land resources from multiple perspectives: Case studies on regencies in Kalimantan

Authors:
Chun Sheng Goh
Birka Wicke
Lesley Potter
André Faaij
Annelies Zoomers
Martin Junginger

"Well, blind men, have you *seen* the elephant? Tell me, what sort of thing is an elephant?" --- Parable of the Blind Men and the Elephant

ABSTRACT

Mobilising under-utilised low carbon (ULC) land resources for future agricultural production can help reducing pressure on high carbon stock land from agricultural expansion, particularly for deforestation hotspots like Kalimantan. However, the potential of ULC land is not yet well understood, especially at regency level which is the key authority for land-use planning in Indonesia. Therefore, this study explored ULC land resources for all regencies in Kalimantan. By analysing information from six monitoring domains, a range of indicators were derived to provide insights into the physical area of ULC land from various perspectives. It was found that these indicators show largely different values at regency level. For example, regency Pulang Pisau has a substantial area of 'temporarily unused agricultural land' but a very limited area of 'low carbon land' – this implies that not all 'temporarily unused agricultural land' is ready for future exploitation when assessing from different aspects. As a result of such diverging indicators, using a single indicator to quantify available ULC land resources is risky as it can either be an over- or under-estimation. Thus, ULC land resources were further explored in the present paper by taking four regencies as case studies and comparing all the indicators, supported with relevant literature and evidence collected from narrative interviews. This information was used to estimate ULC land area by possible land-use strategies. For example, Gunung Mas was found to have a large area of low carbon land which is not occupied and might be suitable for oil palm deployment. However, the major limitation is that physical estimates cannot provide a complete picture of 'real' land availability without considering a broader range of socio-economic factors (e.g. labour availability). Therefore, physical land area indicators from different domains must be combined with other qualitative and quantitative information especially the socio-economic factors underlying land under-utilisation to obtain better estimates.

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Keywords: Under-utilised land; Low carbon; Kalimantan; Indonesia; Oil palm.

5.1 INTRODUCTION

The rate of terrestrial carbon stock loss in Kalimantan (the Indonesian part of Borneo) has grown substantially over the last two decades, largely driven by increasing global demand for timber and agricultural products. The annual emission from land-use change (LUC) has reached to about 52 Tg CO_2/year in 2006-2010 (Agus et al. 2013). Export-oriented agricultural activities, particularly oil palm expansion, are also often associated with carbon stock loss due to deforestation and peat loss (Agus et al. 2013). In 2005-2010, about half of the oil palm expansion (1.8 Mha) has occurred in Kalimantan (Gunarso et al. 2013). Mobilising less-productive lands with low carbon stock and insignificant ecological services may be a solution for increasing agricultural production and preventing further carbon stock loss. To achieve these aims, two general criteria can be employed to assess potential land resources: (i) its current agricultural productivity is insignificant or low compared to its optimal potential; and (ii) it has a low level of carbon stock so that utilisation of the land is unlikely to incur additional carbon stock loss and negative ecological impacts. Land that fulfils the two criteria may be broadly regarded as under-utilised low carbon (ULC) land. In case oil palm is to be cultivated on these lands, the threshold value of above-ground carbon stock can be set, for example, at 40 tC/ha, i.e. the average value of carbon sequestered in an oil palm plantation with a rotation period of 25 years (Khasanah et al. 2012). In terms of soil carbon, areas with potentially high carbon stock in the soil such as wetland should be directly excluded.

5

Various names, e.g. 'abandoned', 'degraded', and 'marginal' land, have been proposed to quantify land available for future expansion but they do not necessarily fulfil both the ULC criteria. Furthermore, their definitions or criteria may be different and some are not entirely clear, e.g. abandoned land is not necessarily degraded, and vice versa (Smit et al. 2013, Suhariningsih 2009). Ambiguous definitions may create unrealistic expectations and unintended consequences in policymaking. For example, in some cases the classification of degraded land was used as an excuse for forest clearing under the guise of reforestation programmes, although the 'degraded' land may still be rich in carbon stock and biodiversity (Barr et al. 2010, Obidzinski and Dermawan 2010).

For Kalimantan, a number of top-down efforts have been initiated to identify ULC land based on remote sensing coupled with biophysical models, by both international (e.g. Gingold et al. 2012, Hadian et al. 2014) and national institutions (e.g. Mulyani and Sarwani 2013, MoF 2013). Most of these analyses focus largely on environmental constraints (e.g. avoiding biodiversity loss) and technical potential, but lack local socio-economic considerations, e.g. land occupancy by indigenous communities. Also, they were often performed between large time-intervals (up to several years) due to resource constraints. Thus, land-use dynamics may not be well captured and technical errors could be significant, e.g. it is difficult to differentiate abandoned land from land which may still be cultivated sporadically by local communities (Treitz and Rogan 2004).

In addition to top-down efforts, also bottom-up approaches have been developed to identify ULC land resources. In contrast to the top-down approaches, the bottom-up approach integrates relatively more locally focused socio-economic information based on expert opinions and household surveys (e.g. BPS 2013b, Lambin et al. 2013). For example, Lambin et al. (2013) have estimated the 'potentially available cropland' in several countries based on expert judgement. Such approaches may include more precise local information on a case-by-case basis. However, 'under-utilisation' is a normative notion that can be interpreted differently, e.g. based on socio-cultural values, economic values or legal perspective. For example, land claimed by local communities for certain purposes e.g. shifting cultivation, is not deemed 'under-utilised' by the occupants. Estimates of available land thus often lack consistency from one case to another (Lambin et al. 2013).

Since ULC land can be defined differently based on the different perspectives of land-use actors across scale, the immediate question is at what level relevant policy can be made to achieve the aim of preventing further carbon stock loss while increasing agricultural production. Among the authorities in the Indonesian hierarchy, regencies (*kabupaten*) and municipalities (*kota*) are the most influential decision makers in terms of land-use policies.[8] Since 2001, they are empowered to implement their own spatial planning policies (Thorburn 2004). Deforestation in Kalimantan in the 2000's was largely driven by regency-oriented policies, which largely promoted (large-scale) oil palm expansion (e.g. Barr et al. 2006). Between regencies, rules and regulations on land-use can be quite different and are enforced with varying degrees of stringency (Fairhurst et al. 2010). Land-use patterns also interact with the wider socio-economic environment within a regency. Understanding and comparing the issues related to ULC land from a regency perspective is thus essential. But at present, most studies on Kalimantan either focus on island, provincial or village level. Quantitative and comparative studies on individual regencies are still rare and only cover a limited number of regencies (e.g. Tomich et al. 1997).

In addition to spatial and scale variations, the changes in land-use patterns across time, e.g. how long has the land been under-utilised or remained in a low carbon state also need to be accounted for when examining its potential for agricultural expansion. Some studies, e.g. Potter (2015), have specifically explored the history of agricultural land-use at regency level by assessing their underlying socio-economic causes, but not quantifying the area changes. Some other studies, e.g. van der Laan et al. (2015), have investigated the land-use trajectories in individual regencies based on land cover changes using spatially explicit methods. However, the interplay of local factors underlying these changes, e.g. land-use intensity and occupancy (whether it is really 'abandoned' or not), has not yet been explored in conjunction with the land-use patterns of ULC land.

This study aims to explore the availability of ULC land by combining information collected with different types of approaches. Firstly, information collected based on distinct perspectives and relevant aspects (e.g. ecological or socio-economic) for assessing ULC land resources are categorised into six monitoring

8 For convenience, the term 'regency' was used throughout the paper to represent all regencies and municipalities.

domains and reviewed. Based on information collected from the six monitoring domains, relevant quantitative indicators are analysed and derived for 55 regencies and municipalities in Kalimantan. Finally, based on these quantitative indicators as well as relevant literature and evidence collected from narrative interviews, the potential of ULC land for possible land-use strategies was estimated for four regencies.

5.2 STUDY AREA

Kalimantan is the Indonesian territory that makes up about 73% of the total land area of Borneo Island. It is divided into five provinces. Throughout this study, the newly formed North Kalimantan province (in 2012) is considered as part of East Kalimantan to incorporate data before 2012, when Kalimantan was divided into 46 regencies and 9 municipalities (both are sub-divisions of provinces) (see the map in Figure S5-1). The island has experienced serious (legal and illegal) logging and deforestation since the 1980's. Then, the 'oil palm boom' began from the 1990's, surging since 2006 (Agus et al. 2013). Kalimantan was a major transmigration[9] site alongside several large land-based projects, such as the Mega Rice Project (MRP)[10] in Central Kalimantan which planned to locate a large number of Javanese transmigrants. By 2011, the population had grown to >14 million with a 2.4% growth rate (BPS Kalbar 2014, BPS Kalsel 2014, BPS Kalteng 2014, BPS Kaltim 2014).

In addition to the analysis for all regencies, case studies were conducted in four regencies in Central Kalimantan with distinctive characteristics in order to assess the potential of ULC land for possible land-use strategies. First, Gunung Mas was chosen due to its vast low carbon lands and unusual average land area claimed by households. Next, Kotawaringin Timur was selected for its rapid industrial oil palm expansion. Palangka Raya, the capital of Central Kalimantan, was included for urbanisation and the formation of ULC land surrounding the city. Finally, Pulang Pisau, the former site of the MRP, was chosen for comparison due to its poor agro-ecological conditions.

5.3 REVIEW OF MONITORING DOMAINS

Relevant information for ULC land in Kalimantan can be gathered from six monitoring domains (Table 5-1) which employ different approaches and have their own advantages and limitations. From an ecological perspective, *land cover* is a key indicator to distinguish land with high carbon stock. Meanwhile, information about *land suitability* can be used to evaluate the technical agricultural potential.

9 The transmigration programme was a population-relocation programme that moved landless people mainly from the densely populated island of Java to less populous parts of the country, e.g. Kalimantan). It was especially active during the Suharto era and continued in a minor way after regional autonomy (Potter 2012). President Widodo now plans to reactivate the scheme, especially in undeveloped areas such as North Kalimantan.

10 The MRP, also called Peat Land Project or 'Proyek Lahan Gambut' (PLG), was a failed programme by the Indonesian Government to develop one million hectares of degraded peatland for rice production from 1996.

For socio-economic aspects, *land occupancy* by small farmers provides an indication for local land-use. In addition, *land-use intensity* can be used to identify land that is used in lower intensity in terms of agricultural activities. The *legal classification and concessions* is another important aspect when land is legally classified as the official 'forest zone' or granted for agricultural activities (which may not be the same as the actual land cover and land-use). Finally, *land degradation* is also monitored as changes in land characteristics from environmental, technical and economic perspectives. Each domain is further explained and described in the following sub-sections.

Publicly available data sources for quantifying these indicators are also listed in Table 5-1. The agricultural land statistics are collected on an annual basis, but most monitoring efforts are only performed once in several years (e.g. the household survey by BPS 2013b is only performed once in a decade). The data sources also have different levels of clarity in methodology as also explained below.

5.3.1 Land cover

Low carbon land cover can be identified using remote sensing (e.g. Gunarso et al. 2013, Hoekman et al. 2010, MoF 2015). Land classes like forests and wetlands which potentially have high carbon stocks and ecological services, as well as other functional land classes like settlements, mines, existing industrial oil palm plantations and wet paddy fields, can be identified and excluded through examining land cover maps. The remaining land forms the maximum of ULC land area that can be mobilised.

The Ministry of Forestry (MoF 2015) has publicly provided spatially explicit land cover maps of Indonesia for 2009 and 2011. Based on the land classification method used in these maps, land cover types which are of low carbon (excluding functional land classes like settlements) are (i) dry-field agriculture, (ii) dry-field agriculture mixed with grass (grassland that is suspected to have sporadic agricultural activities, e.g. shifting cultivation), (iii) dry-field shrub and grass and (iv) open land. The above-ground carbon stock values of these four land classes are reported to be below 40 tC/ha (i.e. less than the average carbon stock of oil palm as reported by Khasanah et al. 2012), and they do not contain peat (Agus et al. 2013). However, these four land classes do not necessarily represent land suitable for productive agricultural activities. Also, relying solely on land cover data at a single temporal point (or with a large time-step, e.g. 5 years) means that it is difficult to explicitly distinguish temporarily and permanently abandoned land. Some of these areas may be used for shifting agriculture (Agus 2011). This is difficult to capture through land cover changes in a short period of time due to the continuous transition of land-use from one type to another (Gunarso et al. 2013). Discrepancies between spatially explicit maps also exist due to technical issues e.g. different interpretation from visual inspection (Treitz and Rogan 2004). Nevertheless, the total area of the four aforementioned land classes can be deemed the upper limit for ULC land resources.

5.3.2 Land suitability

Land suitability, linking to agricultural productivity, is determined by a number of agro-ecological and topographical factors, such as soil suitability, elevation, and water availability (Gingold et al. 2012). In government policies, the term 'sub-optimal' is employed to describe land with lower quality (Haryono 2013). Several monitoring activities have been conducted to assess the amount of sub-optimal land in terms of its agricultural potential (e.g. based on its acidity), as well as a number of case studies on technological aspects performed at regency or sub-regency level (Mulyani and Sarwani 2013). Notably, degraded peatland is also included as one type of sub-optimal land, which is targeted for development but which is not low in carbon stocks. However, no spatially explicit information is freely available to the public[11]. BBSLDP (2014) also assessed the agricultural land resources of Indonesia in terms of acreage, distribution, and potential availability. Among the different types of land assessed, 'dry-field suitable for crops and livestock' is one indicator to estimate the technical potential of ULC land, but data is only publicly available at provincial level.

For oil palm establishment, two prominent studies on land suitability have been conducted by Gingold et al. (2012) and Hadian et al. (2014). Suitable lands are identified based on land cover maps, biophysical models as well as other ecological indicators to ensure agricultural suitability and sustainability. However, such large-scale mapping exercises are often fraught with high uncertainties (e.g. soil distribution is largely estimated through models with limited ground surveys) (Gingold et al. 2012, Sulaeman et al. 2013). Detailed agro-ecological surveys are conducted on plantation scale by companies, but this is very costly and labour-intensive and data is not generally available to the public. It is not realistic to be performed on a larger scale[12].

While the accuracy has largely limited the data usefulness, the available spatially explicit information prepared by WRI (2012) nevertheless provides the best possible estimates for potentially suitable areas for oil palm in terms of agro-ecological properties while excluding areas with high carbon stock or conservation value[13]. However, it does not account for existing uses by local communities that are not easily recognised from maps. Hadian et al. (2014) has pinpointed that social and legal aspects such as local land-use and tenure are not taken into consideration, which is a major drawback of such studies.

11 Personal communication with Yiyi Sulaeman, land specialist at Agency for Agricultural Research and Development (Badan Penelitian dan Pengembangan Pertanian) in Bogor, Indonesia in January 2015.

12 Personal communication with S Paramnanthan, director of PA Soil Survey and Advisor of Malaysian Palm Oil Board in Kuala Lumpur, Malaysia in December 2014.

13 This represents low carbon land with elevation <1000m, soil depth >75cm, soil acidity $<$pH 7.3, slope $<30\%$, water resource buffers >100m, and conservation buffer >1000m. However, other climatic indicators, e.g. rainfall seasonality, were not included in this land suitability map.

5.3.3 Land occupancy

In Kalimantan, a substantial area of land is occupied by local communities for small-scale farming. These lands may largely consist of low carbon land, e.g. dry-field agriculture, but also a wide range of land classes, e.g. forests or peatlands. It is crucial to take this aspect into account when quantifying land availability because local perspectives on land-use, particularly the land claimed by local communities, may vary greatly. The land-use of small farmers in Kalimantan cannot be simply captured by remote sensing because many of them move and change their land-use from time to time, involving the transition of shrub-fallow-agroforests in irregular patterns (Fox et al. 2009), despite some having used their lands more intensively for e.g. oil palm. Although the performance of small farmers varies greatly, most small farmers Kalimantan generally have lower productivity compared to their counterparts in the other parts of the country[14].

To further look into the land occupancy by local communities in Kalimantan, information from two sources can be used. BPS (2013b) has conducted household surveys on the area occupied by small farmers. The strength of the household survey BPS (2013b) is that it provides direct information from the local communities on land-use. The limitation is that it is only conducted once in a decade as such monitoring is labour-intensive. DG Estate Crops (2014a, b), the second source, reported the area of oil palm and rubber smallholdings at regency level. But they do not distinguish between independent and plasma farmers[15]. Unfortunately, there is still no accurate spatial information over land tenure claimed by local communities, whether formal or informal. The best data available is only aggregated at regency level.

5.3.4 Land-use intensity

Distinguishing land by land-use intensity, i.e. identifying (temporarily) abandoned land, is useful for ULC land assessment. In the Indonesian legal context, land that has not been used according to its rights of cultivation (*Hak Guna Usaha*, HGU) is considered under-utilised. The government can then withdraw the land-use right from the holders. The term 'under-utilised' land (*tanah terlantar*) is defined as land that has purposely not been used according to its condition, characteristics, or the purpose of its land-use rights (which is designed by the authority). Land will be considered as under-utilised when over a certain period it has become non-productive, not providing benefits to the land-right holders or local

14 For oil palm, the productivity of smallholders (in 2013), which ranged from 0.7 – 4.0 tCPO/ha at regency level with an average of 1.6 tCPO/ha, is generally lower than the national average of 3.3 tCPO/ha for smallholders and 3.8 tCPO/ha for large private plantations (DG Estate Crops 2014a). Medium-scale farming currently still rarely exists, except in West Kalimantan where cooperatives of oil palm smallholders are growing (Potter 2015). Similarly for paddy, the average yield in Kalimantan is only half of the national average (8.5 t/ha) in 2013 (BPS 2014). Meanwhile, the rubber productivity of the 55 regencies in 2013 ranges from 0.4-1.5 t/ha with an average of 0.8 t/ha, significantly lower than the national average of smallholders (1.0 t/ha) and private enterprises (1.5 t/ha) (DG Estate Crops 2014b).

15 Plasma schemes are outgrower schemes designed to assist small farmers by attaching them to large companies that provide technical and financial supports to them before they become independent plantation growers.

Table 5-1. Monitoring aspects, domains, approaches, sources, spatial scale, types of data, year available and public availability.

Monitoring aspects	Monitoring domains	Monitoring approaches						Source	Types of data	Spatial scale				Year available	Public availability	
		Remote sensing	Stake-holder's survey	Agri-culture statistics	Bio-physical models and field surveys	Expert's and official's opinions	Legal classi-fication			Island	Province	Regency	Spatially explicit		Method-ology	Data
Ecological	Land cover	•						MoF (2015)	Land cover maps				•	2006, 2011	No	Spatially explicit
								Gunarso et al. (2013)		•			•	1990, 2000, 2005, 2010	Yes	Aggregated at island level
Technical	Land suitability				•	•		WRI (2012)	Land suitable for oil palm				•	Processed in 2012	Yes	Spatially explicit
								Hadian et al. (2014)	Land excluding EU-RED zone*		•		•	Processed in 2014	Yes	Aggregated at provincial level
								BBSDLP (2014)	Dry-field suitable for crops and livestock		•		•	Processed in 2014	Yes	
Socio-economic	Land occupancy		•	•				BPS (2013b)	Land occupied by small farmers		•	•		2003 and 2013	Yes	

Table 5-1. (continued)

Monitoring aspects	Monitoring domains	Monitoring approaches						Source	Types of data	Spatial scale				Year available	Public availability	
		Remote sensing	Stake-holder's survey	Agri-culture statistics	Bio-physical models and field surveys	Expert's and official's opinions	Legal classi-fication			Island	Province	Regency	Spatially explicit		Method-ology	Data
Socio-economic	Land occupancy		●	●				DG Estate Crops (2012-2014)	Area of oil palm and rubber small-holdings		●	●		2011 - 2013	No	Aggregated at regency level
Agri-cultural	Land-use intensity	●	●	●				BPS (2013a)	Agricultural land by utilisation		●	●		2008-2012	Yes but lacks clarity	
Legal	Legal classification and concessions					●	●	WRI (2012)	The 'forest zone', timber concessions and oil palm concessions				●	Processed in 2012	Yes	Spatially explicit
Multiple	Land degradation	●			●	●		MoF (2015)	Critical land				●	2011 (every 5 years)	Yes but lacks clarity	

* EU-RED zone is defined as the land area that has fulfilled the requirements of sustainability criteria set by EU-RED (European Union Renewable Energy Directive) for biofuel production.

communities, and experiencing decrease in fertility. This also includes lands that have been purposely kept at low productivity (e.g. uncultivated land within oil palm concessions). Furthermore, selling land to non-locals who have no intention to develop the lands, namely 'absentee land' (*tanah absentee*), is actually forbidden under the Basic Agrarian Law (UUPA) to avoid land under-utilisation. In practice, the definition of under-utilised land is ambiguous with no clear official criteria for determining the utilisation status as well as the effective time frame (Suhariningsih 2009).

An indicator at regency level is 'temporarily unused agricultural land', which is available from the annual agricultural statistics collected by the Central Bureau of Statistics (BPS 2013a). It consists of land that was used regularly but currently has not been used for 1 to 2 years, and also includes paddy fields that have been left unused for >2 years. The area for 'shifting cultivation' is also further distinguished. However, it is not entirely clear how these areas are identified by BPS (2013a), and both land classes also do not necessarily represent low carbon land. Although secondary succession in Kalimantan is more difficult to maintain due to ecological constraints (e.g. repeatedly damaged by wild fire especially in El Nino years) and human disturbance (e.g. salvage logging) (Tolkamp et al. 2001, van Nieuwstadt et al. 2001), some temporarily unused land may have already experienced considerable carbon stock regeneration (Yassir et al. 2010). Also, this land class may consist of land that is not suitable for regular agricultural use, e.g. peatland. Regency Kapuas of Central Kalimantan is a notable example – it has plenty of degraded peatland (previously developed under the MRP), which may be counted here as 'temporarily unused agricultural land' (McCarthy 2001). Thus, while this monitoring domain is useful to understand the local land-use, it cannot be used solely to quantify land availability for future expansion or intensification.

5.3.5 Legal classification and concessions

At national level, MoF has classified about 70% of the total land area as 'forest zone' and the rest as 'other use zone (APL)'. However, the legal classification does not always correspond to the actual physical situation (i.e. the APL is not necessarily non-forested) (Gynch and Wells 2014). Meanwhile, a vast area of land has also been granted as timber, oil palm and mining concessions. These concessions may overlap with each other and the 'forest zone'[16]. Companies wanting to grow oil palm must apply to the MoF to have their land excised from the 'forest zone', otherwise they are illegal. This has made monitoring of legal classification and concessions a complicated subject that involves a wide range of stakeholders. Furthermore, some concessions may not be used for their designated purpose and remain under-utilised for years at low carbon status, having been converted from forest to low carbon land decades ago. For oil palm concessions, the location permit (*izin lokasi*) is supposed to be withdrawn if the area has not been developed within three years, and it is only allowed to be prolonged for one extra year. But in reality, this has not been enforced (Fairhurst et al. 2010). These areas are largely locked away from productive use due to uncertainties in land-use rights.

16 The timber concessions are in the areas designated as 'production forest' or occasionally 'conversion forest'.

Both legal classification and concession maps are available at WRI (2012). These maps can be combined with land cover maps to examine low carbon lands that are locked away from utilisation due to policy or legal constraints. A major drawback is that the concession maps are fraught with overlaps and uncertainties due to conflicting claims based on multiple concession issuances by different authorities from national to regency level (Rosenbarger et al. 2013).

5.3.6 Land degradation

The Land Degradation Assessment by FAO (LADA 2009) defines land degradation as 'a reduction in the capacity of land to perform ecosystem functions and services that support society and development'. This is much broader than the two ULC criteria described in section 5.1 because this may include land that is of high carbon stock or ecological services, e.g. degraded peatland. However, 'degraded' land is a term often used to represent low risk land for agricultural development especially in the context of biofuel development (Wicke 2011).

A term with a similar definition, 'critical land (*lahan kritis*)' is used by the Ministry of Forestry (MoF) to refer to land which is severely damaged due to its loss of vegetation cover, and no longer functions as a medium for water retention and productive elements, but disrupting the ecosystem balance (MoF 2013). Remote sensing, biophysical models and experts' or officers' opinions are employed to assess the level of criticality. Land is categorized by level of criticality based on four criteria: land cover, slope, soil erosion, productivity and level of management. The weight of each criterion is different for forest and non-forested area. Unfortunately, the methodology published by MoF (2013) is not detailed enough to understand how scores are given. Also, the actual carbon stock level is not explicitly accounted for in policymaking based on this monitoring domain. There were cases where degraded forests with substantial carbon stock were classified as 'critical land' and logged intensively under the guise of so-called 'rehabilitation' programmes (Barr et al. 2010, Obidzinski and Dermawan 2010). Still, the indicator for land degradation can be seen as a warning signal - it gives an overview of how much land has undergone degradation and requires further actions.

5.4 MATERIALS AND METHODS

5.4.1 Deriving indicators at regency level

Table 5-2 shows the list of indicators defined for different monitoring domains and how they were derived. The year 2011 was employed as the base year since most information is available for this year (with few exceptions). In addition to indicators directly related to ULC land, other indicators, which could be relevant for investigation (e.g. area of paddy), were also included. For 'legal classification and concessions' and 'land degradation', instead of presenting the original data, the maps were further overlapped with land cover maps to derive new indicators. All GIS operations described in Table 5-2 were performed using ArcInfo© procedures.

5.4.2 Narrative interviews

Table S5-1 listed the 23 sub-regencies (*kecamatan*) visited. Local communities were invited for group discussions, with priority given to local leaders. Each group discussion or interview lasted 0.5 - 3 hours, participated by 2-10 people. The discussions were about land-use characteristics and dynamics in relation to ULC land. They were conducted in a flexible and open way to avoid preconception and to allow unexpected hypotheses to emerge.

5.4.3 Estimating ULC land potential for four case studies

The ULC land potential in the four selected regencies was estimated by comparing indicators derived from the previous section, supported with literature and ground evidence collected through narrative interviews. Firstly, the proportion of land cover was compared with the percentages of land suitable for oil palm, oil palm concessions, and critical non-forested land per total regency area. Next, the land-use change (LUC) within and outside oil palm concessions was inspected by overlaying the land cover maps of 2006 and 2011 with the concession map using ArcInfo© procedures. This was then compared with the other indicators, considering their changes across several years whenever data is available. Particularly, the roles of small farmers and industrial oil palm corporations were inspected. Two socio-economic indicators, i.e. population and household income, were also included for the analysis. Based on these findings, possible land-use strategies (e.g. small- or large-scale oil palm establishment) to mobilising ULC land were generally identified with broad estimates of physical ULC area.

5.5 RESULTS AND DISCUSSIONS

Table S5-2 displayed the comparison of key indicators at provincial level. When comparing different indicators at provincial and island level, it can be seen that although some numbers reported may match well at island level, the numbers are quite different at provincial level (e.g. the land suitability indicators). The numbers become even more different when they are further disaggregated to regency level, for example as shown in Figure 5-1 (see all other indicators in Figure S5-2 – S5-7). These figures clearly show that although regencies could be very different when compare between different aspects. For example, although Ketapang has nearly 1 Mha of low carbon land, only 0.6 Mha is deemed suitable for oil palm.

Table 5-2. List of indicators from different monitoring domains.

Monitoring domains	Spatial scale	Indicators	Source of raw data	Derivation methods
Land cover	Spatially explicit	Dry-field agriculture (excluding plantation)	Provincial land cover maps from MoF (2015)	Land classes used by the source were followed. Low carbon land was defined as the sum of the first four land classes. The map was further dissected to regency level by overlaying with the boundary map.
		Dry-field agriculture mixed with grass		
		Grass / Shrub		
		Open land		
		Low carbon land		
		% Low carbon land per total land area of the regency		
		Paddy*		
		Oil palm plantation (large-scale)*		
		Dry-field forests*		
		Swamp and mangrove forest*		
		Non-forested wetlands*		
		Others*		
Land suitability		Land suitable for oil palm excluding existing plantation	Suitability map from WRI (2012)**, existing plantation from MoF (2015)	The map was further dissected to regency level by overlaying with the boundary map. Existing plantations were excluded. Low carbon land that was not considered suitable was calculated by subtracting suitable land from total low carbon land (which was derived for the land cover domain).
		Low carbon land that is not suitable		
		% Land suitable for oil palm excluding existing plantation per total land area of the regency		
Land occupancy	Regency level	Land occupied by small farmers for paddy	BPS (2013b)	Directly reported by source.
		Land occupied by small farmers for non-paddy agriculture		
		Total land occupied by small farmers for agriculture		Sum of the two above land classes.

Table 5-2. (continued)

Monitoring domains	Spatial scale	Indicators	Source of raw data	Derivation methods
Land occupancy	Regency level	% Land occupied by small farmers for agriculture per total land area of the regency	BPS (2013b)	Sum of the two above land classes.
		Land occupied by small farmers for oil palm	BPS (2013b), DG Estate Crops (2014a, b)	Areas of land occupied by small farmers for oil palm and rubber were adapted from DG Estate Crops (2014a, b). If the total oil palm and rubber area of smallholdings reported by DG Estate Crops (2014a, b) was smaller than area of 'land occupied by small farmers for non-paddy agriculture', the remaining land was assumed to be used for other non-paddy agriculture. Else, the extra area reported by DG Estate Crops (2014a, b) was considered as extra oil palm and rubber area (distributed between the first two and last two indicators using the ratio of total oil palm and rubber area reported).
		Land occupied by small farmers for rubber		
		Land occupied by small farmers for other non-paddy agriculture		
		Total area of oil palm smallholdings reported by DG Estate Crops (2014a)		
		Total area of rubber smallholdings reported by DG Estate Crops (2014b)		
		Extra area of oil palm smallholdings reported by DG Estate Crops (2014a)		
		Extra area of rubber smallholdings reported by DG Estate Crops (2014b)		
		Average land area occupied for agriculture per household	BPS (2013b)	Total land occupied divided by number of households.
		Average agricultural income (from own land) per ha of land occupied for agriculture in 2013 (USD/ha) ****		Directly reported by source.
		Average agricultural income (as labourer) per ha of land occupied for agriculture in 2013 (USD/ha) ****		
		Average non-agricultural income per ha of land occupied for agriculture in 2013 (USD/ha) ****		
Land-use intensity		Temporarily unused agricultural land ***	BPS (2013a)	Directly reported by source.
		Shifting cultivation		
		Irrigated paddy field		
		Non-irrigated paddy field		
		Permanent crops (non-industrial)		

Table 5-2. (continued)

Monitoring domains	Spatial scale	Indicators	Source of raw data	Derivation methods
Land-use intensity	Regency level	Total agricultural land	BPS (2013a)	Sum of the five classes above.
		% Land-use intensity		% Used agricultural land (i.e. agricultural land other than temporarily unused agricultural land) per total agriculture land.
Legal classification and concessions (overlapping with land cover)		Low carbon land inside timber concessions	Concession maps from WRI (2012) and land cover map from MoF (2015)	The concession maps (WRI 2012) were overlaid with the land cover map (MoF 2015) to distinguish low carbon land, and further dissected with the regency boundary map. Some overlaps between concessions and 'forest zone' exist. For all overlaps with oil palm concessions, lands were included in oil palm concessions; for overlaps between timber concessions and 'forest zone', lands were included in timber concessions.
		Low carbon land inside oil palm concessions		
		Low carbon land outside the 'forest zone' and concessions		
		% Low carbon land inside the 'forest zone' and concessions per total low carbon land		
		% Low carbon land inside oil palm concession per total low carbon land		
Land degradation (overlapping with land cover)		Critical non-forested land	Critical land map of Kalimantan from MoF (2015)	The critical land map was overlaid with the land cover map (MoF 2015) to distinguish forested and non-forested land that falls under categories 'very critical', 'critical' and 'moderately critical', and with the regency boundary map to dissect to regencies.
		Critical forested land*		
		% Critical non-forested land per total land area of the regency		
		% Forest in critical status per total forested land		

* These indicators are not directly related to ULC land, but were included here to provide overviews of land-use in the regencies.

** This represents low carbon land with elevation <1000m, soil depth >75cm, soil acidity <pH 7.3, slope <30%, water resource buffers >100m, and conservation buffer >1000m. However, other climatic indicators, e.g. rainfall seasonality, were not included in this land suitability map.

*** Land that was regularly used but temporarily (1-2 years) unused, and paddy fields that have been left unused for >2 years.

**** These are socio-economic (non-physical) indicators, but were included here as they were also reported by BPS (2013b), and useful for comparison in case studies.

Based on the wealth of data presented in Figure S5-2 to Figure S5-7, regency policymakers together with other stakeholders, e.g. national policymakers, NGO's, industry or others, may attempt to devise more appropriate land-use strategies at regency level. For example, large-scale establishments should be restricted in regencies with high rate of land occupancy by small farmers even if it has a substantial area of low carbon land. Instead, in the future these regencies might be prioritized for a more diversified portfolio of agricultural activities, e.g. agro-forestry, which may be more suitable in environmental aspect. Seruyan is a prominent example with a low percentage of land remained suitable for oil palm and a large area of critical land. In comparison, regencies in West Kalimantan, which have a large amount of low carbon land and land suitable for oil palm production, could be a better starting point to explore possibilities for large-scale establishment. At the same time, these regencies in West Kalimantan also show high amounts of critical land. This implies that they are degraded and that further expansion would have to take this into account and make sure that the situation is not further exacerbated. To demonstrate how strategies can be drawn based on these indicators, a more detailed investigation was made for four selected regencies in Central Kalimantan with distinctive characteristics as illustrated in the following.

5.5.1 Case study on Gunung Mas

Land-use characteristics and dynamics

Gunung Mas is a land-locked regency mainly covered with two distinctive land cover types, i.e. 56% of dry-field forest (611 kha) and 39% of low carbon land (416 kha) (see Figure 5-2). Among the four regencies, Gunung Mas has the largest area of land considered suitable for oil palm (378 kha), but only a very small percentage of the regency is planted with oil palm (9 kha).

As shown in Figure 5-3, which portrays the spatially explicit LUC in 2006-2011 in the four regencies, Gunung Mas has experienced relatively small LUC across 2006-2011 (only on 5% of the total regency area). This includes 41 kha of deforestation (without cultivation) and new establishment of 9 kha of oil palm plantation on both existing low carbon land and dry-field forest. The large area of low carbon land has existed already since before 2006.

Figure 5-4 shows that land occupied by small farmers in Gunung Mas has increased 35 kha within 2003-2013 to a total of 77 kha, with about 42 and 1 kha are planted with rubber and oil palm, respectively. But, as illustrated in Figure 5-5, only 4 kha is planted with permanent crops in 2012. It is likely that majority of the rubber owned by the small farmers is grown as 'jungle' rubber in a secondary forest, thus it is not easy to be traced without direct information from the farmers (EIA 2014).

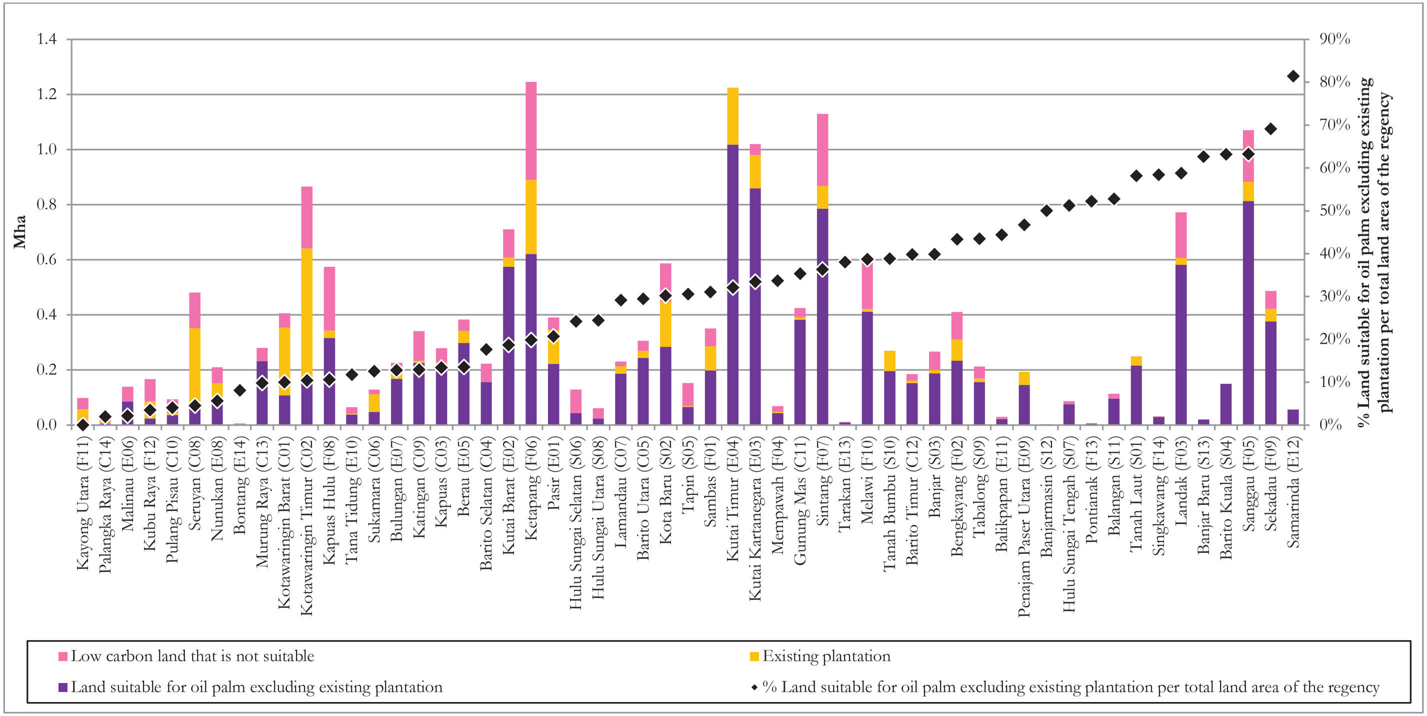
On average, the small farmers in Gunung Mas occupy the largest area of land (about 6 ha per household) among the 55 regencies (Figure 5-5). The narrative interviews reveal a possible explanation for the exceptional high average area occupied by small farmers, i.e. claiming of deforested land remained in the timber concession. As Gunung Mas has undergone rapid deforestation at the hands of logging companies in recent decades, vast areas of former timber concessions have been turned into grassland or shrubs but are officially included in the 'forest zone' (see Figure 5-6). For example in Tewah, about 6 kha of deforested land is locked inside a former timber concession. The villagers have announced their ownership on these areas, and attempted to free these areas up for large-scale oil palm plantation.

Possible land-use strategies

At first sight, Gunung Mas may be a potential candidate for the future establishment of industrial plantations in conjunction with plasma schemes. This is because up to 306 kha of low carbon land which is deemed suitable for oil palm cultivation may be still unoccupied with a rough assumption that another 76 kha is occupied by farmers (comparing Figure 5-2 and 5-10). However, experiences with rogue firms that have routinely disregarded regulations and exploited local people (even though the number of companies is still small), may incur serious social consequences (also see EIA 2014).

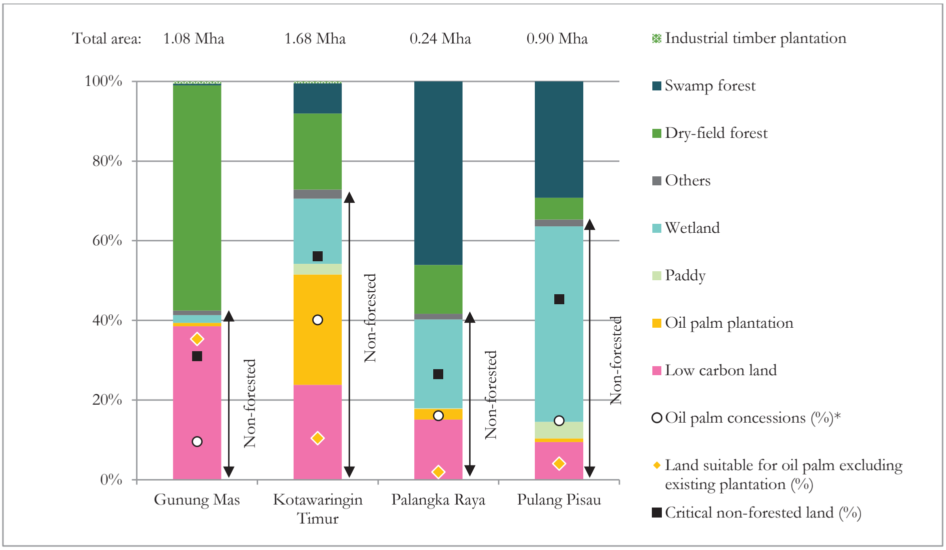
In this context, intensification of small farmers seems to be a suitable starting point for increasing agricultural production, as they have occupied relatively large areas of land. But, the large area occupied per household also implies that labour scarcity could be also an issue, not to mention the distraction from non-agricultural income opportunities (Figure 5-6). Compared to other regencies, Gunung Mas has not experienced large influxes of transmigrants, and the population growth has been slow and steady (Figure 5-5) (see also the map of transmigration sites in Potter 2012).

Overall, although Gunung Mas has a lot of potential in terms of physical land area, the socio-economic factors and continuing isolation (in terms of logistics) are likely to be the major constraints on future agricultural development in the regency. This requires further investigation beyond physical land area estimation.



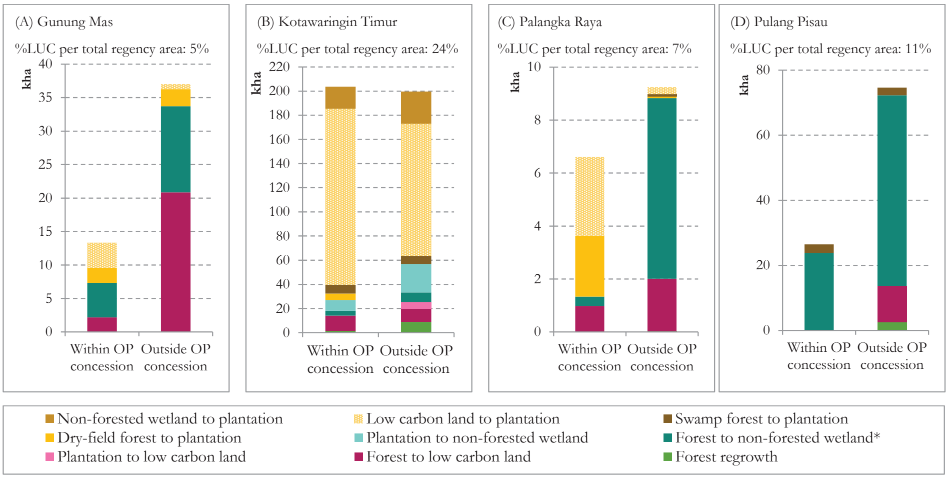
Suitability criteria are: low carbon land with elevation <1000m, soil depth >75cm, soil acidity < pH 7.3, slope <30%, water resource buffers >100m, and conservation buffer >1000m.

Figure 5-1. Land suitability: Land suitable for oil palm in Kalimantan as identified by WRI (2012) in comparison to low carbon land and existing oil palm plantation identified by MoF (2015).



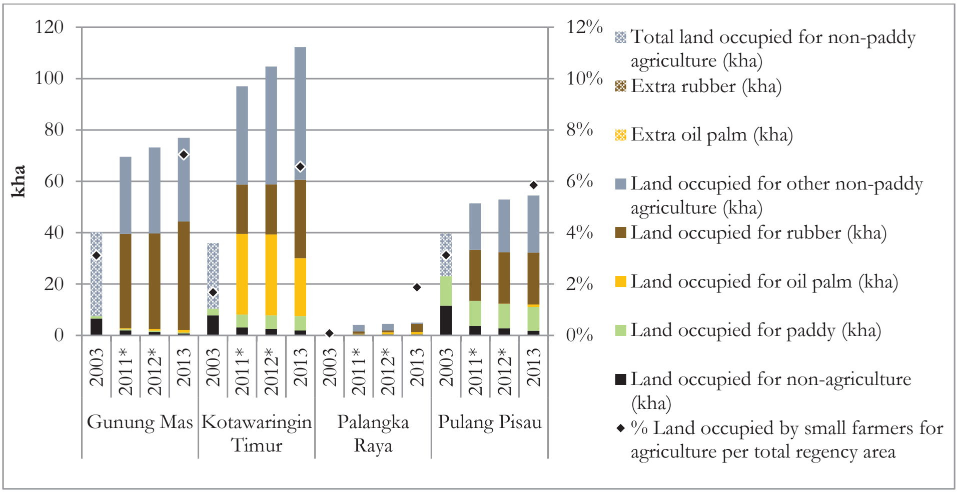
* Some oil palm concessions are forested.

Figure 5-2. Land cover types by proportion, % land suitable for oil palm, % oil palm concessions, and % critical non-forested land per total regency area in the four regencies in 2011.



* This includes some conversion of dry-field forest to wetland, which may be due to technical error in distinguishing dry-field forest and swamp forest.

Figure 5-3. Land-use changes in 2006 – 2011 in the four regencies.



* Areas of land occupied are interpolated for 2011 and 2012 based on data of 2003 and 2013.

Figure 5-4. Land occupancy by small farmers in 2003 and 2013.

5.5.2 Case study on Kotawaringin Timur

Land-use characteristics and dynamics

After decades of intensive logging throughout the 1980's and 1990's, Kotawaringin Timur has been undergoing rapid expansion of industrial oil palm plantations in the 2000's. By 2011, about one third of the regency was covered by oil palm (Figure 5-2). Another one fifth of the regency remained low carbon (400 kha), but only less than half of that is suitable for oil palm.

Figure 5-3 shows that the LUC has been rapid in 2006-2011 - about 24% of the regency has experienced changes in land cover. This is mainly caused by the cultivation of 255 and 45 kha of oil palm on low carbon land and wetland, respectively.[17] About 40% of the total new oil palm was planted outside oil palm concessions (133 kha in total, with 110 kha on low carbon land). Small farmers may partly contribute to the oil palm expansion outside concessions, i.e. under plasma schemes, which theoretically should account for 20% of the total plantation area. But as shown in Figure 5-4, only 31 kha of oil palm area in 2013 was occupied by smallholders, either plasma (mainly transmigrants) or independents. This suggests that small farmers were involved in oil palm expansion but in a much lower magnitude than industrial establishment. This also means that industrial plantations have largely expanded beyond the

17 A strange situation is that 32 kha of plantation in 2006 is reclassified into unplanted wetland in 2011. One possibility is that some oil palm might be abandoned due to unfavourable agro-ecological condition like fire, but it could also be due to technical errors in the analysis of satellite images.

concessions. Also, the low share of land given to smallholders has made Kotawaringin Timur having the greatest number of disputes between companies and locals in any regency.[18]).

Ironically, about 200 kha of oil palm concessions in Kotawaringin Timur still remain as uncultivated low carbon land until 2011 (Figure 5-6). This consists of 50% of the total low carbon land in the regency. There are many cases where areas are abandoned after timber extraction although the land-use right was originally given for oil palm development (also reported by Sandker et al. 2007). Many of these could be part of the land banks of the large corporations.

Another notable change in the regency shown in Figure 5-5 is the loss of 12 kha of irrigated paddy field in 2012. From the narrative interviews with villagers in the paddy-oriented villages in Teluk Sampit and Pulau Hanaut, poor water management has been indicated as a major problem for paddy cultivation. Not only productivity has become low due to absence of irrigation, but drought and flooding have also frequently destroyed their harvest.

Possible land-use strategies

As only less than half of the 400 kha of low carbon land in the regency is considered suitable for oil palm, a diversified strategy may be more suitable for this oil palm-oriented regency in the future. While oil palm plantation is the major agricultural activity, other crops such as paddy, rubber and coconut are widely grown. Also, the land-use intensity is comparatively high (i.e. the share of temporarily unused agricultural land is lower). Thus, an applicable strategy is to support small farmers to intensify and expand on the large area of low carbon land, depending on its suitability for different crops, e.g. paddy and rubber which are already widely grown, or to convert the low carbon land into agro-forestry. Meanwhile, further expansion of industrial plantation beyond the oil palm concessions should be prevented to reduce risk of future deforestation, but the vast area of low carbon land located in the concessions (200 kha) should be better utilised.

5.5.3 Case study on Palangka Raya

Land-use characteristics and dynamics

As the capital of the province, Palangka Raya actually spans a much larger area of land (240 kha) compared to other municipalities in Kalimantan. It is mainly covered by swamp forest (60%), and also a significant area of non-forested wetland (22%) and low carbon land (15%) (Figure 5-2). The low carbon land is largely not suitable for oil palm, probably because most of the low carbon land is surrounded by wetland and swamp forest. However, the regency has 25% of its land granted for oil palm concessions.

18 Presentation by Pak Arie Romp as head of WALHI Kalteng in March 2015 'Penglolalan Gambut dan Konflik Agraria di Kalimantan Tengah'.

Overall, about 7% of the municipality has undergone land cover changes in 2006-2009, which involved 9 kha of deforestation outside oil palm concessions (Figure 5-3). About 5 kha of oil palm was cultivated within concessions, of which more than half were cultivated on low carbon land, but the rest involved conversion of dry-field forest.

The area of land occupied by small farmers is relatively low compared to the other three regencies – only 2% per total regency area (Figure 5-4). The reasons could be land abandonment due to severe agro-ecological conditions (e.g. uncontrolled fire in Rakumpit and flood in Bereng Bengkel), coupled with massive speculative land trading (Rakumpit and Bukit Batu) where most of the land has been sold to outsiders and remained unproductive.

Possible land-use strategies

Since large-scale expansion is risky (only 2% of land remained suitable for oil palm), further agricultural intensification by small farmers could be a feasible strategy in Palangka Raya as they were able to generate relatively high income from agricultural activities compared to the other regencies (Figure 5-6). This may be credited to their exposure to more information and infrastructure due to urbanisation. However, despite the presence of about 36 kha of low carbon land, most of this might be owned by (extra-local) speculators who do not intend to perform agricultural activities, as small farmers only occupy 1.1 ha per household. This will be a barrier for future mobilisation of ULC land.

5.5.4 Case study on Pulang Pisau

Land-use characteristics and dynamics

Pulang Pisau, one of the main sites where the MRP took place during the Suharto era, is rich in swamp forest and wetland (80%) and has rather limited dry-field that is suitable for large scale agricultural activities (9%) as illustrated in Figure 5-2. Similar to Palangka Raya, about 19% of the regency is granted for oil palm concession despite the fact that only 4% is considered suitable for oil palm.

In the period 2006-2011, the deforestation rate was still high (Figure 5-3). The area of swamp forest declined 82 kha, where 24 kha of this deforestation occurred inside oil palm concessions. However, no oil palm has been planted in 2006-2011, and the total oil palm cultivation in the regency was quite low (around 7 kha in estates and 1 kha under smallholdings) (Figure 5-4). The oil palm concessions are unlikely to be cultivated in the near future due to unfavourable agro-ecological conditions - oil palm did not thrive and turned yellow when attempted to be grown on the ex-MRP peatland.

The total land occupied by small farmers did not increase much since 2003 compared to Gunung Mas, despite both regencies share a similar land size. Paddy and rubber are the two major crops cultivated. The farmers are troubled with difficulties in farming due to lower soil quality and frequent peat fire. Pulang

Pisau in general performs worse than the other three regencies in terms of agricultural income. The average income generated from own farms is only 316 USD/ha (Figure 5-6).

Possible land-use strategies

For this regency, the debates lie within the utilisation of degraded peatland - these areas are under-utilised, but not low carbon. While these areas are certainly not of low carbon, it is considered 'under-utilised' by both farmers and policymakers to be considered for further intensification. In fact, many farmers (especially transmigrants) in the regency rely on degraded peatland which is the only property they have for their living (they were relocated and given these peatland during the MRP). The problem is quite different from the other three regencies.

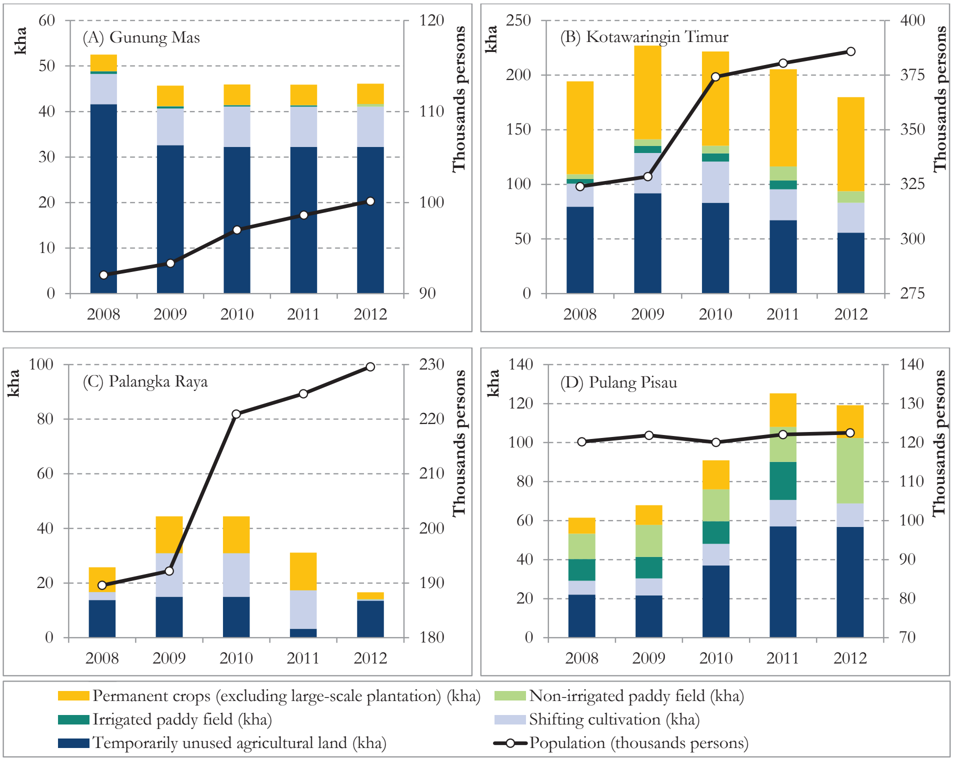


Figure 5-5. Land classes by land-use intensity and population changes in the four regencies in 2008-2012.

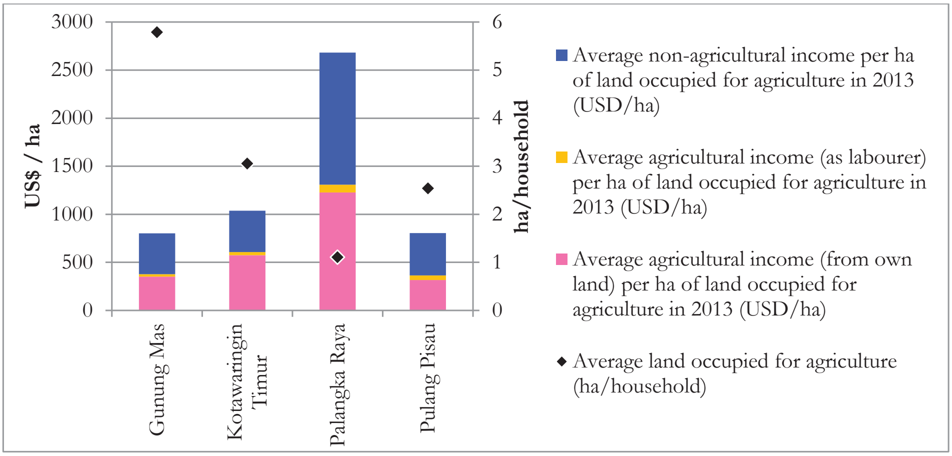


Figure 5-6. Household income by activities in 2013.

5.6 CONCLUSIONS AND RECOMMENDATIONS

This study has attempted to quantitatively explore the ULC land resources in Kalimantan at regency level by utilising the available information from multiple perspectives. Firstly, the review unravelled that the indication of ULC land resources based on six monitoring domains, i.e. land cover, land suitability, land occupancy, land-use intensity, legal classification and concessions, and land degradation, carry different meanings and have their own limitations. These aspects have been well-studied, but the findings were hardly used complementarily when assessing ULC land resources. While the scope of ULC land has a strong focus on carbon stocks, other environmental factors, such as biodiversity and water, are also crucial to ensure sustainable land use (as is shown in HVC assessments for individual oil palm plantations[19]. These aspects, however, have not been covered in this study because there is to our knowledge no quantitative data available for these aspects for all the regencies in Kalimantan.

To improve the assessment of ULC land resources, a range of quantitative physical land indicators was derived by analysing the available information from the six domains. The results show that the values vary substantially for individual regencies. For example, regency Pulang Pisau has a substantial area of 'temporarily unused agricultural land' but a very limited area of 'low carbon land' – this implies that not all temporarily unused agricultural land is ready for future exploitation. Using a single indicator to quantify ULC land is risky as it is likely to be either an over-estimation (potentially inducing more unsustainable large-scale expansions) or under-estimation (potentially leaving a large area of land unused for decades).

19 See https://www.hcvnetwork.org

In order to reduce such risks, all indicators from different monitoring domains were compared together. This was demonstrated for the four selected case studies. By comparing information from different sources, ULC land potential was assessed for possible land-use strategies (e.g. intensification of small farmers or large-scale expansion), resulted in preliminary estimates of ULC land that may be available for mobilisation. This study shows that by combining available data from different aspects, the assessment of ULC land resource can be significantly improved from over- or under-estimation. This is, however, depending on data availability and reliability for a particular region. The case of Kalimantan shown in this study has revealed that there are significant uncertainties due to lack of reliable data, which has to be carefully cross-checked with ground evidence and literature.

In addition to the issues of data availability and reliability, there are still questions left unanswered by physical land area indicators. For example, labour availability was mentioned in the interviews with local communities to be a major barrier for the case of Gunung Mas that affects the ‘real’ potential of ULC land (i.e. land will remain under-utilised due to lack of labourers to carry out the intensification, thus it is not ‘readily available’), but the physical land area indicators used in this study cannot tell much about this. Meanwhile, the addition of other information into the case study analysis, i.e. population, household income and other qualitative information, was found to be crucial in examining the suitability of different land-use strategies. This shows that a more in-depth analysis of ULC land potential must be performed in the context of socio-economic progress in individual regencies.

Therefore, it is important to further investigate ULC land resources beyond physical land indicators. Especially the socio-economic factors underlying land under-utilisation at regency level are crucial to be analysed in more details in order to understand and address the key factors in mobilising ULC land, e.g. labour scarcity, soil quality or potential land-use conflicts. Particularly important is the analysis of these factors through the lenses of different actors, i.e. indigenous communities, (trans)migrants, industry, government officials and civil society. These deserve greater scrutiny in the exploration of ULC land resources, not only in quantitative manner, but also using a narrative approach for collecting opinions from the different actors in order to understand the opportunities and barriers which cannot be directly ‘measured’ in numbers.

ACKNOWLEDGEMENT

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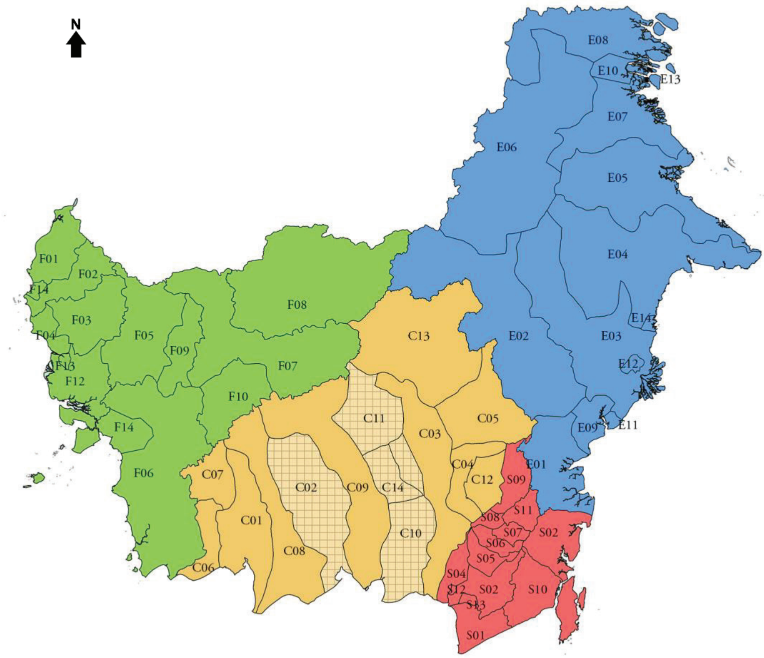
SUPPLEMENTARY MATERIALS

Study area

Table S5-1. List of villages visited.

	Village / Desa or Kelurahan	Sub-regency / Kecamatan	Regency / Kabupaten	Date of visit	No. of interviewees
1	Bereng Bengkel	Sebangau	Palangka Raya	30-11-2014	3
2	Sei Gohong	Bukit Batu	Palangka Raya	8-12-2014	2
3	Petuk Bukit	Rakumpit	Palangka Raya	8-12-2014	2
4	Pager	Rakumpit	Palangka Raya	8-12-2014	3
5	Tuwung	Kahayan Tengah	Pulang Pisau	30-11-2014	2
6	Bukit Liti	Kahayan Tengah	Pulang Pisau	3-12-2014	2
7	Ramang	Banamatingang	Pulang Pisau	5-12-2014	2
8	Tewah	Tewah	Gunung Mas	4-12-2014	3
9	Kasintu	Tewah	Gunung Mas	4-12-2014	3
10	Sandung Tambun	Tewah	Gunung Mas	4-12-2014	4
11	Kuala Kurun	Kurun	Gunung Mas	4-12-2014	2
12	Tarakas	Manuhing	Gunung Mas	8-12-2014	2
13	Bapinang Hilir	Pulau Hanaut	Kotawaringin Timur	15-12-2014	10
14	Babirah	Pulau Hanaut	Kotawaringin Timur	15-12-2014	2
15	Babaung	Pulau Hanaut	Kotawaringin Timur	15-12-2014	2
16	Bapinang Hulu	Pulau Hanaut	Kotawaringin Timur	15-12-2014	2
17	-	Cempaga Hulu	Kotawaringin Timur	16-12-2014	2
18	Karang Sari	Parenggean	Kotawaringin Timur	16-12-2014	2
19	Sumber Makmur	Parenggean	Kotawaringin Timur	16-12-2014	4
20	Sampit	Sampit	Kotawaringin Timur	17-12-2014	2
21	Pasir Putih	Sampit	Kotawaringin Timur	17-12-2014	4
22	Lampuyang	Teluk Sampit	Kotawaringin Timur	18-12-2014	6
23	Kampung Bugis	Teluk Sampit	Kotawaringin Timur	18-12-2014	2



Central Kalimantan		East Kalimantan		West Kalimantan		South Kalimantan	
C01	Kotawaringin Barat	E01	Pasir	F01	Sambas	S01	Tanah Laut
C02	Kotawaringin Timur	E02	Kutai Barat	F02	Bengkayang	S02	Kota Baru
C03	Kapuas	E03	Kutai Kartanegara	F03	Landak	S03	Banjar
C04	Barito Selatan	E04	Kutai Timur	F04	Mempawah	S04	Barito Kuala
C05	Barito Utara	E05	Berau	F05	Sanggau	S05	Tapin
C06	Sukamara	E06	Malinau	F06	Ketapang	S06	Hulu Sungai Selatan
C07	Lamandau	E07	Bulungan	F07	Sintang	S07	Hulu Sungai Tengah
C08	Seruyan	E08	Nunukan	F08	Kapuas Hulu	S08	Hulu Sungai Utara
C09	Katingan	E09	P. Paser Utara	F09	Sekadau	S09	Tabalong
C10	Pulang Pisau	E10	Tana Tidung	F10	Melawi	S10	Tanah Bumbu
C11	Gunung Mas	E11	Balikpapan	F11	Kayong Utara	S11	Balangan
C12	Barito Timur	E12	Samarinda	F12	Kubu Raya	S12	Banjarmasin
C13	Murung Raya	E13	Tarakan	F13	Pontianak	S13	Banjar Baru
C14	Palangka Raya	E14	Bontang	F14	Singkawang		

* Shaded regencies are regencies selected for case studies (see also section 5.4).

Figure S5-1. Map of the regencies and municipalities in Kalimantan in 2012.

Indicators for ULC land at provincial level

Table S5-2 shows the key indicators at aggregated island and provincial level from all monitoring domains. Of the four provinces, South Kalimantan is the smallest province, but more than half of its land is of low carbon, and largely considered suitable for oil palm by WRI (2012). Nevertheless, about 13% of the province is occupied by small farmers, which is the highest among the four provinces. Meanwhile, East Kalimantan has the lowest percentages of low carbon land and land suitable for oil palm. About half of West Kalimantan is considered non-forested and under critical status, while East Kalimantan has only about 10% of such land but more than half of its forests are considered degraded.

Table S5-2. Comparison of key indicators at provincial level (million ha).

Monitoring domains	Indicators *	Provinces				Total
		Central	East	West	South	
General land cover	Total area (MoF 2015)	15.4	19.5	14.7	3.8	53.3
	Forested land (MoF 2015)	8.0	13.5	6.4	0.9	28.8
	Non-forested land (MoF 2015)	7.4	6.0	8.3	2.9	24.6
Land cover	Low carbon land in 2011 (MoF 2015)	3.1	3.9	6.2	2.0	15.2
	Low carbon land in 2010 (Gunarso et al. 2013)	-	-	-	-	15.5
Land suitability	Land suitable for oil palm excluding existing plantation (WRI 2012)	2.2	3.6	4.4	1.5	11.8
	Land suitable for oil palm including existing plantation (WRI 2012)	3.4	4.3	5.3	1.8	14.7
	Land excluding EU-RED zone ** (Hadian et al. 2014)	3.2	4.1	4.8	1.9	14.0
	Dry-field suitable for crops and livestock (BBSDLP 2014)	4.2	6.1	4.0	0.0	14.3
Land occupancy	Total land occupied by small farmers for agriculture (BPS 2013b)	0.8	0.5	1.6	0.5	3.4
	Total area of oil palm and rubber smallholdings in 2013 (DG Estate Crops 2014a, b)	0.4	0.3	0.6	0.2	1.5
Land-use intensity	Temporarily unused agricultural land (BPS 2013a)	1.4	1.2	1.2	0.2	3.9
Land legal classification	Low carbon land within the 'forest zone', oil palm and timber concessions (WRI 2012, MoF 2015)	3.0	3.8	5.3	1.0	13.0
	Low carbon land within oil palm concessions	1.0	1.0	1.9	0.1	3.9
	Dry-field suitable for crops and livestock within the 'forest zone' (BBSDLP 2014)	3.4	3.1	1.2	0.0	7.7
Land degradation	Critical non-forested land (MoF 2015)	4.9	2.1	7.2	1.5	15.6
	Critical forested land (MoF 2015)	1.5	7.6	2.9	0.6	12.6

* Some indicators were further processed in this study and not directly reported by the source shown in the brackets, see Table 5-2 for details. These numbers are presented on a detailed regency level in Figures 2 - 7. ** EU-RED zone is defined as the land area that has fulfilled the requirements of sustainability criteria set by EU-RED (European Union Renewable Energy Directive) for biofuel production.

Indicators for ULC land at regency level

Figure S5-2 shows the land cover indicators by regencies. For about half of the regencies, >30% of their total land is low carbon land. Several smaller regencies and municipalities also appear to have large percentages of low carbon land, e.g. Hulu Sungai Selatan (S06), the heartland of the Banjarese people with little forest and extensive wet rice fields, but the actual areas are small. In contrast, most of the large regencies have smaller ratios of low carbon land. For example, the largest regency, Malinau (E06), has only 4% of low carbon land, because it is mainly still forested with a low indigenous Dayak population. A few regencies, however, do not follow this general trend. This is especially prominent for regencies in West Kalimantan, e.g. the top three regencies with the highest percentages of low carbon land are located in that province.

In Figure S5-3, land suitability for oil palm in each regency is shown. The top five regencies with the largest area of such land, which are large regencies located in East and West Kalimantan, accounted for >5 Mha alone. Compared to the other regencies, they have a larger potential for future development. In contrast, the regencies where oil palm is currently rapidly expanding, e.g. Kotawaringin Timur (C02), have far less suitable land left – this signals that any further large-scale expansion will likely come at the expense of land with high carbon stocks. In terms of percentage of land that is suitable for oil palm, the values vary from very low (2%) to very high (83%), illustrating that local situations may very strongly deviate from the provincial averages.

Figure S5-4 depicts the total and average area claimed by small farmers by crops. The pattern greatly varies from regency to regency. In terms of land occupied per household, farmers from Gunung Mas (C11) have occupied relatively much larger areas. Meanwhile in the crowded and old major cities like Pontianak (F13) and Banjarmasin (S12), the area of land per household is relatively much smaller. Combining information from BPS (2013b) and DG Estate Crops (2014a, b), we found that in large regencies in West Kalimantan like Sintang (F07), Sanggau (F05), Ketapang (F06) and Landak (F03), substantial areas of land were occupied not for paddy, oil palm or rubber, but other form of agriculture. However, in several cases, the reported area of oil palm smallholding is much larger than the area claimed by small farmers (see 'extra oil palm' in the figure). One explanation is that these extra areas are not directly managed by the small farmers but probably controlled by larger private enterprises through plasma scheme.

The indicators that reflect intensity are shown in Figure S5-5. A prominent trend is that regencies with a relatively small share of 'temporarily unused agricultural land' often have sizable areas of 'non-irrigated paddy fields' and vice versa. In several regencies, substantial areas of agricultural land are also used for 'shifting agriculture'. These three land classes are difficult to be clearly distinguished because criteria used in BPS (2013a) are not clearly defined. They may share similar land cover types, i.e. fallows of various lengths[20].

In terms of legal classification and concessions, the distribution of low carbon land within concessions and the 'forest zone' is shown in Figure S5-6. In two-thirds of the regencies, more than 80% of low carbon land has the status of either 'forest zone', timber concession and/or oil palm concession. Some regencies even have >50% of low carbon land located within oil palm concessions. These areas are probably the undeveloped land banks of the companies in major oil palm regencies, e.g. Landak (F03), Ketapang (F06) and Sanggau (F05) in West Kalimantan, as well as Kutai Timur (E04) in East Kalimantan, the biggest oil palm producing regency in that province. It was reported in 2005 that 1.5 Mha of planted oil palm land had been abandoned in West Kalimantan. In East Kalimantan, millions hectares of land were originally given for oil palm under the 'oil palm safety belt' policy, but many were not planted after the timber was taken (Potter 2011).

Figure S5-7 depicts the indicators for land degradation for the regencies. Overall, the share of critical land ranges widely across the regencies, but two marked trends are that seven out of ten regencies with the highest share of non-forested land categorised as 'critical' are situated in West Kalimantan, while the regencies for which forested land is in a 'critical' state are those in East Kalimantan, e.g. Kutai Timur (E04) and Kutai Barat (E02).

20 In Seruyan and Katingan (Central Kalimantan), there is still considerable shifting cultivation in the middle and upper reaches of the rivers beyond the oil palm zone. Kutai Barat in East Kalimantan also has considerable areas of swidden. Also for the case in Kapuas Hulu and Sanggau, there is considerable development of 'padi paya', i.e. wet swiddens in Dayak agriculture, with shorter fallows but less water control than the normal wet rice technology, either irrigated or rain fed (to the personal knowledge of the co-author, Lesley Potter).

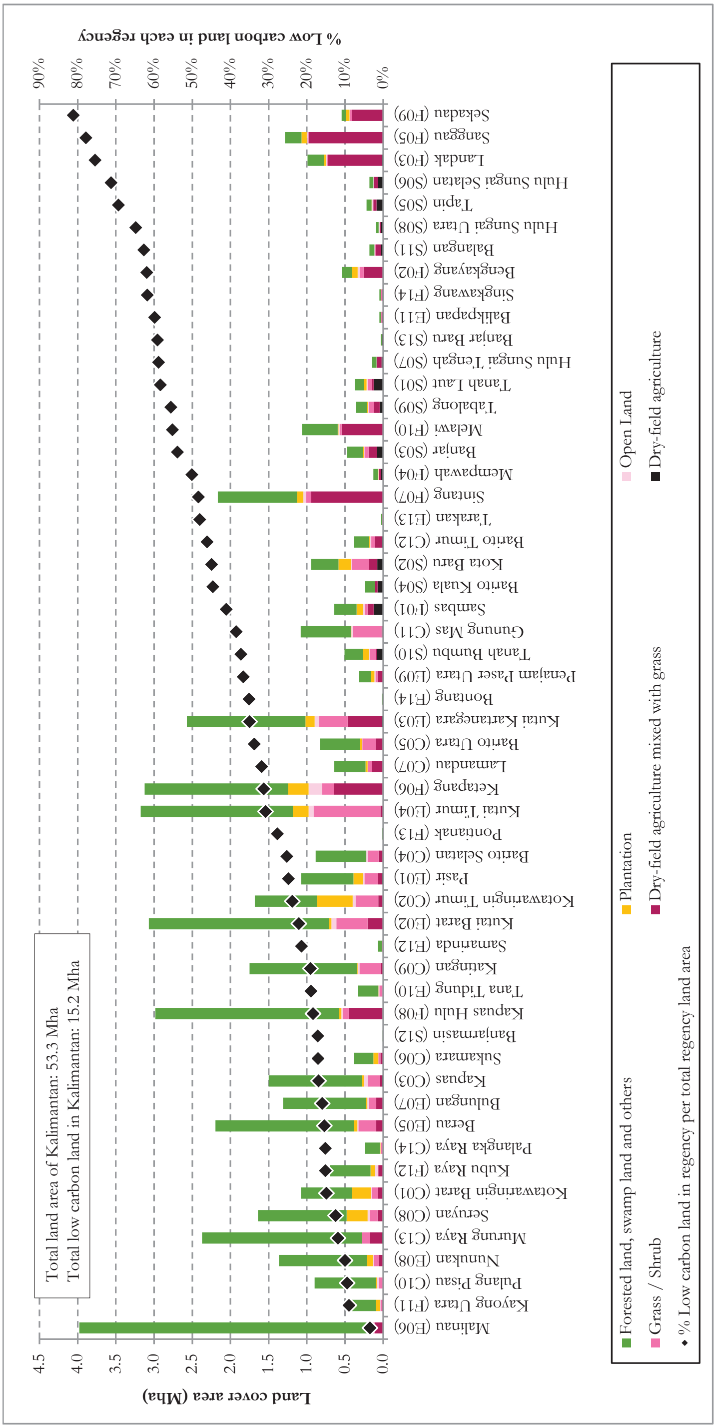
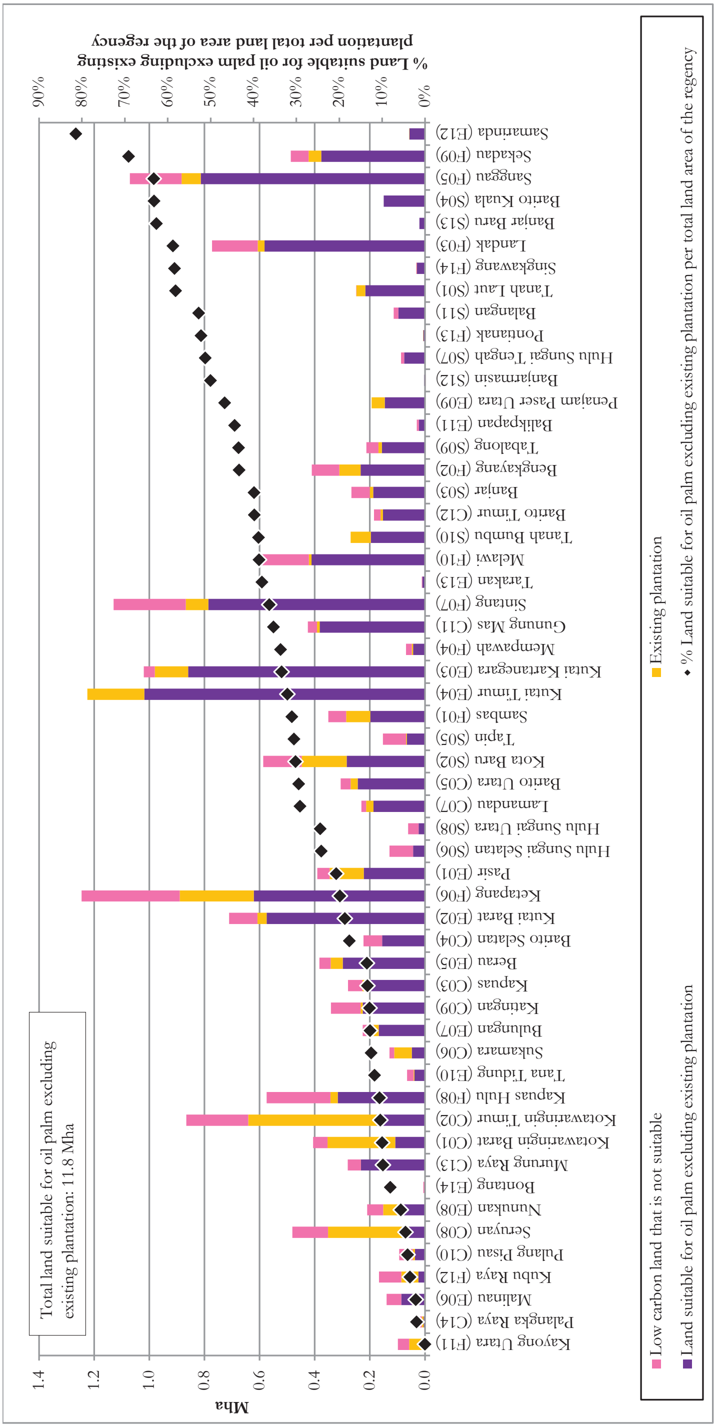
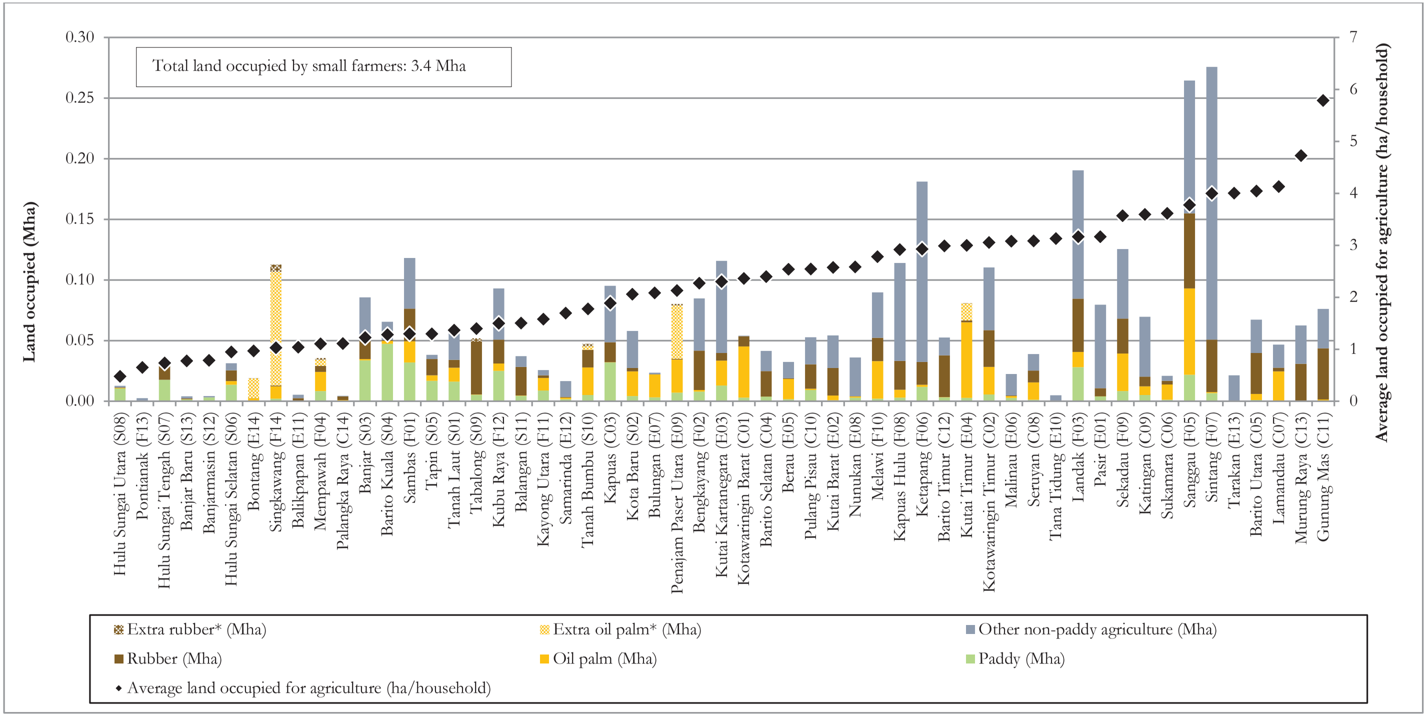


Figure S5-2. Land cover: Distribution of low carbon land and land cover types by regencies in Kalimantan in 2011.



Suitability criteria are: low carbon land with elevation <1000m, soil depth >75cm, soil acidity < pH 7.3, slope <30%, water resource buffers >100m, and conservation buffer >1000m.

Figure S5-3. Land suitability: Land suitable for oil palm in Kalimantan as identified by WRI (2012).



* There are discrepancies between the smallholding area reported by DG Estate Crops (2014a, b) and area occupied by small farmers reported by BPS (2014b). Extra rubber and extra oil palm areas are the differences between the two sources.

Figure S5-4. Land occupancy: Land occupied by small farmers for agriculture by regencies in Kalimantan in 2013.

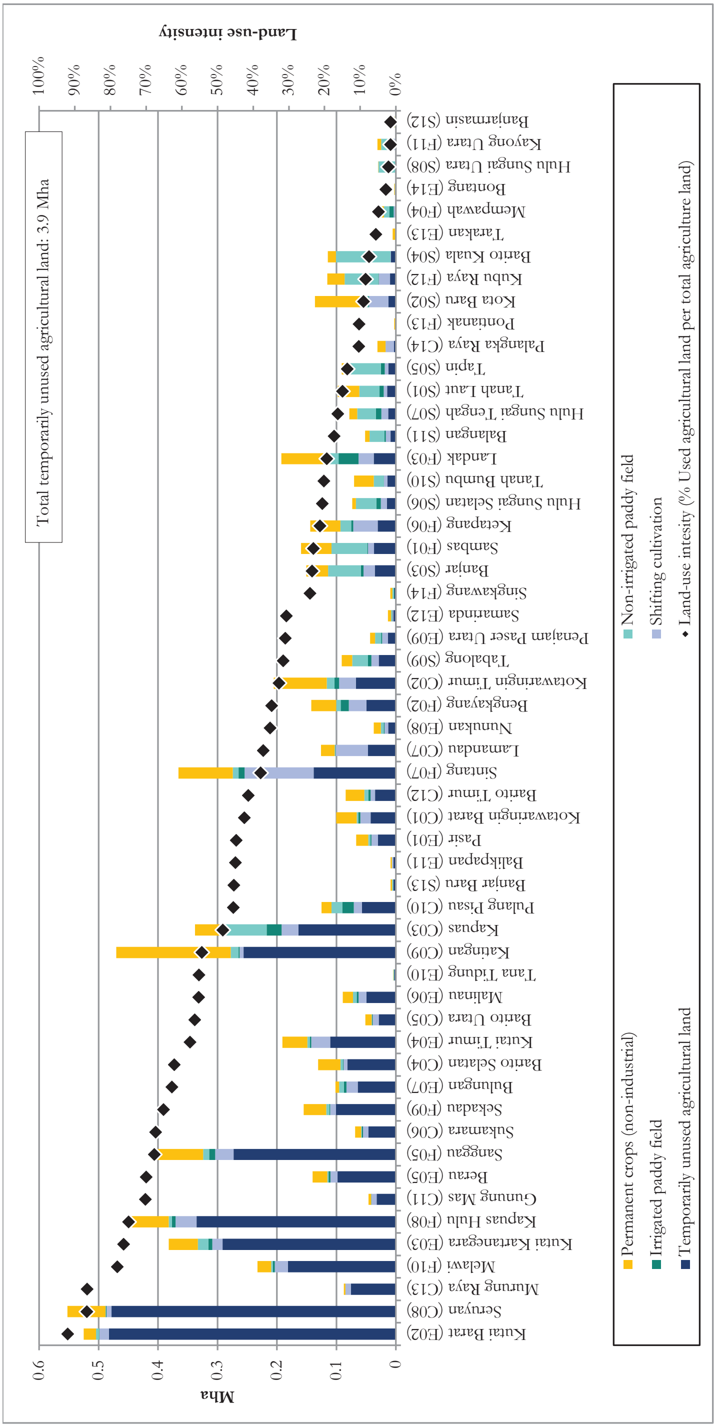


Figure S5-5. Land-use intensity: Agricultural land-use status by regencies in Kalimantan in 2011.

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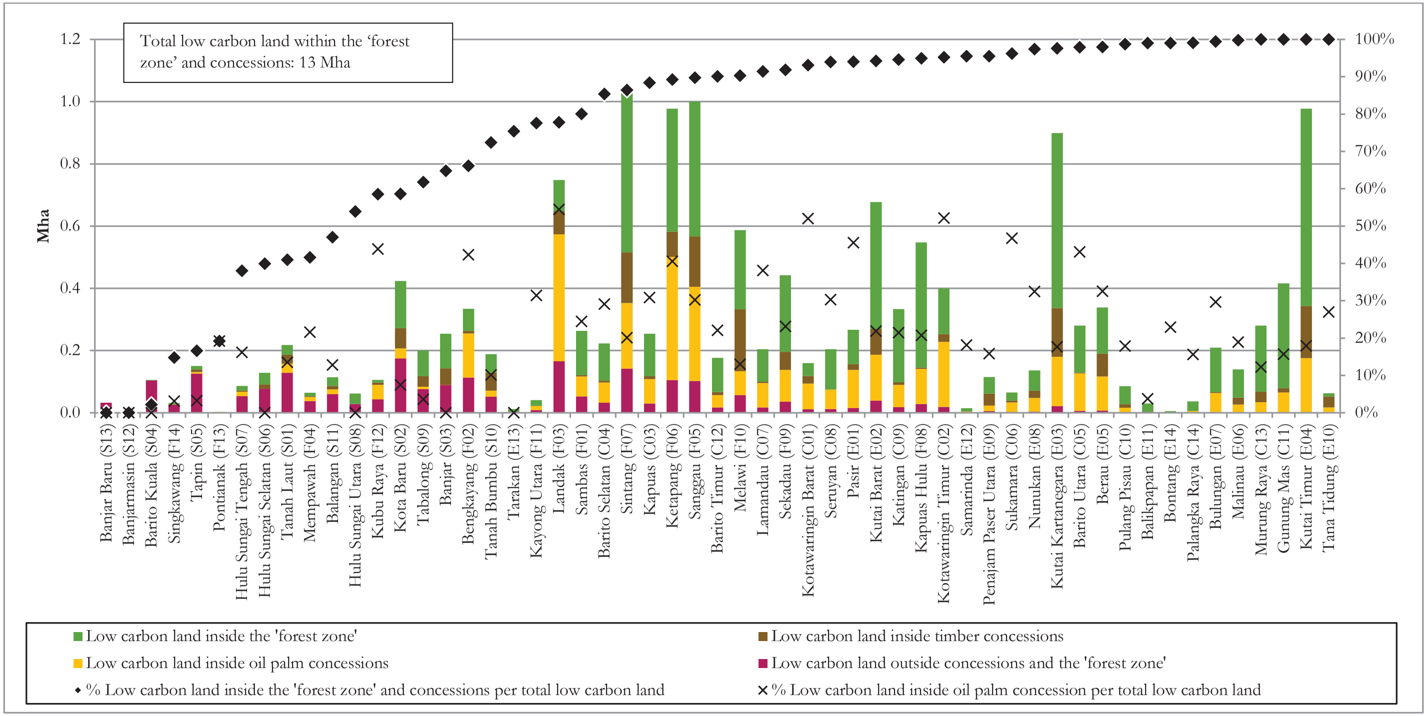

Note that some overlaps between concessions and 'forest zone' exist. All overlaps with oil palm concessions was included in oil palm concessions; all overlaps between timber concessions and 'forest zone' was included in timber concessions.

Figure S5-6. Legal classification and concessions (overlapping with land cover): Low carbon land falling within concessions and the 'forest zone' in Kalimantan in 2011.

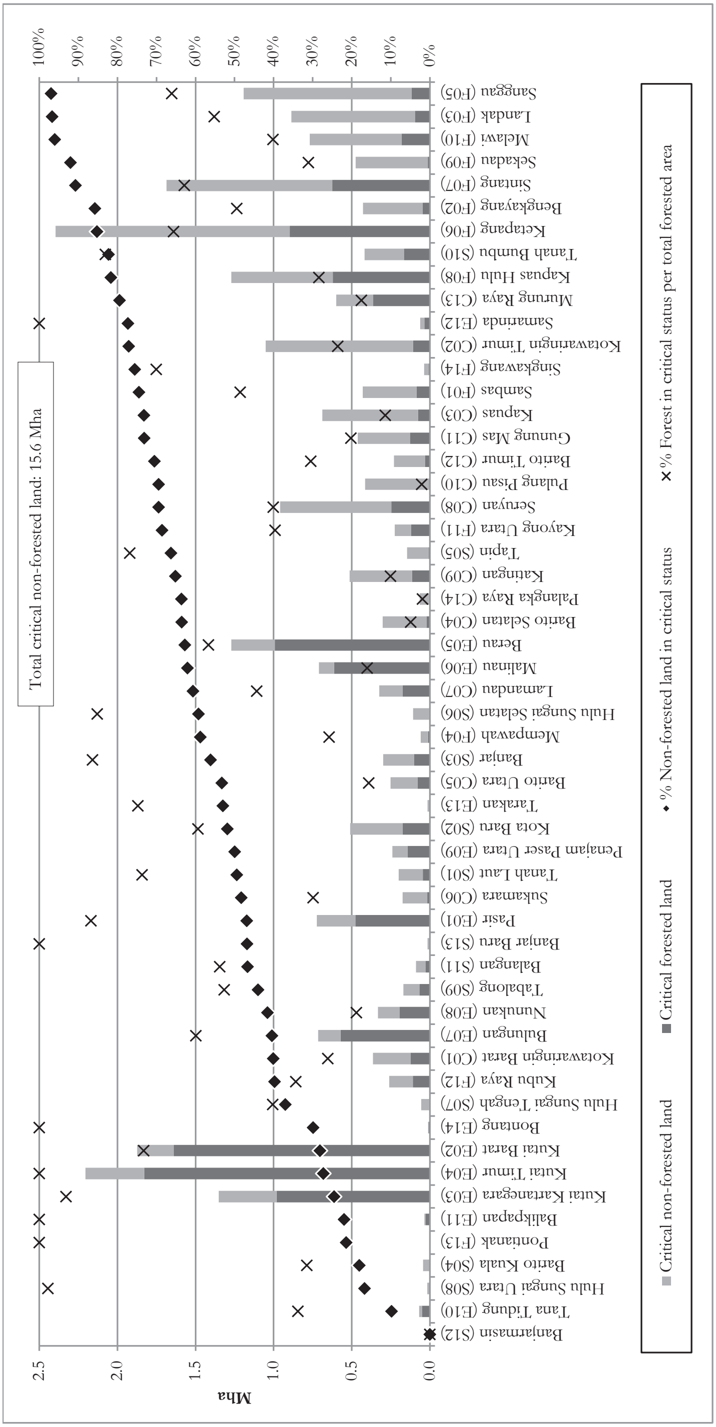

Figure S5-7. Land degradation: Critical land in Kalimantan in 2011.

CHAPTER 6

Identifying opportunities and barriers to mobilising under-utilised low carbon land resources: A case study on Kalimantan

Authors:
Chun Sheng Goh
Martin Junginger
Lesley Potter
André Faaij
Birka Wicke

"When I see an elephant *fly*." --- Dumbo

ABSTRACT

Mobilising under-utilised low carbon (ULC) land for future agricultural expansion helps ensure no further carbon stock loss. This study examined the regency cases in Kalimantan, a carbon loss hotspot, to understand the key factors for mobilising ULC land via narrative interviews with a range of land-use actors and complementary desktop analyses. The factors were broadly categorised into economic, agro-ecological, institutional and cultural factors, which were perceived as opportunities and/or barriers by different land-uses and stakeholders (with different business models), and can vary across regencies. Generally, oil palm was regarded by most interviewees as an economic opportunity, reflecting that there were no other more attractive options. However, oil palm may also be limited by various factors. For example, labour availability may greatly limit the actual amount of land that can be mobilised in many regencies due to low population density. These economic factors were interlinked with the agro-ecological factors, such as soil quality, which was often regarded as the reason of low economic attractiveness. The other two categories, institutional and cultural factors, are more subtle and complex, involving socio-political elements across the hierarchy of authorities. Past analyses on ULC land largely focus on a single crop or end-use. This study shows that mobilisation of ULC land has to depart from analysing the specific conditions within individual regencies, especially considering the views of multiple land-use actors on different land-use options and business models. For example, Gunung Mas has potential for large-scale deployment, while in Pulang Pisau oil palm can be part of the small scale mixed cropping which generates extra income. Future research is recommended to assess available land-use options and business models by matching them with each factors, based on the policy targets set by individual regencies (e.g. economic development or food security), and the preference and capability of local actors.

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Keywords: Under-utilised land; Low carbon; Kalimantan; Indonesia; Small farmers; Oil palm.

6.1 INTRODUCTION

Rapid land-use change (LUC), particularly deforestation and conversion of peatland, has led to many environmental problems in Kalimantan (Indonesia) in the past decades (see e.g. Moore et al. 2013, Tacconi et al. 2008). One of the most serious problems is the substantial loss of carbon stock from both deforestation and peat loss. Annual carbon stock loss in Kalimantan contributed to roughly 30% of the total carbon stock loss of Indonesia, ranging from 0.3 to 0.6 billion tonne CO_2 per year (Abood et al. 2015). Agricultural expansion due to increasing demand, especially for export-oriented oil palm plantation, is recognised as one of the major culprits (Agus et al. 2013, Austin et al. 2015, Wicke et al. 2011). In 2011, the total area planted with oil palm in Kalimantan increased to about 3 Mha, and half of this area involved direct conversion of upland forest and wetland (Gunarso et al. 2013). Since then, the oil palm area increased to 3.5 Mha in 2014 (DG Estate Crops Indonesia 2014), while global demand for palm oil is expected to grow further in the future (FAOSTAT 2016, OECD/FAO 2016). It is thus necessary to ensure that future agricultural production, especially palm oil, does not cause further carbon stock loss. Overall, these aims can be translated into two basic criteria when searching for potential land resources for future agricultural activities: (i) the current agricultural productivity of the land is insignificant or low compared to its optimal potential (i.e. there is significant room for more production per unit land); and (ii) the level of carbon stock is low so that land utilisation is unlikely to incur additional carbon stock loss and negative ecological impacts (e.g. forest and wetland must be excluded). Such land may be broadly regarded as under-utilised[21] low carbon (ULC) land.

Various studies have tried to quantify the physical area of ULC land using environmental criteria (especially in terms of carbon stocks) and agro-ecological criteria (in terms of land suitability for certain crops) at national, regional or provincial level (e.g. Hadian et al. 2014, Gingold et al. 2013). The analyses were performed for a specific crop (particularly oil palm, e.g. Gingold et al. 2013) or a specific end-use (particularly bioenergy, e.g. Hadian et al. 2014), but rarely linked this to the agrarian transformation in socio-economic aspect that involves different crops and actors across multiple sectors. Recent work by van der Laan et al. (2016) has demonstrated an integrated approach that also accounts for yield and supply chain improvements to assess the technical land potential for future agricultural production covering a range of crops. However, this study did not connect physical land availability and suitability to socio-economic conditions. But in reality, a wide range of socio-economic factors, e.g. labour availability and local preferences (Baumann et al. 2011), largely define whether ULC land can actually be mobilised for additional agricultural production or not. This missing socio-economic perspective also often concerns developing regions in general. For example, the study by Pirker et al. (2016) represents state-of-the-art quantitative analysis of potential future oil palm expansion, yet socio-economic factors are not incorporated.

21 'Under-utilised' is a normative notion that can be interpreted in different ways depending on e.g. socio-cultural values, economic values or legal perspectives. In this paper, it only refers to agricultural productivity to reflect criterion (i).

The various socio-economic factors influencing the availability of ULC land may be perceived as either opportunities or barriers to mobilising ULC land depending on the actor (e.g. private company, farmers, local communities, government officials), their land-use preferences (e.g. mixed crop farming or monoculture oil palm) and business models (e.g. small-scale farming or industrial plantation). The viewpoints may also change from global, national to local level. For example, local land-users may see local labour shortage as a major barrier for intensification, while large-scale players may see it as an advantage in obtaining land-use permit with less land conflicts with local communities (Byerlee and Rueda 2015). Many qualitative and narrative studies have investigated the relationship between land-use and socio-economic transformation in Kalimantan and Indonesia, e.g. Casson (2006), Potter (2011) and McCarthy (2013). However, they are not explicitly designed to identify ULC land, and evidence only exists either in the form of individual case studies (e.g. Tomich et al. 1997) or at a more aggregated level with a broader scope beyond ULC land (e.g. Shantiko et al. 2013, Gatto et al. 2015).

Our previous work assessed ULC land resources by reconciling information available from different sources, but have not specifically examined the individual factors that affect the mobilisation of these land resources (Goh et al. 2016). Based on these shortcomings, this study aims to identify the actual factors for mobilising ULC land resources, including not only agro-ecological factors, but also economic, institutional and cultural factors. To achieve the aim of the study, information and opinions were collected from actors involved in land-use and assessed for differences and similarities in what factors were seen as opportunities and barriers by the different actors. This is especially crucial to be performed within a relevant administrative level, i.e. the regency level, at which the authorities are the most influential in the actual implementation of land-use policies in Kalimantan. The detailed research sites were selected in Central Kalimantan, covering four regencies with distinctive characteristics. In addition, an important factor identified through the narrative interviews, i.e. labour availability, was further quantitatively investigated. This part was applied to all the regencies in Kalimantan. Extra attention was given to oil palm as a predominant land-use that has experienced rapid expansion in the past decades in Kalimantan, but other land-use options are also discussed.

6.2 MATERIALS AND METHODS

6.2.1 Obtaining viewpoints from land-use actors through narrative interviews

Narrative interviews were conducted to obtain positions and perspectives from different land-use actors on two research questions: (a) what are the key factors in mobilising ULC land from local and industrial perspectives, and (b) how do these affect the mobilisation of ULC land. Four regencies (names in italic) with distinctive characteristics were selected as case studies (Figure 6-1), which broadly represent the following cases:

(i) Subsistence farming with alternative income sources - *Gunung Mas*. The regency is mainly occupied by subsistence farmers who did not undergo agricultural modernisation but have developed alternative income sources, i.e. small-scale (illegal) mining activities.

(ii) Integration with international market - *Kotawaringin Timur*. The regency, which has access to ports, has been rapidly developing intensive export-oriented agricultural activities, particularly industrial-scale oil palm plantations.

(iii) Urbanisation - *Palangka Raya*. The capital of Central Kalimantan is a suitable example to assess the impact of urbanisation on surrounding land-use[22].

(iv) Unsuitable agro-ecological conditions - *Pulang Pisau*. The regency has a limited area suitable for agricultural activities due to unfavourable agro-ecological conditions (it is largely covered with swamp and peatlands). Nevertheless, its land-use patterns have been greatly influenced by policy intervention – it is the former site of the Mega Rice Project (MRP)[23] with a large influx of transmigrants[24].

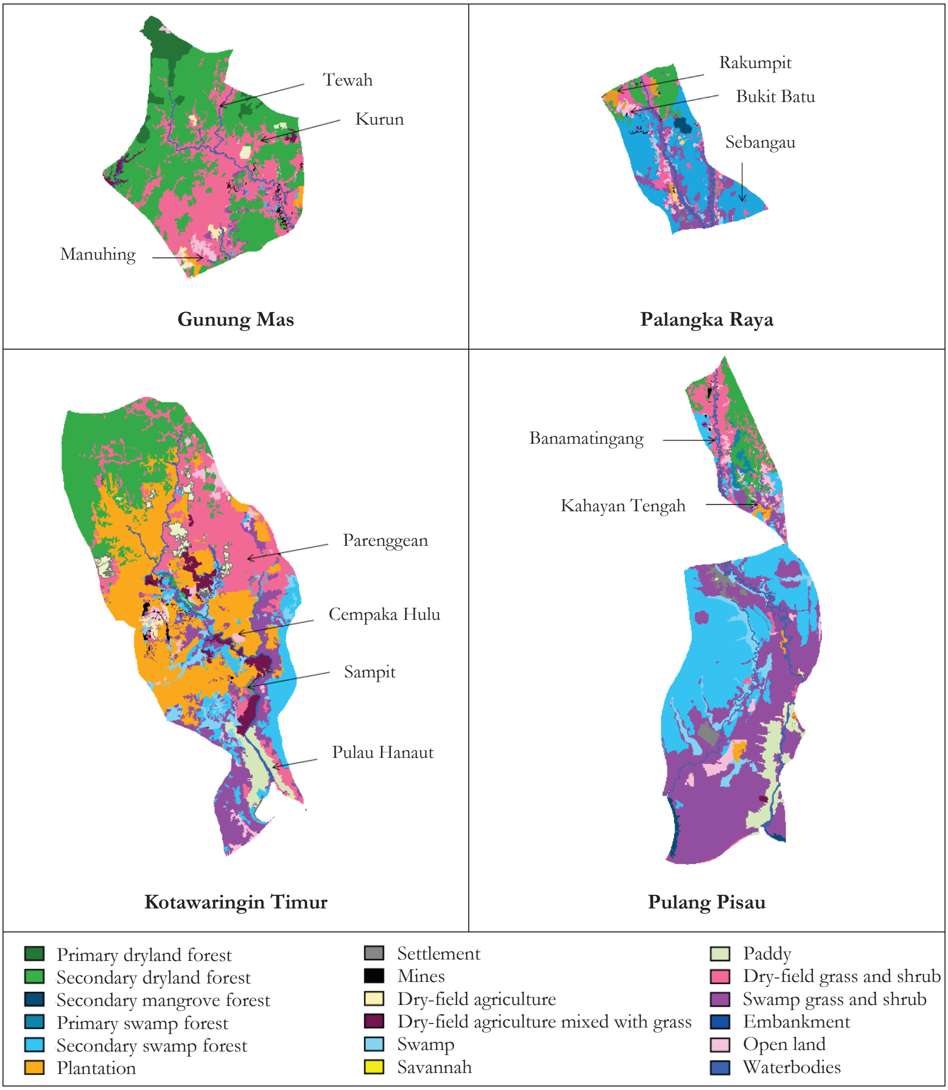
The field study was conducted by the first author, with the help of a small local team, between November 2014 and January 2015 in these four regencies. The potential sites (those with potentially low carbon land covers and likely under-utilised, like grass and shrub land) were screened based on the publicly available land cover maps (MoF 2015). Then, the data collection started with short surveys with the local communities to identify places to visit and people to meet. Decisions were also made with consideration of logistical constraints. The targeted groups for interviews and discussions were local communities in the four regencies (Table 6-1). In addition, industrial perspectives were also examined through interviews with key industrial informants who have experience with oil palm establishment in Kalimantan (Table 6-2). Government officers, experts and scientists were also consulted for their views on land-use issues in relation to ULC land in the four regencies. A few key questions were formulated (see Box S6-1) to kick-start the discussion, but the interviews (mostly in the form of group discussions) were conducted in a flexible way to avoid preconception and allow unexpected hypotheses to emerge. The team was able to communicate with the interviewees using both the common tongue, i.e. Bahasa Indonesia, and the relevant native Dayak language.

In total, 13 sub-regencies (*kecamatan*) were visited (Figure 6-1). Group discussions were conducted in 23 villages (Table 6-1). In terms of geographical distribution, Kotawaringin Timur has the most villages visited (11) while Pulang Pisau has the least (3). The majority of the group discussions have 2-3 participants (mostly family members or neighbours), but some involved larger groups, e.g. 10

22 Municipalities are usually small in area. Palangka Raya is considered a special case as a municipality with a relatively large area allocated. This situation allows the examination of how urbanisation affects LUC based on the LUC statistics at municipal level. For municipalities with much smaller areas, the urbanisation effect spreads across neighbouring regencies and difficult to trace with aggregated data.

23 The Mega Rice Project was a failed programme initiated by the Indonesian Government to develop one million hectares of degraded peatland for food crop production in 1996.

24 The transmigration programme is a population-relocation programme that moves landless people mainly from the densely populated Java Island to less populous islands of the country, e.g. Kalimantan. See e.g. Potter (2012).



* Not to actual scale

Figure 6-1. Land covers of the four selected regencies in 2011 and the sub-regencies (*kecamatan*) visited to gather information from local stakeholders. (Source: adapted from MoF 2011) participants in Bapinang Hilir (Pulau Hanaut). The length of discussion also varies from 0.5 to 2 hours, and sometimes followed by short field trips organised by the interviewees. Most interviewees have also non-agricultural income (e.g. mining or fishing), except the plasma farmers in Parenggean who rely solely on oil palm. Regarding industrial viewpoints, key informants from two major international oil palm companies were interviewed. One company invited the first author and his team to their plantation for field study (see section 6.2.3) and group discussions with managers at different levels. In addition, 5 government officials and 7 experts with various backgrounds were interviewed (Table 6-2).

Table 6-1. List of villages visited.

	Village / Desa or Kelurahan	Sub-regency / Kecamatan	Regency / Kabupaten	Date of visit	No. of interviewees	Ethnicity of the interviewees
1	Bereng Bengkel	Sebangau	Palangka Raya	30-11-2014	3	Dayak
2	Sei Gohong	Bukit Batu	Palangka Raya	8-12-2014	2	Javanese
3	Petuk Bukit	Rakumpit	Palangka Raya	8-12-2014	2	Dayak
4	Pager	Rakumpit	Palangka Raya	8-12-2014	3	Dayak
5	Tuwung	Kahayan Tengah	Pulang Pisau	30-11-2014	2	Dayak
6	Bukit Liti	Kahayan Tengah	Pulang Pisau	3-12-2014	2	Dayak
7	Ramang	Banamatingang	Pulang Pisau	5-12-2014	2	Dayak
8	Tewah	Tewah	Gunung Mas	4-12-2014	3	Dayak
9	Kasintu	Tewah	Gunung Mas	4-12-2014	3	Dayak
10	Sandung Tambun	Tewah	Gunung Mas	4-12-2014	4	Dayak
11	Kuala Kurun	Kurun	Gunung Mas	4-12-2014	2	Dayak
12	Tarakas	Manuhing	Gunung Mas	8-12-2014	2	Javanese
13	Bapinang Hilir	Pulau Hanaut	Kotawaringin Timur	15-12-2014	10	Banjarese
14	Babirah	Pulau Hanaut	Kotawaringin Timur	15-12-2014	2	Banjarese
15	Babaung	Pulau Hanaut	Kotawaringin Timur	15-12-2014	2	Banjarese
16	Bapinang Hulu	Pulau Hanaut	Kotawaringin Timur	15-12-2014	2	Banjarese
17	-	Cempaga Hulu	Kotawaringin Timur	16-12-2014	2	Javanese
18	Karang Sari	Parenggean	Kotawaringin Timur	16-12-2014	2	Javanese
19	Sumber Makmur	Parenggean	Kotawaringin Timur	16-12-2014	4	Javanese
20	Sampit	Sampit	Kotawaringin Timur	17-12-2014	2	Javanese
21	Pasir Putih	Sampit	Kotawaringin Timur	17-12-2014	4	Javanese
22	Lampuyang	Teluk Sampit	Kotawaringin Timur	18-12-2014	6	Javanese
23	Kampung Bugis	Teluk Sampit	Kotawaringin Timur	18-12-2014	2	Javanese

Table 6-2. List of interviewees: government officials, industrial informants and other experts.

	Category	Level	Job title and affiliation of interviewee	Date of interview
1	Industrial informants	Company A	Group level senior manager, plantation managers, operation managers - A major international oil palm conglomerate	Nov-Dec 2014*
2		Company B	Group level senior manager - A major international oil palm conglomerate	Dec 2014*
3		Industrial Association	CEO - Malaysian Palm Oil Council (MPOC)	Dec-2014
4	Government officials	Provincial government (Central Kalimantan)	Head - Department of Plantation and Agriculture	Dec-2014*
5			Secretary of Provincial Government & Leader of Dayak Misik	8-12-2014
6		Regency government (Gunung Mas)	Senior officer - Department of Plantation and Agriculture	5-12-2014
7		Regency government (Kotawaringin Timur)	Secretary - Department of Forest and Plantation	18-12-2014
8			Section head - Land development and irrigation (Dep. of Agriculture)	18-12-2014
9	Experts	Smallholders association	Secretary General – Indonesian Oil Palm Smallholders Union (SPKS)	12-11-2014
10		Private consultancy firm	Project manager - The Forest Trust (TFT)	Jan-2015
11		University	Institute for Land-use and Agriculture Research (PILAR), Climate Policy Initiative (CPI), University of Palangka Raya	1-12-2014
12		International research centre	Senior scientist - Centre for International Forestry Research (CIFOR)	12-11-2015
13		Private consultancy firm	Soil scientist – Independent consultant	Jan-2015*
14		National research institutes	Senior scientist – Agency for Agricultural Research and Development	23-12-2014
15			Soil scientist – Malaysian Palm Oil Board (MPOB)	Jan-2015*

* Multiple times of contact (by physical meetings, phone calls, and/or e-mails)

6.2.2 Estimating labour availability per regency

Labour availability was identified by the interviewees as a major factor for mobilising ULC land in the four regencies. However, previous literature has not investigated how local labour availability may constrain mobilising ULC land. While we focused on four regencies to identify the factors for mobilising ULC land, here we assessed all regencies in Kalimantan. This is because labour availability may also be a factor for other regencies due to Kalimantan having a rather low population density (from 25 person/km^2) compared to Java (1055 person/km^2) and Sumatra (105 person/km^2) in general (BPS 2015, numbers for 2010). As mentioned earlier, oil palm expansion is a major concern in Kalimantan and therefore we specifically chose to focus the assessment on this crop. To assess this factor, 6 steps were taken to build two scenarios, as explained next.

Firstly, the size of the labour force for each regency was estimated. The percentage of labour force per total population based on age structure has not changed much between 2008 and 2012 (BPS 2016). For all the four provinces in Kalimantan, about 45-52% of the population were in the labour force, and 27-33% were children under 15-year-old. The rest were those considered eligible to work (i.e. >15 year-old) but are currently not in the labour force, e.g. housekeepers, senior citizens and students. Based on the population statistics (2008-2012) reported by BPS Kalbar (2014), BPS Kalsel (2014), Kalteng (2014) and BPS Kaltim (2014), the population per regency was linearly forecasted until 2030. The year 2030 was chosen because this year marks the end of the life cycle of most oil palm area in Kalimantan, which was established in the early 2000's. The situation of land-use by then will largely depend on global palm oil supply and demand. Conservatively, the percentage of labour force for all regencies in Kalimantan was assumed to be 45%, and the size of labour force per regency in 2030 was estimated by multiplying this percentage with the forecasted population as in Eq. (1). It was also assumed that 33% will be children (<15 year-old) and the rest (>15 year-old) will not be in the labour force.

$$Labour\ force\ per\ regency\ (Lf) = Regency\ population \times 45\% \qquad (1)$$

One limitation is that the number of labourers in non-agricultural sectors was not known. To address this limitation, two scenarios were built in the second step. For Scenario 1, Eq. (2a) was employed, where the case of maximum labour availability was used, assuming that becoming an oil palm smallholder (with intensification) or working on an oil palm plantation is more attractive than subsistence and non-agricultural activities (e.g. mining, logging or working in the cities). For Scenario 2, the labour force diverted to non-agricultural sectors was determined by comparing the income ratio from agricultural and non-agricultural sources using data in 2013 from the household survey by BPS (2013) as shown in Eq. (2b). The underlying assumption is that the labourers will divide their manpower in the two sectors simply based on economic considerations. For example, the higher rates of urbanisation and mining in East Kalimantan may largely distract many labourers from being available for working on oil palm plantations. Naturally, this scenario will lead to a significantly lower labour availability than in Scenario 1.

$$Labour\ force\ per\ regency\ in\ agricultural\ sector\ (Lt_1) = Lf \qquad (2a)$$

$$Labour\ force\ per\ regency\ in\ agricultural\ sector\ (Lt_2) = Lf \times \frac{Income\ from\ agricultural\ sector}{Total\ household\ income} \qquad (2b)$$

Thirdly, for each scenario, the labourers who Lt_2would already be working on existing large-scale plantations were deducted from the labour force. Budidarsono et al. (2011) estimated that the labour requirement of a plantation during a 25-year cycle ranged from 59 to 144 person-days per ha per year, depending on the age of the oil palm trees. This was translated to labour requirement factors of about 0.2 to 0.5 person per ha, considering 300 working days per year. Taking the average value of 0.35, this factor was multiplied with the area of large-scale plantation in each regency in 2011 to deduce the number of labourers on existing plantations (MoF 2015, Goh et al. 2016) as in Eq. (3):

$$Labourers\ on\ existing\ plantations\ (Le) = Area\ of\ large\ scale\ plantation\ in\ each\ regency \times 0.35 \quad (3)$$

Fourthly, the labour requirement for mobilising ULC land was calculated with a demonstration on oil palm. WRI (2012) provided estimates of low carbon land suitable for oil palm with elevation <1000m, soil depth >75cm, soil acidity <pH 7.3, slope <30%, water resource buffers >100m, and conservation buffer >1000m. These estimates, however, did not consider labour availability as a constraint to how much of ULC land may be mobilised. Labour requirement was calculated if these lands (excluding those that were already cultivated with oil palm, as calculated in Goh et al. 2016) were to be converted into oil palm plantation, by multiplying the area per regency by the labour requirement factor of 0.35 person per ha (at industrial efficiency as of the existing large-scale plantations) as in Eq. (4):

$$Labour\ requirement\ (Lr) = Area\ of\ suitable\ land\ in\ each\ regency\ (excluding\ planted\ area) \times 0.35 \quad (4)$$

The fifth step, as shown in Eq. (5), was to calculate whether the labour force in 2030 (excluding those who would be working on existing plantations) will be enough to fulfil the new labour requirement. The step was repeated for both Scenario 1 and 2 using Lt_1 and Lt_2 as Lt in Eq. (5), respectively.

$$If\ (Lt - Le) > Lr$$

$$Labourers\ available\ for\ mobilising\ land\ suitable\ for\ oil\ palm\ (excluding\ existing\ plantation)(La) = Lr \quad (5a)$$

$$Labour\ surplus = (Lt - Le) - Lr \quad (5b)$$

$$Extra\ local\ labourers\ required\ to\ fully\ mobilise\ all\ land\ suitable\ for\ oil\ palm = 0 \quad (5c)$$

Else

$$Labourers\ available\ for\ mobilising\ land\ suitable\ for\ oil\ palm\ (excluding\ existing\ plantation)(La) = (Lt - Le) \quad (5d)$$

$$Labour\ surplus = 0 \quad (5e)$$

$$Extra\ local\ labourers\ required\ to\ fully\ mobilise\ all\ land\ suitable\ for\ oil\ palm = Lr - (Lt - Le) \quad (5f)$$

Finally, the sixth step, the maximum amount of land suitable for oil palm that can be fully mobilised per regency in 2030 with forecasted labour availability in both Scenario 1 and 2 was estimated. This was done by dividing the labourers available per regency (La) by the labour requirement factor as in Eq. (6).

$$Maximum\ land\ that\ can\ be\ fully\ mobilised\ with\ local\ labour\ availability = La\ /\ 0.35 \qquad (6)$$

6.3 RESULTS AND DISCUSSIONS

6.3.1 Key factors for mobilising ULC land in the four regencies

Overview of the key factors

The factors were broadly categorised into economic, agro-ecological, institutional and cultural factors. Within each of these categories, interviewees pointed out that a specific factor could be an opportunity and/or a barrier for specific land-use (or in general). For example, labour availability was regarded as a general barrier to all land-use in Gunung Mas, but was seen as a more specific barrier to paddy cultivation in Kotawaringin Timur due to labour competition with oil palm plantation. Table 6-3 summarises the key factors identified by the interviewees from the four regencies as well as by the industrial informants on large-scale industrial oil palm establishment; more details for this classification are provided in the remainder of section 6.3.

In general, all interviewees understood the two criteria proposed to define ULC land, but they also pinpointed that sometimes ULC land cannot be clearly distinguished from 'regularly' used land as land-use is dynamic and different land-uses interweave with each other. For many cases, the discussion on ULC land can thus not be isolated from the general land-use dynamics in that area.

Below, we first discuss commonalities and differences in perspectives from different actors. In the following subsections, we then discuss each of the identified factors and whether they are seen as opportunities or barriers and cross-checked with literature. References are given when the information is from the literature; all other findings are from the interviews.

Many common views were observed. For example, many interviewees, whether industrial players, independent oil palm smallholders, plasma farmers[25], or small farmers who practise mixed-crop farming, have regarded oil palm as an economic opportunity. This reflects that at that moment there were not many other economically attractive land-use options for them. While paddy is widely grown in Indonesia (especially in Java) as the major food staple, improving food security was less a concern among the

25 Plasma schemes are outgrower schemes designed to assist small farmers by attaching them to large companies that provide technical and financial supports to them during the establishment of oil palm. Later on, they become independent growers that sell their fresh fruit bunches to the company.

interviewees in the four regencies, except some Javanese paddy farmers in Kotawaringin Timur, who practise wet-field paddy farming, and raised their concerns that more and more paddy fields may turn into ULC land. Agro-forestry, which is highly advocated by researchers and NGOs as a suitable land-use option for future expansion on ULC land (see e.g. De Foresta and Michon 1996, Roshetko et al. 2007),

Table 6-3. Identification of factors in mobilising ULC land and specification of these factors in terms of opportunities and barriers to a specific land-use or in general by interviewees.

	Local actors perspectives (small-scale farming) on opportunities and barriers to **a specific land-use** or in **general**				Industrial perspectives
Regency	Gunung Mas	Kotawaringin Timur	Palangka Raya	Pulang Pisau	
Regency characteristics	Subsistence farmers with alternative income sources	Integration with international market	Urbanisation	Unsuitable agro-ecological conditions	
Economic factors					
Labour availability	General	Paddy	General	-	-
Land trading	-	General	General	-	Oil palm
Logistics	Oil palm	Paddy	General	-	-
Land fragmentation and scale	Oil palm	Oil palm	Oil palm	Oil palm	Oil palm
Profitability, flexibility and maintenance	Oil palm	Oil palm	Oil palm	Oil palm	Oil palm
Extra-local involvement and financing	Oil palm	Oil palm	Oil palm	Oil palm	Oil palm
Agro-ecological factors					
Soil quality	General	Oil palm Paddy	General	General	Oil palm
Uncontrolled fire	Permanent crops	Permanent crops	Permanent crops	Permanent crops	-
Poor water management	-	Paddy	Paddy	-	-
Institutional factors					
Logged and locked	General	General	-	-	Oil palm
Institutional capacities	-	General	General	-	Oil palm
Cultural factors					
Land-use preference	General	Oil palm	General	General	Oil palm

Legends: Dark grey cells represent opportunities, light grey cells represent both opportunities and barriers, white cells represent barriers, and dashes represent no opinions or no issues.
Note on how to read the Table: Taking the case of Gunung Mas as an example, 'labour availability' is deemed a barrier in general (for all land-uses), while 'logistics' is deemed a barrier for planting oil palm. For the latter, no other crops were mentioned by the interviewees.

was seldom discussed by the interviewees. Some of them are aware of the concept, but they do not deem it economically attractive, as returns are lower than for oil palm production, and any added value for e.g. organic production generally does not reach them.

However, findings show that opportunities and barriers can be different from one regency to another for different land-use options. For example, labour availability was found to be a barrier by small farmers in Gunung Mas which has not experienced any significant influx of migrants, but it was mentioned as an opportunity by their counterparts in Palangka Raya due to a relatively high unemployment rate as part of recent urbanisation. Meanwhile, the industrial informants have also shared different views on certain factors. Labour availability has not been an issue for the industry (at the moment) as extra-local labourers can be introduced from other islands.

Economic factors

Labour availability: This factor was found to strongly influence the land-use intensity of ULC land (also reported by Ananda and Herath 2003, Baumann et al. 2011). Labour scarcity was indicated as a barrier for mobilising ULC land in Kalimantan. Three phenomena were observed from the field trips: (i) labour competition between agricultural and non-agricultural activities, (ii) labour competition between different agricultural activities, and (iii) uneven labour distribution between regencies due to urbanisation. Phenomenon (i) was prominent in Gunung Mas due to income opportunities from (illegal) mining, which reduce interest in cash crop farming. Phenomenon (ii) was represented by the case observed in Pulau Hanaut (the only part in Kotawaringin Timur that still has paddy fields), where young labourers preferred to work on industrial plantations for better income instead of staying with traditional paddy farming. Consequently, agricultural land was abandoned due to lack of labourers. In contrast, phenomenon (iii) was found when comparing the general situation in most places with the trend in Rakumpit (Palangka Raya) where young people were struggling with unemployment in facing rapid urbanisation, and have no land to farm (mostly sold to outsiders). This illustrates a highly uneven labour availability across the regencies.

Overall, these findings suggest that parallel income opportunities (e.g. mining), food security (e.g. maintaining paddy production) and labourers' preference (e.g. preference to stay in an urban area) are three local factors that need to be further explored on regency-by-regency basis to better estimate the labour availability for mobilising ULC land. This factor was less of a concern by the industry as they often source their labourers from other Indonesian islands.[26] For exploratory purpose, labour availability per regency was estimated in section 6.3.2 for the case of oil palm cultivation on ULC land under industrial management in all of Kalimantan to estimate how labour availability influences the mobilisation of ULC land.

26 For example, the industrial plantation visited (see section 6.3.3) has about 74% of the staff come from the other islands.

Land trading: Despite uncertainties in land tenure, speculative land trading was frequently found in Kalimantan (see also Fox et al. 2009, Li 2007). In Palangka Raya, opportunities for local communities to sell their land at higher price to extra-local buyers motivated the villagers to expand further into forests, especially those located at the edges of city centre, roadsides or land that is expected to be converted to oil palm concessions. They let shrub and grass grow, and only sporadically planted rubber and fruit trees to mark their ownership (see also Potter 1997, Tyynela et al. 2002, Fairhurst et al. 2010). Many of these lands were sold to extra-local buyers who do not intend to perform agricultural activities but speculate on the land price to increase. Similar cases were also observed in the outskirts of Sampit (the capital of Kotawaringin Timur), where a large area of deforested land at the edge of the city was systematically divided into small pieces and sold to the public as a form of investment rather than for agricultural purposes.

From the industrial perspectives, the uncertainties and confusion in land tenure have been the main barriers to obtaining a continuous area of ULC land for large-scale deployment. Multiple claims on the same pieces of lands have led to serious social conflicts, especially between private enterprises and local communities (see sub-section 'Socio-cultural factors'). Due to uncertainties in land tenure and rapid land trading, it is difficult to distinguish ULC land owned by local communities and extra-local speculators. When developing strategies for using ULC land, clarification of land ownership and the roles of different land-use actors is critical.

Logistics: In all the four regencies, large areas of land along the main roads were found deforested but left unused by the local communities (or sold to extra-local speculators already), speculating that the land price will go up later. However, roads also represent entry points into modern agricultural practices, e.g. access to knowledge, fertilisers and fuels, which stimulates intensification. The case in Tewah (Gunung Mas) where farmers have given up intensification due to poor logistics and lack of access to fertilisers has supported the claim of Garrity et al. (1995, 1997) that the pathways of intensification are determined by access to fertilisers. Also in Lampuyang (Kotawaringin Timur), although many of the farmers were equipped with hand tractors, they did not have a secure and stable fuel supply due to poor logistics.[27] The logistics have been gradually upgraded in the past decades, but it still requires further improvement. Low quality roads may not be functional all the time. For example, in Gunung Mas, a large part of the regency will be isolated after heavy rain because it is too dangerous to travel on roads full with potholes. A contradictory case is Palangka Raya – where the income per hectare of land occupied for agriculture is the highest (about USD 1,300/ha) among the four regencies, far higher than the other three (the second highest is Kotawaringin Timur, amounted to about 600 USD/ha) (BPS 2013b). This is likely due to urbanisation.

These findings are in line with the literature - it was widely documented that the availability of a quality road network has effects on both deforestation and utilisation of grasslands (e.g. Laurence et al. 2015,

27 The farmers also do not receive fuel subsidies as in the transportation sector.

Tomich et al. 1997). Particularly, roads constructed for logging were often followed by both local communities and migrants to expand their agricultural activities (Fox et al. 2009). This was, however, less discussed by the industrial informants as they perceived road building as part of the cost of deployment.

Since logistics is the key determinant for mobilising ULC land particularly for small farmers, spatially explicit mapping of road distribution, road quality, elevation and other factors that affect logistics is required to better evaluate land accessibility.

Land fragmentation and scale: Scale is a key economic factor for cash crops like oil palm. For industrial scale, a large continuous concession with area >10 kha (with a 60 tonne FFB per hour mill) is more economically attractive compared to a small concession (with a 30 tonne FFB per hour mill). A senior industrial representative has emphasized the issue with large-scale investment in Central Kalimantan – most grass or shrub lands exist as small fragmented areas. Meanwhile, independent small farmers in Kalimantan, in the absence of their own mills, are highly dependent on large companies to buy their fruits.[28] While a few independent small farmers in West Kalimantan have managed to co-operatively build their own mills, 'stand-alone' mills that cater to the needs of independent farmers have not yet emerged in the four studied regencies.[29] Still, in Palangka Raya, Pulang Pisau and Kotawaringin Timur, opportunities for profitable, independent, small-scale oil palm cultivation already exist. Farmers in Pulang Pisau claimed that it was an easy business for them because middlemen will come and harvest the fruits themselves – what they needed to do was simply to grow some oil palm in their farms. Also in Gunung Mas, some independent pioneering farmers with 5-10 ha of immature oil palm have expressed their confidence in small-scale oil palm. From an environmental viewpoint, a land-use expert expressed that a lot of ULC land may also exist in patches interwoven with forests or wetlands, and may be more suitable for conservation and reforestation. Therefore, mobilisation strategies of ULC land should also be designed based on the size and continuity of the area, whether for large-scale, small-scale or conservation.

Profitability, flexibility and maintenance: Profitability, largely reflected by commodity prices, is the key factor that encourages or prohibits cash crops intensification and expansion on ULC land.[30] In Kalimantan, prices of FFB were more attractive than other cash crops to small farmers. In Manuhing and Kurun (Gunung Mas), independent small oil palm cultivations have emerged because the profitability appeared to be very attractive to them. However, the oil palm industry representatives pinpointed that this crop could be economically risky for independent small farmers because of its 'inflexibility' – it requires longer waiting time before harvest but draws large inputs at the early stage, and its price is fluctuating.

28 Plasma farmers are bound to sell their fruits to the attached plantation, but independent farmers are not.

29 Independent mills are common in Riau and Jambi.

30 A notable comparative example is the case of cultivating Imperata-cassava on degraded acid upland soils in Lampung (Sumatra) reported by Purnomosidhi et al. (2005). In that case, the farmers abandoned their lands when they lost the market access due to the influence of EU quotas for imports of tapioca as fodder.

Despite the fact that other options like agro-forestry are economically less attractive, maintaining flexibility with multiple crops may be a better strategy for small actors in long term. For the case observed in Kahayan Tengah (Pulang Pisau), oil palm was generally planted as an additional crop (in combination with rubber and paddy) which generates easy income (although the productivity is relatively low compared to those under industrial management, it is still profitable). Small-scale monoculture oil palm cultivations may face the risk of being abandoned when palm oil price is low and small farmers cannot afford the upkeep anymore. To avoid such a situation, a long-term economically resilient land-use strategy should be adopted for mobilisation of ULC land for different land-use actors.

Extra-local involvement and financing: Intensification requires skills and investments, but small farmers (especially the indigenous groups, Dayaks) generally lack both. For example in Kahayan Tengah (Pulang Pisau), although the farmers have gained access to better seeds and fertilisers due to its proximity to the city of Palangka Raya, they lacked the cash to acquire them as well as the skills to better manage their farms. Industrial establishment of oil palm on ULC land with small farmers attached to it is one option which provides investment and skill that local communities lack. This option has received different responses from the local communities.[31] In Tewah and Manuhing (Gunung Mas), some Dayak villagers were ready to accept large-scale development in their area as they were generally land-rich, yet struggle to manage such large areas of unused land. In Sebangau (Palangka Raya), widespread negative experiences from the neighbouring areas with large-scale investment, such as empty promises and violent evictions, have reduced the willingness of the Dayak communities to be open for extra-local schemes. In Banamatingang (Pulang Pisau), the Dayak villagers have been struggling with negotiation with the large oil palm corporation – on the one hand, they hoped to bring in investment for development; on the other hand, they had little trust in the companies.[32] In many cases, claiming and selling more land to extra-local buyers was the option that provided them the quickest cash.

The industrial informants presented a different perspective – they claimed that successful plasma schemes can only be realised if a third party such as World Bank (as in the past) or local banks are willing to (co-) fund the scheme. This is, however, not in line with the legal requirement as they are obliged to provide assistance to smallholders, either 20% of their land or their profits (Potter 2016b). On the government side, the officials have emphasized that their fiscal capacity is very limited. Worse still, the government has no clear guidelines on how the partnership should be formed, but allows the companies to determine the participation of the smallholders (see also Potter 2016b).

This complex situation points towards a key aspect for mobilising ULC land – with what business models can these ULC land be effectively mobilised? This requires more local-specific assessments to search for

31 With the exposure to modern lifestyle, it would be misleading to assume all the indigenous communities prefer to live in accordance with the forest. Most villagers interviewed voiced their demand for pragmatic solutions that could address poverty and improve their living standard.

32 They complained that companies took control of their lands but did not keep their promises e.g. providing facilities and services.

comprehensive strategies that are suitable for individual regencies. An example of extra-local involvement is knowledge transfer and financial support from trustworthy independent sources.

Agro-ecological factors

Soil quality: Soil quality of ULC land in Kalimantan, which is generally lower than on the other islands (see also Mulyani and Sarwani 2013), was often regarded as a key constraint of intensification by most interviewees.[33] For small farmers who lack capital and knowledge, the solution is to expand their farms to a larger area to compensate for the low return. Under industrial management, the problem can be reduced with intensive agro-inputs and proper practices, but small farmers cannot afford this. Some industrial informants had the impression that the economic return is lower as higher agro-inputs are required. It is therefore important to account for the impact of soil quality on the economic attractiveness and feasibility of mobilising ULC land.

Uncontrolled fire: In all the studied regencies (also generally in Central Kalimantan), fire has played a major role in the formation of ULC lands. Fire usually occurs naturally in the dry season, but could also be deliberately initiated by the farmers to prepare land for new farming cycles (see Tomich et al. 1997, Murdiyarso et al. 2004). Due to uncontrolled fire, local farmers have been losing their farmlands. The worst case was observed in Rakumpit (Palangka Raya) where farmers abandoned or sold almost all of their lands because their farms were destroyed by fire. This is a vicious cycle – those abandoned lands are often occupied by *alang-alang* grass which is very vulnerable to fire. The problem was further exacerbated when the fire spreads onto peatlands, making it even more difficult to put out. Interviewees reflected that there was lack of proper plans and tools to overcome this problem. In recent years, the provincial government of Central Kalimantan has set very strict 'no burning' rules. Local communities were well-informed and deliberate large-scale burning has been reduced, but some farmers still insisted to use fire for land preparation. When designing mobilisation strategies for ULC land, risk of fire should be taken into account, and effective fire control should be given priority.

Poor water management: One key reason for abandoning paddy fields or failed harvests is poor water management. During the field trip, interviewees from paddy-oriented villages in Teluk Sampit and Pulau Hanaut (Kotawaringin Timur) and Sebangau (Palangka Raya) have specifically complained about this issue. It does not only cause low productivity due to absence of irrigation, but drought and flooding have also frequently destroyed their harvest. In Bereng Bengkel of Sebangau, the villagers have lost both their farmlands and access to the city due to frequent floods. They have to rely only on fishing and collecting forest products to support their lives. This suggests that paddy field in Kalimantan may still have a large room for intensification, and be prioritised among the ULC land for increasing food production while preventing further expansion especially on forested land.

33 Exceptionally, there was an area of unused land in the southern part of Kotawaringin Timur which was deemed high quality land for paddy by the interviewees. For this case, the area was economically attractive to be utilised but the factors like land tenure and labour shortage have prevented its use.

Institutional factors

Logged and locked: In Central Kalimantan, vast areas of former timber concessions have turned into grassland or shrubs since the rapid logging in the past decades, but are still included in the 'forest zone', such as the cases in Tewah (Gunung Mas) and Pulau Hanaut (Kotawaringin Timur). Also, some lands remained uncultivated after deforestation although these were originally given for oil palm concessions (see also Sandker et al. 2007 & Goh et al. 2016). In 2011, about 32% of the 0.7 Mha oil palm concessions in Kotawaringin Timur were uncultivated land with sparse vegetation (Goh et al. 2016). These 'logged' over lands are 'locked' up from further utilisation. Several active attempts to reclaim land ownership by the indigenous communities were observed during the field visit. For example, the villagers in Tewah have demanded the 6,000 ha of former timber concession nearby their villages to be freed up for large-scale oil palm plantation. A movement at provincial level, namely '*Dayak Misik*', was initiated to obtain land rights for indigenous communities, including lands located within the 'forest zone' and concessions. Previously, a top-down effort was made by WRI and Sekala to demonstrate a land swap to unlock low carbon lands from the 'forest zone' to divert industrial oil palm development on these lands, but it was stalled due to complexity and cost of the legal process (Rosenbarger et al. 2013). In 2014, the Indonesian Ministry of Home Affairs, Forestry and Public Works, together with National Land Agency (BPN) have promulgated the 'Procedure for settlement of land tenure in the forest zone' which allows land located within the 'forest zone' to be legally claimed by individuals or communities (Kompas 2015). This has opened a door to mobilise ULC lands which were previously locked in concessions. However, the new law does not distinguish ULC lands and forests, and no rules or guidance are given to secure sustainable land-use or prohibit land selling. Furthermore, it is unclear how to account for such land if the land is claimed by multiple actors. For example, the transmigrants in Parenggean (Kotawaringin Timur) who participated in a plasma scheme, as well as the industrial representatives, have argued that the same piece of land may be claimed multiple times by different people, i.e. the land inside concessions may be still occupied by a group of farmers although some other farmers have already 'sold' it. For this type of ULC land, sorting out the complexity of land-use rights is of the highest priority to clarify if a piece of ULC land is considered 'available' or not and to 'whom' it is available.

Institutional capacities: Interview with representatives from national government agencies revealed that the implementation of national policies at regency level has been difficult. A representative from the Ministry of Agriculture was disappointed about the fact that their policy recommendations were often not taken on by the local authorities due to lack of trust. In contrast, local authorities in Kotawaringin Timur as well as the provincial government have argued that they have very limited fiscal capacity to support these policies - most programmes were usually discontinued after the first few years. The villagers pinpointed that they have to abandon their farms after the programmes were ended due to lack of financial capabilities to maintain. Many interviewees also emphasized their worries about corruption in the land and agriculture sectors. From the industrial viewpoint, the main institutional barrier to mobilising ULC lands was the rules (and enforcement) that vary from one regency to another. It is therefore necessary to take into account the capability and efficiency of regency authorities when designing regency strategies to mobilise ULC land. Especially, programmes to support the small farmers need substantial financial and technical support as well as proper monitoring.

Cultural factors

Land-use preference: A cultural barrier is the farmers' resistance to 'new' agricultural practices to increase production through intensification. In the four regencies, there are clear distinction in land-use practices between indigenous communities and (trans)migrants (mainly Javanese). The indigenous Dayaks usually practise rotational swiddens, while Javanese (trans)migrants tend to establish paddy fields with cattle stall-fed with *alang-alang* or participate in small-scale oil palm plasma schemes. Most interviewees, including indigenous people themselves, agreed that the indigenous communities were not used to intensified farming or working on plantations. Most Dayak interviewees described that they were 'spoiled by the enormous natural resources', and thus had no motivation to intensification. This is different for (trans) migrants from Java, who have a stronger sense of land ownership (see also Purnomosidhi et al. 2005, Whitten 1987, Potter 1997). The Dayaks prefer to develop and manage agro-forestry, but they also tend to make quick money by selling their lands.[34] However, some of them also possessed a different economic vision. For example, a Dayak farmer who owns 10 ha of oil palm in Kurun (Gunung Mas) has purposely learnt the production techniques from a large-scale plantation, and hired a professional company for fertilisation. Many of his peers were also observing his results before they may follow his move. While more integration is expected in the future, many Dayaks still showed deference to intensive agriculture.[35] This is also reflected in Kotawaringin Timur: Although the regency has a relatively large supply of domestic labour, most labourers on plantations are hired from other Indonesian islands. Transmigrants have been introduced in the oil palm plasma schemes as outgrowers as seen in Parenggean (Kotawaringin Timur), but they have been entangled with serious land disputes with the indigenous people. As land-use activities in Kalimantan are largely characterised by the differences in preference and interest of different ethnic groups, ethnic distribution is a factor that should be carefully analysed. Of particular interest is whether these cultural factors provide opportunities or barriers to the mobilisation of ULC land.

6.3.2 Labour availability: A case study on oil palm

In section 6.3.1, labour availability was identified as a possible constraint for the utilisation of ULC land. In this section, we explore quantitatively for which regencies of Kalimantan this could be a serious constraint, assuming that all ULC land suitable for oil palm would actually be taken into use (see Section 6.2.2). Figure 6-2 and 6-3 show the estimates of maximum labour availability in each regency

34 The situation is different in West Kalimantan, e.g. in Sanggau where most of the oil palm smallholders are Dayaks (Potter and Badcock 2007).

35 In Kahayan Tengah (Pulang Pisau), the Dayak village chief pinpointed that many villagers do not believe that using better (and more costly) seeds and fertilizers will result in higher yields.

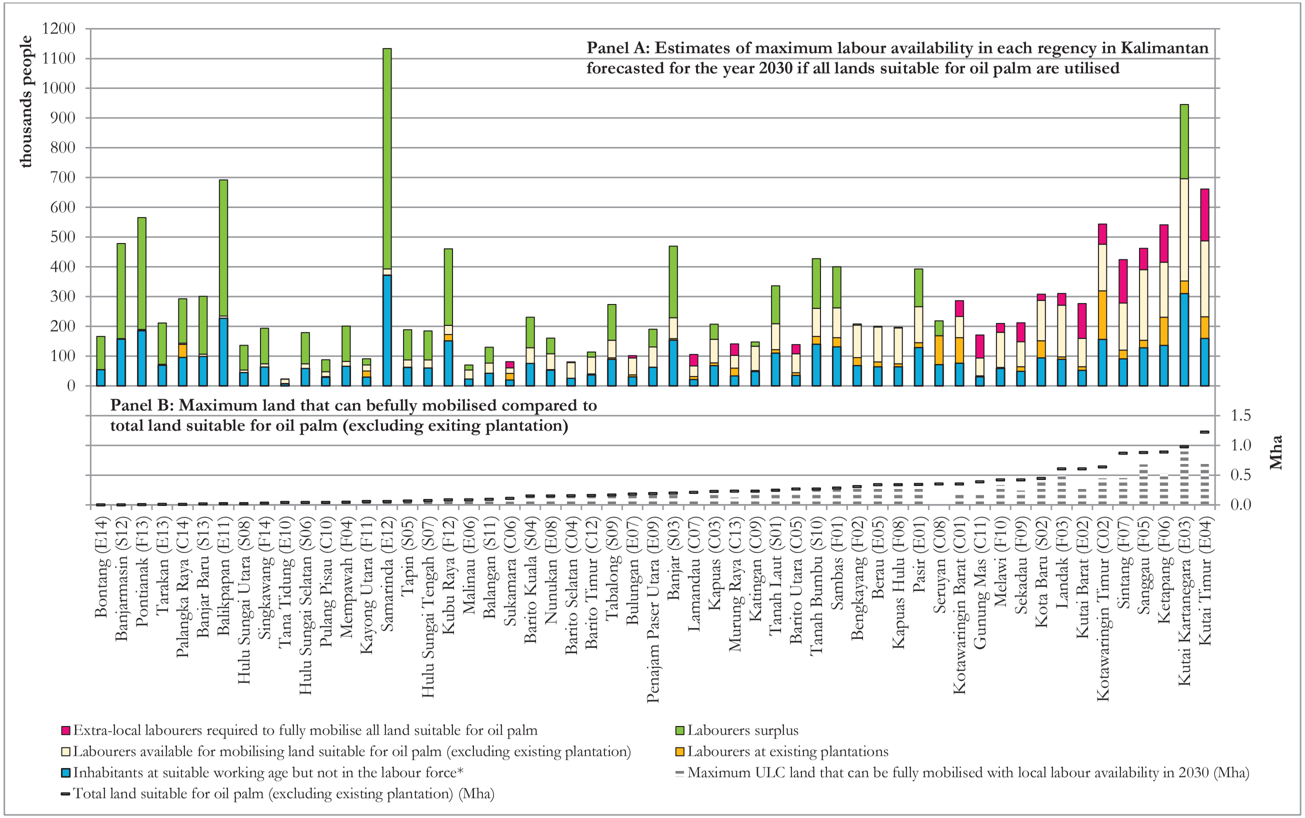
in Kalimantan forecasted for the year 2030 if all lands suitable for oil palm are utilised (Panel A) and maximum land that can be mobilized as limited by local labour availability (Panel B), sorted by the area of suitable land per regency, in two different scenarios. For Scenario 1, where the whole labour force is assumed to take part in the agricultural sector, the top 20 regencies with large areas of land suitable for oil palm are mostly short of local labour (or just have merely sufficient labourers) by 2030 to fully mobilise the suitable lands, only 5 of them (Kutai Kartanegara, Seruyan, Pasir, Sambas and Tanah Bumbu) have sufficient labour availability. In Scenario 2, where part of the labour force is diverted to non-agricultural sector, the labour shortage is even more prominent, and only 3 out of the top 20 regencies have very small labour surpluses (Pasir, Sambas and Tanah Bumbu).

Labour surpluses are mostly concentrated in regencies with small areas of suitable land. Almost all of these regencies are either large cities, industrial towns like Bontang, oil mining and business centres like Balikpapan and Tarakan, or university cities like Banjar Baru.[36] But, there are also larger regencies like Pulang Pisau which is largely covered by swampland or Malinau which is largely forested. These regencies are largely unsuitable as sites for large-scale oil palm plantations, and it is questionable whether this labour force will be interested to move to the other regencies as farmers.

In Scenario 1, the maximum amount of ULC land that can be mobilised with optimistically forecasted level of labour availability in 2030 is 11 Mha, about two-thirds of the 14 Mha of land in Kalimantan considered suitable for oil palm according to WRI (2012). Compare to 8 Mha in 2011 (see Figure S6-1, this number has increased significantly up to almost 40% due to population growth. This maximum estimate comes with optimistic conditions that the new cultivation is operated at industrial efficiency (0.35 person/ha) and all the labour force is attracted to the oil palm sector. In reality, the amount of land that can be effectively mobilised could be much lower considering actual labour efficiency and preferences to participate in agricultural activities. This is illustrated in Scenario 2, where part of the labour force is diverted to non-agricultural sector. The maximum amount of ULC land that can be mobilised dropped to only slightly more than 7 Mha. If the labour requirement becomes higher due to lower efficiency (0.5 person/ha as the minimum requirement reported by Budidarsono et al. 2011), the estimate would further drop to <7 Mha.

In 2006-2010, about 1.8 Mha of oil palm was planted in Kalimantan (0.35 Mha per year) (Gunarso et al. 2013). At this pace, it would take more than 40 years to have all the ULC areas that are suitable for oil palm fully intensively used. But it should be noted that these expansions are concentrated in several regencies. For example, about 0.3 Mha of oil palm has been planted in Kotawaringin Timur in that period (about 18% of the total regency area) (Goh et al. 2016). For this regency, Figure 6-2 shows that in the next decade, at maximum 0.4 Mha out of the 0.6 Mha of suitable ULC land could be planted and managed with local labourers.

36 Educational establishments located in the cities are indicated by the high numbers of people over age 15 but not in the work force, i.e. students.



* Including housekeepers, senior citizens and students (>15 year-old)

Figure 6-2. Scenario 1: Estimates of maximum labour availability in each regency in Kalimantan forecasted for the year 2030 if all lands suitable for oil palm are utilised (Panel A) and maximum land that can be mobilized as limited by local labour availability (Panel B) (sorted by the area of suitable land) given none of the labour force is diverted to non-agricultural sector.

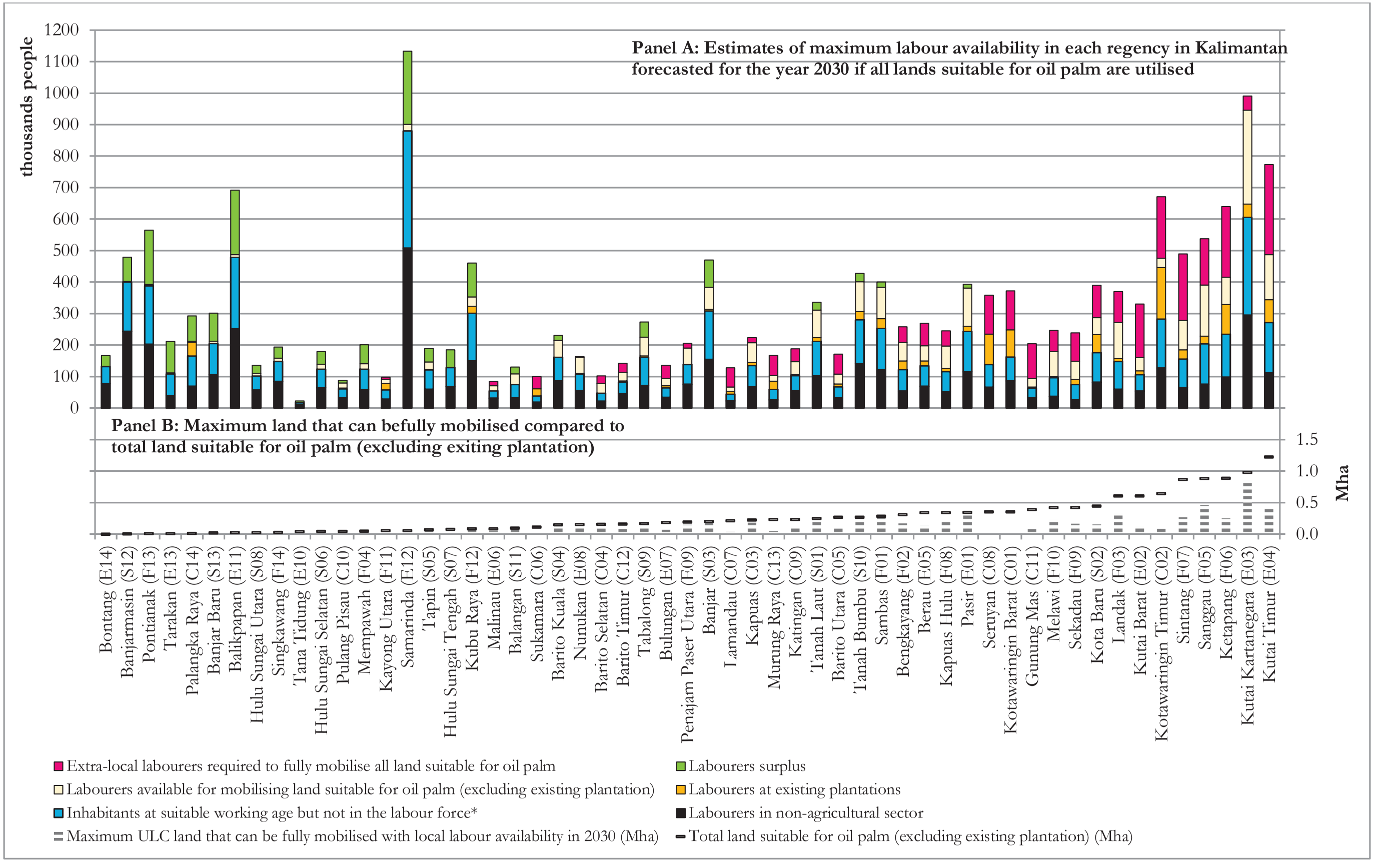


Figure 6-3. Scenario 2: Estimates of maximum labour availability in each regency in Kalimantan forecasted for the year 2030 if all lands suitable for oil palm are to be utilised (Panel A) and maximum land that can be mobilized as limited by local labour availability (Panel B) (sorted by the area of suitable land) given part of the labour force is diverted to non-agricultural sector.

This analysis shows how the labour factor limits the mobilisation of ULC land taking industrial oil palm as an example. This may vary significantly if the ULC land in a regency would be used for a combination of crops with different types of management. For example, paddy cultivation requires about 0.3 person/ha if it is managed as the lowland rice field in Java (Gérard and Ruf 2001). The choice of land-use very much depends on market and policy drivers, as well as a range of local factors such as those identified in section 6.3.1.

Overall, Kalimantan has an uneven labour distribution across regencies and the current forecast is limited by uncertainties in labour mobility over time. This implies that it is important for a regency to consider multiple land-use options (which require different number of labourers) and business models (which have different levels of attractiveness and suitability for multiple land-use actors) when planning for utilising the ULC land resources.

6.4 CONCLUSION AND RECOMMENDATION

This study identified key factors that influence the mobilisation of ULC land based on the direct inputs of local and industrial land-use actors, with the findings cross-checked with literature. Case studies were performed on four regencies with distinctive characteristics in Kalimantan. The interviewees identified a spectrum of factors which create various opportunities and/or barriers to them, depending on the land-use options and business models.

The importance of economic factors were widely recognised by the interviewees. They generally agreed that *labour availability* is a major factor in Kalimantan due to its low population density. The additional desktop analysis presented in section 6.3.2 shows that labour distribution among the regencies is largely uneven, and greatly limits the actual amount of land that can be mobilised in some regencies. Another factor, *land trading*, was broadly regarded as a barrier in the case of Kalimantan by the local interviewees, as most buyers have no intention to perform agricultural activities but speculate on future land price. While *logistics* is a barrier to small farmers who – unlike large industrial palm oil plantations - are incapable of building their own roads, *land fragmentation and scale* is more of a concern for the industry as they prefer large-scale deployments. For a long-term consideration, *profitability, flexibility and maintenance* of farming on ULC land is a key factor to avoid land being abandoned and returned to under-utilised state again during economic downturn. This is critical for small farmers who lack financial power to maintain their plantations with sufficient fertilisers. Finally, most interviewees acknowledged that *extra-local involvement and financing* is necessary but they have quite different views and doubts on how this should be set up. While the regencies are highly dependent on extra-local financing, the current model of involvement has created a number of issues, e.g. the land conflicts resulted from large-scale oil palm deployments by extra-local investment.

The discussions on agro-ecological factors are more technically oriented. The major barrier, *soil quality*, was often associated with low economic attractiveness by the interviewees. The requirement of high agro-inputs to use land with lower quality was prohibitive for small farmers who generally have low access to capital. Another factor, *uncontrolled fire*, is not just an issue for ULC land, but in many cases ULC land is a direct result of fire which destroyed farms and caused land abandonment. Similarly, *poor water management* has led to a large area of low productive paddy fields which can be regarded as a type of ULC land. Tailor-made strategies based on local agro-ecological conditions are required to recover the productivity of these areas.

The other two categories, institutional and cultural factors, are more subtle and complex as they involve more socio-political elements across the hierarchy of authorities. One barrier to mobilising ULC land is that a large area of ULC land has been *logged and locked* in the 'forest zone' and concessions and is not legally available for utilisation. Many interviewees also have doubts in *institutional capacities* to address the multiple issues related to ULC land. Furthermore, *land-use preference*, which can be largely identified by ethnicity (especially the clear difference between the indigenous Dayak tribes and Javanese transmigrants), was also mentioned as a crucial factor to be recognised when designing mobilisation strategies for ULC land. These two types of factors may only be tackled with more subtle approaches that can be accepted by different stakeholders.

Given the limited number of interviews and group discussions, the findings cannot be generalised for the whole of Kalimantan, yet we deem them sufficient to identify the prominent factors of mobilising ULC land resources in the four regencies investigated. Furthermore, perspectives were taken from a diverse mix of land-use actors to cover different aspects of mobilising ULC land. Combining and cross-checking the comprehensive comments and detailed explanations from different interviewees, it became clear that many prominent trends in the regencies have been captured. Due to the limited amount of resources, it was not possible to conduct further investigations on all individual sub-regency cases despite they are interesting examples for mobilising of ULC land.

As an example, the labour factor was further analysed by regency, and it was found to be a major limiting factor to mobilise ULC land in many regencies with large areas of ULC land, as labour distribution is highly uneven across regencies. The result of this analysis, however, is still uncertain as it does not include the dynamics of labour mobility. Furthermore, the analyses only estimated the labour requirement if ULC land would be converted to oil palm cultivation under industrial management. Other land-use options, especially those which require less labour, may fit better into the mobilisation of ULC land in face of labour shortage. While the labour factor was quantitatively analysed, it also requires further qualitative understanding of the underlying causes of, in particular, labour mobility. For example, the transmigration policies in the past has triggered large fluxes of labour movement into Kalimantan. This could have major impacts on the labour availability in the regencies. Based on the current findings, it is recommended to further assess each single factor, as they vary from one to another in terms of types of possible approaches and scale. For example, extra-local involvement and financing has an international relevance and formulating financially viable business models needs further analysis considering both extra-local and local conditions. Another example is to entangle the underlying complexity of the *logged and locked* land, which needs to be understood in both national and local context. It requires a combination of different approaches, from mapping of ULC land located within different concessions to the land-use dynamics of these lands in different perspectives.

This study concludes that a range of factors affect the mobilisation of ULC land, and they can be perceived differently by land-use actors in different regencies. This has strong influences on the actual mobilisation of ULC land, and need to be carefully accounted for in addition to physical estimates of land potential. **Most importantly, as a starting point, a comprehensive local assessment of the opportunities and barriers to utilising ULC land is needed to formulate practical and realistic land-use policies on a regency level for mobilising ULC land. In other words, the policies must be acceptable by the different stakeholders especially the local communities, economically viable for continuous implementation, and minimising the risk to the environment. Instead of focusing only on a single crop or end-use, this has to depart from analysing the specific conditions within individual regencies, especially considering the views of multiple land-use actors on different land-use options and business models.** Therefore, it is crucial for future research to connect narrative studies on socio-economic aspects to quantitative land potential estimates which are based on environmental and agro-ecological factors. Narrative studies can provide direction for further quantitative, qualitative and mapping analyses on ULC land, as demonstrated by this study:

- *Labour availability*: Measuring the availability of labourers in three key local aspects, i.e. parallel income opportunities, food security and labourers' preference.
- *Land trading*: Clarifying ownership of ULC land and the roles of different land-use actors in utilising and claiming these land resources.
- *Logistics*: Spatially explicit mapping of road distribution, road quality, elevation and other factors that affect logistics.
- *Land fragmentation and scale*: Measuring the size and continuity of the ULC area and assessing its suitability for different land-use options and business models, e.g. large-scale plantation, small-scale farming or conservation.
- *Profitability, flexibility and maintenance*: Designing long-term economically resilient land-use strategy in different future economic scenarios.
- *Extra-local involvement and financing*: Identifying extra-local funding sources and matching those to local needs in order to set-up tailor-made partnerships between extra-local and local actors depending on local situations.
- *Soil quality*: Analysing the impact of soil quality on the economic attractiveness and feasibility of mobilising ULC land, as well as mapping the soil distribution.

- *Uncontrolled fire*: Examining and mapping the risk of fire and designing effective fire control measures.
- *Poor water management*: Prioritising under-utilised paddy field in Kalimantan for increasing food production and improving productivity through proper water management.
- *Logged and locked*: Sorting out the complexity of land-use rights and mapping ULC land by accessibility.
- *Institutional capacities*: Monitoring the capability and efficiency of regency authorities in implementing ULC mobilisation strategies.
- *Land-use preference*: Analysing land-use preference in Kalimantan by mapping the ethnic distribution based on the unique/traditional/typical land-use practices of each group.

Combining these as inputs to a holistic land-use planning covering both aspects can help deriving more realistic expectation, formulating tangible policies, and minimising unintended consequences. This is especially crucial for long-term successful implementation of policies and avoid project failures (e.g. land abandonment due to discontinuity of financing or loss of interests from farmers).

6.4.1 Recommendations for future research

Future research on mobilising the ULC land resources in each regency is recommended to focus on the locally desired outcomes, which could for example be economic development, food security, conservation/afforestation or a combination of all. In addition to identifying ULC land and understanding the reasons of land under-utilisation, this leads to the search of (i) available land-use options and (ii) business models that can be employed to achieve the outcome. Opportunities and barriers associated with different land-use options and business models can be assessed by matching them with the key local factors that influence the mobilisation of ULC land. This largely depends on the preference of the local land-users, and their capability in adopting new business models. Careful considerations on local suitability, especially understanding the land-use dynamics (why is it under-utilised), and innovation in land-use planning (e.g. swapping of ULC land in the concession with high carbon stock land outside the concession) is thus required to answer these questions. This can be formulated in a matrix as shown in Table S6-1. For individual regencies, such a matrix can be developed through multi-stakeholder's surveys, workshops or collaboration to ensure different perspectives are taken into consideration.

In addition, the *environmental* risks accompanied by the choices of land-use option and business model have to be thoroughly examined. This paper started out on the premise that ULC land can be mobilized whilst minimizing or even mitigating further carbon stock loss, but this needs to be safe-guarded. Also, other environmental impacts (e.g. provision of ecosystem services, loss of biodiversity) need to be assessed on a local level. Existing sustainability measures, such as the RSPO standards, albeit designed for other purposes instead of ULC land exploration, could be partly borrowed as a basis to mitigate environmental and partly socio-economic risks. Employing certification schemes like this as guidelines for mobilising ULC land, however, may need significant modification as they are mostly designed specifically for a crop (e.g. RSPO) or an end-market (e.g. certification schemes for biofuel). ULC land, however, can be used in various ways for different crops which serve multiple end-markets. Monitoring the environmental impact of using ULC land has to cover the entire landscape and how the different types of land-use – from small household mixed farming to industrial monoculture – can co-exist and interact.

The *social* risks, such as the risk associated with governance in terms of corruption and rent-seeking, should be carefully examined as this will undermine the benefits for the society or even trigger conflicts when large-scale investment takes place on under-utilised land, which may be occupied and used in an extensive manner. This is largely linked to the legal aspect, not only in terms of the formulation of local rights, land-use rights and other regulations, but also in terms of their enforcement.

Additional guidelines in an *economic* sense are also needed for ULC land exploration to make mobilising of ULC land economically sustainable. For example, risk of project failures and land abandonment due to price changes should be taken into account. Financing schemes for shifting production onto ULC land do not exist yet, but there are conservation programmes like REDD+, which provide incentives to conserve carbon stock on land and may be an option in the future also for tree planting on ULC land.

As mobilisation of ULC land covers a range of issues and cuts across multiple sectors and scales, leveraging existing programmes, instruments and tools (such as the above-mentioned REDD+ programme) is necessary, but could also be very challenging. It is important to reframe the simple idea of ‘planting a piece of ULC land with some crops’ into a more complex scenario of (i) creating workable business cases (acceptable by different stakeholders, meeting local needs and conditions and economically viable), (ii) formalising the land-use scheme (particularly to protect the rights of all parties by e.g. empowering relevant authorities to monitor and enforce), (iii) providing long-term benefits for the environment, and (iv) managing it sustainably with continuity for a long period of time. Putting all relevant efforts in place requires collaboration of all relevant agencies, local communities, industries, researchers and civil society, as well as tolerance and compromise for common interests by all parties.

An example can be drawn from the current study (see Table S6-1 which includes some sample questions formulated based on the factors previously identified in the four regencies). Investigations on the factor ‘extra-local involvement and financing’ lead to the search for funding options for cash crops, food crops and/or conservation, as well as preferred business models by the funders to implement these options. A potential risk, which has happened in the past, is the possible conflicts between local and extra-local actors. In general, the cultivation of oil palm attracts the most extra-local investment as it provides the highest economic returns. However, until now it has been dominated by large-scale deployment, and only a small amount of financial support was given to plasma farmers. Other major crops, i.e. rubber and paddy, are dominated by independent smallholdings, but financing channels are missing for intensification and expansion on ULC land. Other options, such as agroforestry and carbon credit programmes, are currently lacking financial support. Should a regency aim to have a more balanced development, it is likely that extra-local financing for small farmers as well as conservation programmes are necessary.

In summary, a better understanding of the multiple local factors and whether they are considered opportunities or barriers for mobilising ULC land resources in a specific setting can help to provide more accurate estimates of the ULC land resources that can be mobilised and can serve as a starting point for more informed decision-making on future land-use. Comparing the pros and cons of different land-use option and business model helps the individual regencies to capture the benefits while avoiding adverse effects in environmental and socio-economic aspects.

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SUPPLEMENTARY MATERIALS

Box S6-1. Key questions formulated for the interviews and group discussions.

Definition:
- What land is considered “under-utilized” and / or “low carbon”?
- What size is such land? What kind of soil? Who owns these lands? What are the neighbouring land covers?

Previous land-use:
- Forests: Were these lands forested in the interviewee’s memory? Since when were they deforested and by who? Why were these lands deforested?
- Productive use: Were they being used before turning into ULC? If they are agricultural lands, what crops were planted? Why were these lands abandoned?
- Regeneration: Was there any regeneration of forest? If not, why?

Present land-use:
- Are these lands being used now for agriculture and at what frequency and intensity? What crops are planted, and by who?

Opportunities and barriers:
- What are economic opportunities and barriers of ULC land?
- What are agro-ecological opportunities and barriers of ULC land?
- What are institutional opportunities and barriers of ULC land? E.g. what policies, programmes or regulations related to the ULC lands have been introduced? What are your experience with / opinions on these?
- What are socio-cultural opportunities and barriers of ULC land?

Table S6-1. An exploratory checklist with example questions to assess opportunities and barriers of different land-use options and business models.

Overall questions for individual regencies:	What would the regency like to achieve with mobilisation of ULC land – economic development, food security, conservation or a combination of these?		
Questions to be asked for all factors	*Land-use options*: What are the available land-use options?	*Business models*: What are the suitable business models to achieve the goals?	*Risks*: What are the short- and long-term risks of selected land-use options and business models (environmental, social and economic)?
Economic factors			
Labour availability	How much labour is needed for different land-use options and business models? Does the regency have enough labour force? If not, is sourcing extra-local labourers a feasible option?		If extra-local labour is needed, what will be the social impacts?
Profitability, flexibility and maintenance	How profitable are different land-use and business models in both the short- and long-term? How economically resilient they are?		Will there be risks of land abandonment in the future?
Land trading	-	Who own these ULC lands? Are the owners willing to participate in the new land-use models?	Will mobilisation of ULC land trigger more deforestation for speculation?
Extra-local involvement and financing	What are the funding options for different land-use options?	What models would be preferred by these extra-local funders?	Will there be differences in opinions on land-use options or business models between local and extra-local actors?
Logistics	Is ULC land accessible? If not, is it strategic to build new infrastructure to access these lands, or is afforestation a better option?		Will the construction of new roads trigger more deforestation?
Land fragmentation and scale	What is the physical continuity of the ULC land, and what is the suitability for large- and small-scale establishment for different land –use options?		How does the use of small patches of ULC land (surrounded by forests) affect deforestation?
Agro-ecological factors			
Soil quality	What is the suitability of the soil for different land-use options?	Can the soil quality be overridden by more agro-inputs (thus higher investment) and improved management, and still be economically attractive?	Will the use of agro-inputs cause more adverse effects to the environment (e.g. pollution of rivers)?
Uncontrolled fire	Which options are more vulnerable or more likely to cause fire? What measures can be practically used to prevent fire spreading on ULC land?		How will the efforts of controlling fire within a piece of ULC land (e.g. planted with permanent crops) affect (prevention of) the fire from spreading?

Poor water management	Which option is more suitable in terms of water management, and can it be improved?	What is the effectiveness of water management of different business models?	Will the management of water reduce/increase adverse effects to the environment?
Institutional factors			
Logged and locked	How to utilise the ULC land in different types of concession previously granted (e.g. oil palm or timber planting)? How to sort out the complexity of concessions and land ownership for the piece of ULC land of interest?		Will the land-use rights of local communities be affected?
Institutional capacities	Do the regency authorities have sufficient capacity (financial and human resources) to execute the land-use policies?		How to avoid projects failures due to serious corruption when extra-local funding is not properly monitored?
Cultural factors			
Land-use preference	What are the preferred land-use options and business models for local people? Are they willing to adapt to new land-use models?		Will the new land-use models bring disadvantages to the local communities?

CHAPTER 7

Summary and conclusion

"By *joining* the tail to the trunk one makes up the whole elephant."
--- Indian proverb.

7.1 INTRODUCTION

Global interest in developing the 'bio-economy (BE)' and the 'bio-based economy (BBE)' has grown substantially since the beginning of the 21st century (FAO 2016). To be more specific, the term BBE is used to describe economic activities that utilise bio-based materials and products, either in raw form, intermediates or finished products (hereafter referred to as 'biomass') for non-food purpose (FAO 2016). This concept falls under the larger BE framework which involves all end-uses of biomass, including food and feed. Sometimes these two terms are used interchangeably due to their crosscutting nature (FAO 2016).

As the BE and BBE share the same feedstock, particularly agricultural products that utilise land, they are therefore closely linked to each other and also the larger topics of food security, climate change and rural development (FAO 2016). This is also characterised by complex cross-sector flows (e.g. from the food sector to the energy sector) and cross-border trade of biomass. The internationally traded volumes of agricultural products increased substantially from 7 EJ in 1995 to 12 EJ in 2010, while the share of traded products in total primary agricultural products has also increased from 18% in 1995 to nearly 22% in 2010 (FAOSTAT 2014).

As one of the common goals of developing the BE is to reduce GHG emissions from fossil feedstocks, it is crucial to monitor the associated GHG emissions along the global biomass supply chain, covering production and processing of raw materials, transportation and logistics from multilateral cross-border trade, and final consumption in different end-markets. Among these components, the carbon stock change (CSC) as a consequence of land-use change (LUC) (hereafter referred to as CSC-LUC) is one of the major component in contributing to the overall emissions from the biomass supply chain. Not only is it a major component of supply chain emissions, also total CSC-LUC has caused 8-20% of annual global anthropogenic CO_2 emissions in the past decades (van der Werf et al. 2009, Bos et al. 2016).

To understand the implication of creating new demand on global CSC-LUC, tracking the production, consumption and biomass flows for the BE across sectors and borders (e.g. countries) is the essential first step. This helps to identify the consumption patterns for different end-uses, trends in cross-border trade to and from different places, and how these affect the direction and volume of biomass. This requires a clear mapping of the flows of diverse forms of raw materials, intermediates, products, and by-products that go into different end-markets (i.e. energy, chemicals and food).

The second step is to assess the roles of biomass consumption in driving CSC-LUC, such as through logging and agricultural expansion. This can be quantified by associating CSC-LUC with measurable consumption and trade patterns in different locations and end-markets. Monitoring of this aspect requires developing mechanisms to link CSC-LUC to these flows. To do so, in-depth understanding of the direct drivers and complex underlying causes of CSC-LUC is needed.

With the identification of the role of different drivers on global CSC-LUC, the next step would be addressing CSC-LUC in local land-use systems, especially unsustainable expansion or inefficient local land-use practices. One way is shifting production onto less-productive land with low carbon stock and insignificant ecological services. The identification and utilisation of such land resources, however, varies from one location to another due to local differences in agro-ecological and socio-economic aspects, as well as local actors' perspectives on land-use. It is therefore necessary to understand the local land-use dynamics in multiple aspects.

7.2 AIMS AND RESEARCH QUESTIONS

This thesis aims to address the knowledge gaps described earlier on tracking the biomass flows for the BE, measuring the impacts of additional demand on CSC-LUC, and assessing land availability for future biomass production. The following research questions are formulated to meet the aforementioned aims:

i. How can the biomass flows from production to consumption for the expanding bio-economy be monitored on local and global scales, and what are the patterns of the major flows?
ii. How can the carbon stock changes from land use change associated with the additional demand from the expanding bio-economy be monitored, and what are the effects of applying different methodological settings using different perspectives?
iii. What are the land resources that can be potentially utilised to meet the additional biomass demand without causing undesired carbon stock changes from land use change, and what are the key factors for effective mobilisation of these land resources?

Table 7-1 is an overview of chapters and research questions addressed. Different research approaches have been employed with a wide geographical focus.

Table 7-1. Overview of geographical focus and research questions addressed in each chapter.

#	Key elements and features	Geographical focus	Research questions		
			i	ii	iii
2	Biomass flow analysis, Interviews, Surveys	The Netherlands	•		
3	Detailed literature review of the key methodological factors of linking consumption with CSC-LUC and benchmarking 12 quantitative studies on Indonesian palm oil	Indonesia		•	
4	Methodology development to quantitatively link CSC-LUC to consumption	Global and regional	•	•	•
5	Assessment of different domains for monitoring and evaluation of under-utilised low carbon land resources, data processing and analysis, GIS analysis, Interviews	Indonesia (Kalimantan)			•
6	Identification of opportunities and barriers for mobilising under-utilised low carbon land resources through primary data collection from field trips, interviews, labour availability analysis	Indonesia (Kalimantan)			•

7.3 SUMMARY OF THE FINDINGS

In Chapter 2, a methodological framework for mapping national biomass flows was proposed for domestic production-consumption and cross-border trade, and respective share of sustainably-certified biomass in order to improve monitoring efforts of the biomass flows of the BE. A case study was performed on the Netherlands for 2010-2011, focusing on three categories relevant for the country, i.e. (i) woody biomass, (ii) oils and fats, and (iii) carbohydrates, which have a wide range of application from food and feed to materials and energy. In terms of the amount of biomass used for energy purposes, it was found that the consumption of woody biomass increased to 3.5 MT, including 1.3 MT imported wood pellets of which >85% were certified. For the other two categories, about 0.6 MT of oils and fats and 1.2 MT of carbohydrates were used for liquid biofuel production. In terms of certification, it was discovered that >50% of woody biomass for non-energy material uses was either certified or derived from recycled streams. Meanwhile, certified vegetable oils have entered the Dutch food sector since 2011, accounted for 7% of total vegetable oils consumption. Overall, the attempt to capture these numbers for the Dutch case show that it is possible to employ existing dataset and information to monitor the biomass flows of the BE despite the need to overcome several methodological challenges such as inconsistency in data definitions. This monitoring work, especially with the assessment of cross-border trade, is important to understand the links between biomass consumption in different sectors and end-markets with carbon stock changes from land use change (CSC-LUC).

Following that, a review was made in Chapter 3 on numerous analyses that have been performed to quantitatively link CSC-LUC to consumption by the BE. It was revealed that the results differ significantly, even for studies focussing on the same region or product. This is due to the different interpretations of the links between direct drivers and underlying causes of CSC-LUC, which can be translated into differences in key functions, i.e. specific methods, algorithms and parameters embedded in the analysis. Using the example of Indonesian palm oil production (often associated with CSC-LUC), a meta-analysis of 12 existing studies on CSC-LUC was performed. This analysis determined the different settings for the key functions embedded in these studies and discussed their implications for policymaking. It identified the underlying reasons of adopting different settings within the eight key functions and their advantages and trade-offs. Examples are the way of determining how deforestation is linked to oil palm, and the inclusion of non-agriculture and non-productive drivers in the accounting to weigh their roles in CSC-LUC in comparison to palm oil consumption. Following that, the quantitative results from the selected studies were processed and harmonised in terms of unit, allocation mechanism, allocation key and amortisation period. This resulted in ranges of 0.1 - 3.8 and -0.1 - 15.7 t CO_2/t crude palm oil for historical and projection studies, respectively. It was observed that CSC-LUC allocated to palm oil was typically lower when propagating effects and non-agricultural or non-productive drivers were accounted for. Values also greatly differed with marginal and average allocation mechanisms employed. Conclusively, individual analyses only answered part of the question about CSC-LUC drivers and have their own strengths and weaknesses. Since the context can be very different, using quantitative results from a single study for accounting purposes in policymaking was not recommended. Instead, the relative roles of different drivers (e.g. logging vs oil palm), or the relative contribution to CSC-LUC in regional and global perspectives, should be further examined.

Based on the conclusion from Chapter 3, an analysis was conducted in Chapter 4 to assess the magnitude of CSC-LUC caused by additional demand in different perspectives by tuning the methodological settings (e.g. spatial boundaries). Specifically, it examined the relative role of agricultural expansion driven by growing demand compared to non-agricultural and non-productive drivers, as well as to examine its impacts in regional and global setting considering the propagating effects. To do so, a method was developed to allocate historical CSC-LUC to agricultural expansions by land classes (products), trade, and end use. The analysis for 1995-2010 led to three key trends: (i) agricultural land degradation and abandonment was found to be a major (albeit indirect) driver for CSC-LUC, (ii) CSC-LUC was spurred by the growth of cross-border trade, (iii) non-food use (excluding liquid biofuels) has emerged as a significant contributor of CSC-LUC in the 2000's. The study demonstrated that exact values of CSC-LUC at a single spatio-temporal point may change significantly with different methodological settings. For example, CSC-LUC allocated to 'permanent oil crops' changed from 0.53 Pg C (billion tonne C) of carbon stock gain to 0.11 Pg C of carbon stock loss when spatial boundaries were changed from global to regional. Instead of comparing exact values for accounting purpose, key messages for policymaking were drawn from the main trends. Firstly, climate change mitigation efforts pursued through a territorial perspective may ignore indirect effects elsewhere triggered through trade linkages. Secondly, policies targeting specific commodities or types of consumption were unable to quantitatively address indirect CSC-LUC effects because the quantification changes with different arbitrary methodological settings.

Finally, it was recommended that mobilising non-productive or under-utilised lands for productive use should be targeted as a key solution to avoid direct and indirect CSC-LUC.

The results from Chapter 4 indicated that mobilising under-utilised low carbon (ULC) land resources for production can help meeting additional biomass demand without causing undesired CSC-LUC, while reducing pressure on high carbon stock land from agricultural expansion. However, the potential of ULC land was not yet well understood, especially at regency level which is the key authority for land-use planning in Indonesia. Taking Kalimantan, i.e. the deforestation hotspot in Indonesia as an example, Chapter 5 explored ULC land resources in individual regencies in the region. The analysis was performed at the regency level because it is the most relevant authority in the hierarchy in terms of the implementation of land-use policies. By analysing information from six monitoring domains, a range of indicators was derived to provide insights into the physical area of ULC land from various perspectives. It was found that these indicators show largely different values at regency level. For example, the regency of Pulang Pisau has a substantial area of 'temporarily unused agricultural land' but a very limited area of 'low carbon land' – this implies that not all 'temporarily unused agricultural land' is ready for future exploitation when carbon stock is taken into account. As a result of such diverging indicators, using a single indicator to quantify available ULC land resources is risky, as it likely to result in over- or under-estimation. Thus, ULC land resources were further explored by taking four regencies as case studies and comparing all the indicators, supported with relevant literature and evidence collected from narrative interviews. This information was used to estimate ULC land area by possible land-use strategies. For example, the regency of Gunung Mas was found to have a large area of low carbon land which is not occupied and might be suitable for oil palm deployment. However, the major limitation is that physical estimates cannot provide a complete picture of 'real' land availability without considering a broader range of socio-economic factors (e.g. labour availability). Therefore, physical land area indicators from different domains must be combined with other qualitative and quantitative information especially the socio-economic factors underlying land under-utilisation to obtain better estimates.

Chapter 6 examined the regency cases in Kalimantan, a carbon loss hotspot, to understand the key factors for mobilising ULC land via narrative interviews with a range of land-use actors and complementary desktop analyses. The factors were broadly categorised into economic, agro-ecological, institutional and cultural factors, which were perceived as opportunities and/or barriers by different land-uses and stakeholders (with different business models), and can vary across regencies. Generally, oil palm was regarded by most interviewees as an economic opportunity, reflecting that there were no other more attractive options. However, oil palm may also be limited by various factors. For example, labour availability may greatly limit the actual amount of land that can be mobilised in many regencies due to low population density. These economic factors were interlinked with the agro-ecological factors, such as soil quality, which was often regarded as the reason of low economic attractiveness. The other two categories, institutional and cultural factors, are more subtle and complex, involving socio-political elements across the hierarchy of authorities. Past analyses on ULC land largely focus on a single crop or end-use. This study shows that mobilisation of ULC land has to depart from analysing the specific conditions within individual regencies, especially considering the views of multiple land-use actors on different land-use options and business models. For example, Gunung Mas has potential for large-scale deployment, while in Pulang Pisau oil palm can be part of the small scale mixed cropping which generates extra income. Future research is recommended to assess available land-use options and business models by matching them with each factors, based on the policy targets set by individual regencies (e.g. economic development or food security), and the preference and capability of local actors.

7.4 ANSWERS TO THE RESEARCH QUESTIONS

Based on the findings of Chapters 2-6, the following answers to the research questions are given. In order to better illustrate the findings, the case of palm oil was further elaborated throughout the text as a key example for monitoring the BE.

i. How can the biomass flows from production to consumption for the expanding bio-economy be monitored on local and global scales, and what are the patterns of the major flows?

This thesis monitors biomass flows on two scales: national and regional (continents and sub-continents). Chapter 2 showed how the biomass flows within a country can be quantitatively mapped by sector together with cross-border trade, taking one of the most active countries in terms of biomass trade, i.e. the Netherlands, as a case study. Chapter 4 zoomed this out to regional level, by computing the production, consumption and trade volume in different regions. The following elaborates first on how to monitor flows at these different scales and then on what the main patterns of actual flows are.

When zooming into the national case study, details can be captured in the flow of biomass within and across different sectors. In Chapter 2, a methodological framework was proposed for monitoring and mapping biomass and bioenergy by quantifying both cross-border trade and domestic cross-sectorial flows, and examining the share of sustainable certified biomass in different markets. Biomass flows were measured in three dimensions: (i) import and export, (ii) domestic production and consumption, and (iii) share of sustainable certified biomass. A first quantitative assessment of sustainable biomass and bioenergy flows in the Netherlands, a country which is active in biomass trade, was carried out as a case study. For this case, three major categories of biomass in the country were covered: woody biomass, oils and fats, and carbohydrates. Three key steps were taken: Firstly, biomass supply chains and sustainability certification schemes were inventoried. This covers all flows, including inputs of raw materials, the secondary, tertiary and end users, and finally releases of materials to the environment. Secondly, system boundaries were drawn depending on data availability and feasibility. Thirdly, each flow was quantified in as much detail as possible.

The core data contributors are usually monitoring bodies and general statistics portals. A monitoring body can be a governmental department or agency, an industrial association, or a non-profit institution that monitors the products' mass flows within the country or region. For example, palm oil as an important commodity was monitored by MVO, an agency that monitor the oils and fats market in the Netherlands. Following that, trade flow information can be taken from trade statistics portals which cover a large range of products categorized using combined nomenclature (CN) codes. In some extreme cases, when reliable data of certain important biomass streams is not available anywhere, data can only be collected directly from industry in the form of surveys and interviews. Data may also be found scattered in many public available sources, such as press releases, news, reports by companies, or other organizations, and scientific literature. For example, the amount of palm oil certified with Roundtable Sustainable Palm Oil (RSPO) imported to the Netherlands was reported annually by a special taskforce formed by companies and organisations. Volume of certain streams such as by-products, waste, and recycling streams can be deducted through mass balance calculations. Information, however, is mostly available in different forms (e.g. monetary value vs physical volume), and not every single biomass flow is monitored. The framework overcomes these challenges by matching all data together, supplementing each one to illustrate the big picture of biomass flows. By assembling, improving and updating the data from time to time, the biomass flows in the country can be quantitatively connected to provide a comprehensive overview of the status and changes of biomass flows within the BE.

Taking a broader perspective, Chapter 4 captured the total flows of all agricultural products across different regions in the world from 1995 to 2010. The analysis divided the world into separate regions (continental and sub-continental level), which were treated as individual closed territories that were linked via trade. At this scale, biomass flows were measured for production-consumption and trade, but the detailed flows across sectors within the region, (like demonstrated in the case of the Netherlands) were not captured due to data limitation.

For this case, FAOSTAT was used as the major source because it provides most of the required data using (i) consistent definitions, (ii) consistent geographical setting, and (iii) harmonised trade balance and consumption volume across different sectors. For 'geographical region', 'product class' and 'end-use', definitions from FAOSTAT were adapted. Annual data of production, consumption and trade flows were collected from different sources. The challenge of connecting datasets from different sources which are usually less compatible was overcome by harmonising them by making assumptions.

By combining and analysing these datasets, the patterns of major biomass flows were captured. The results are summarised in Figure 7-1, 7-2, 7-3 and 7-4. Figure 7-1 is an example of mapping the flows of oil and fats in the Netherlands. It shows the flows entering and leaving the country, as well as flows into different processes and end-markets within the country. Soybean was the largest importing stream of oil seeds (which contain both vegetable oil and protein), while palm oil was the leading vegetable oil in terms of volume entering the Netherlands. The overview of the major biomass cross-border flows for the case of the Netherlands is presented in Figure 7-2. It clearly depicts that the country highly depended on biomass trade, where oils and fats and woody biomass were mostly imported. Beyond national scale, the flows across bigger regions were illustrated in Figure 7-3 for agricultural biomass. Europe was found to be the most active region in terms of agricultural biomass trade with large streams of import and export. Meanwhile, South America, North America and Southeast Asia were the three largest exporters among the regions. The results were further broken down by types of crops and animal products in Figure 7-4. Although the total consumption of 'permanent oil crops' is the lowest among all categories, about 71% of that (largely palm oil) was traded across regions. The percentages of 'cereals' and 'temporary oil crops' traded are much lower, but they were leading in terms of the actual amount traded.

Chapter 2 and Chapter 4 illustrated how to monitor biomass flows for the expanding BE at different levels. The case of the Netherlands showed that the flows of biomass can be tracked in more details at national level, covering not only production and consumption, but also processing and feedback. This is because most existing monitoring efforts have been conducted at the major administrative level, i.e. country, to provide relevant indicators for policy development. Zooming out to a larger scale at regional level, the biomass flows can be monitored at a more aggregated way. The large database of FAOSTAT, in combination with other global and regional datasets, form the basis for monitoring at higher level. Together with other data sources on land-use and carbon stock, the information of biomass flows can serve as the basis to answer research question (ii).

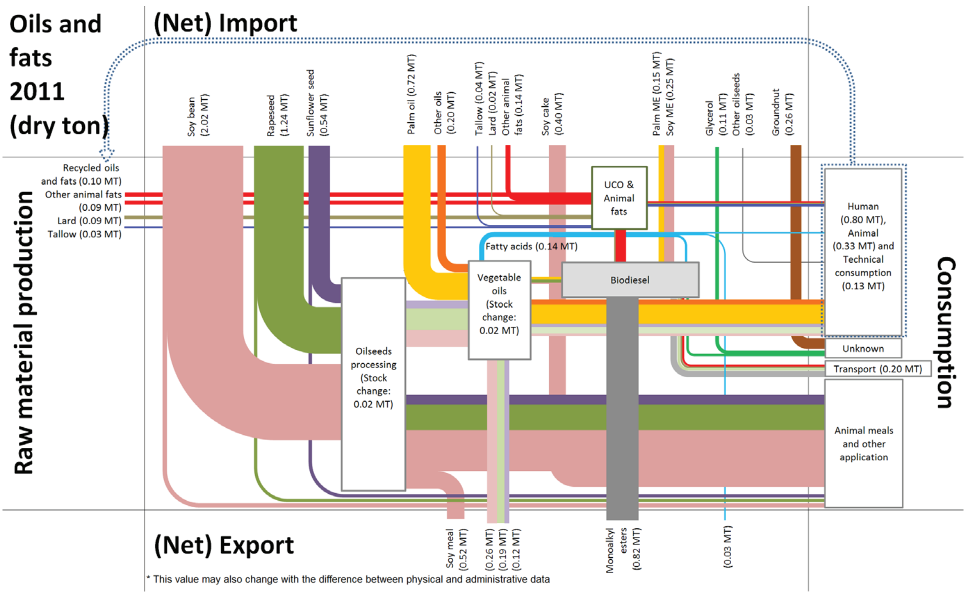


Figure 7-1. Mass flow diagram of oils and fats in the Netherlands in 2011.

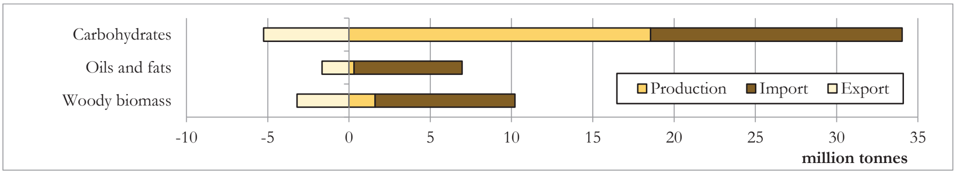


Figure 7-2. National biomass flows for the case of the Netherlands by the three main categories in 2010.

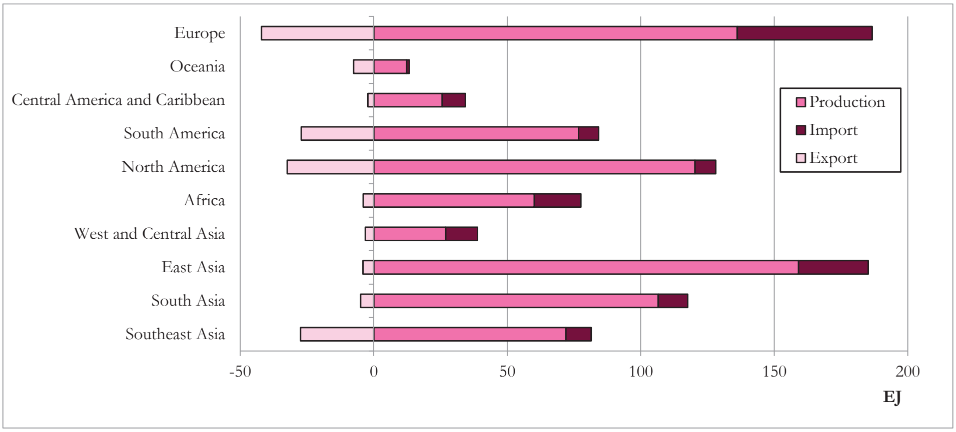


Figure 7-3. Cumulative agricultural biomass flows across regions in 1995-2010.

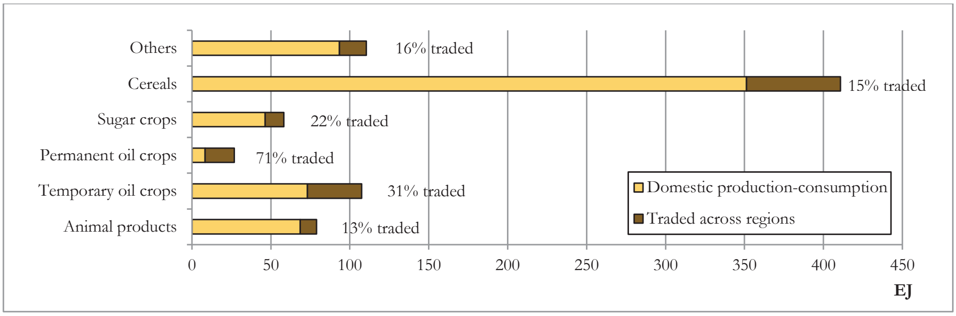


Figure 7-4. Cumulative global agricultural biomass flows by types of crops and animal products and shares of traded products in 1995-2010.

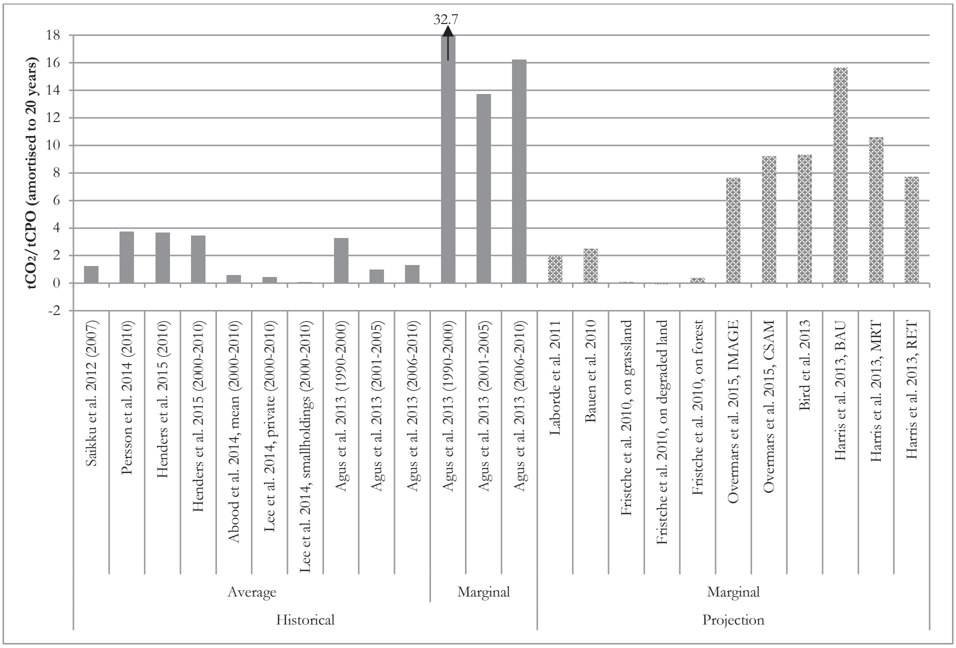
ii. How can the carbon stock changes from land use change associated with the additional demand from the expanding bio-economy be monitored, and what are the effects of applying different methodological settings using different perspectives?

Based on the findings from the research question (i), this thesis further examined how to quantitatively link the additional demand from the expanding BE to the carbon stock changes from land use change (CSC-LUC), and what are the effects of applying different methodological settings. In Chapter 3, a meta-analysis was performed on 12 existing studies to understand how different methods were applied to quantify CSC-LUC caused by the additional demand and to identify the key functions, i.e. specific methods, algorithms and parameters embedded in such analyses. Based on this review, a method was developed in Chapter 4 to assess the effects of different methodological settings on the quantitative results of CSC-LUC linked to consumption. Specifically, it examined the relative role of agricultural expansion driven by growing demand compared to non-agricultural and non-productive drivers, as well as the impacts in regional and global setting considering the propagating effects.

In Chapter 3, the review made for the case of Indonesian palm oil production illustrated an important example of quantifying CSC-LUC associated with a controversial product: In 2006-2010, the carbon stock loss in Indonesia has contributed to at least 3% of global anthropogenic CO_2 emissions, for which oil palm expansion can be anything from a negligible to major driver – strongly depending on the chosen methodological assumptions, as is demonstrated by the results of this chapter. The role of palm oil in CSC-LUC (and its links to export) has been quantitatively evaluated in various manners but the quantitative results of various studies are often inconsistent, and some are even contradictory in their policy advises. To analyse the underlying mechanisms of how CSC-LUC is allocated to palm oil, the sets of methods, algorithms and parameters embedded in the methodological components (which were collectively named as 'functions' for communication purpose) were thoroughly inspected, taking 12 studies as examples. The 8 functions are:

- Classification of lands and products
- Interactions between land classes and product classes
- Propagating effects of marginal changes in land and product use
- Delineation of spatial boundaries
- Inclusion of non-agricultural and non-productive drivers
- Allocation mechanism and allocation key
- Temporal dynamics
- Extent of trade linkages

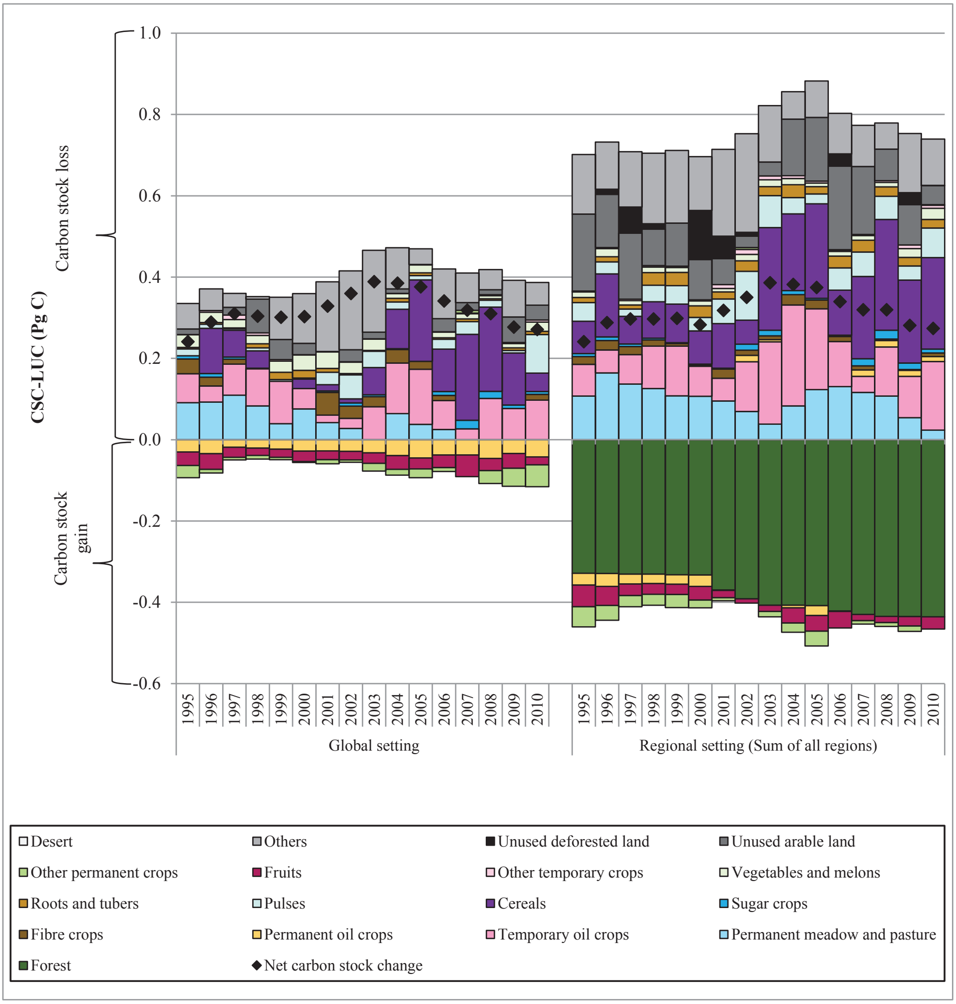
Overall, the selected studies were found to vary greatly in terms of the level of details in each function. For example, some have made detailed classification of lands, some have only employed highly aggregated land classes. Various (arbitrary) assumptions and choices (sometimes based on value judgement) have to be made for each function, and these depend on different perspectives of and interactions between different actors and institutions at different geographical level. As a result, the CSC-LUC associated with Indonesian palm oil quantified by the 12 studies are scattered over a wide range although they were harmonised to (i) same unit (tCO_2/tCPO) and (ii) consistent amortised years (20 years) (Figure 7-5).



Note: To visually distinguish two approaches, projection studies are represented by shaded bars and historical studies by solid bars.

Figure 7-5. Harmonised CSC-LUC values for Indonesian palm oil from selected studies.

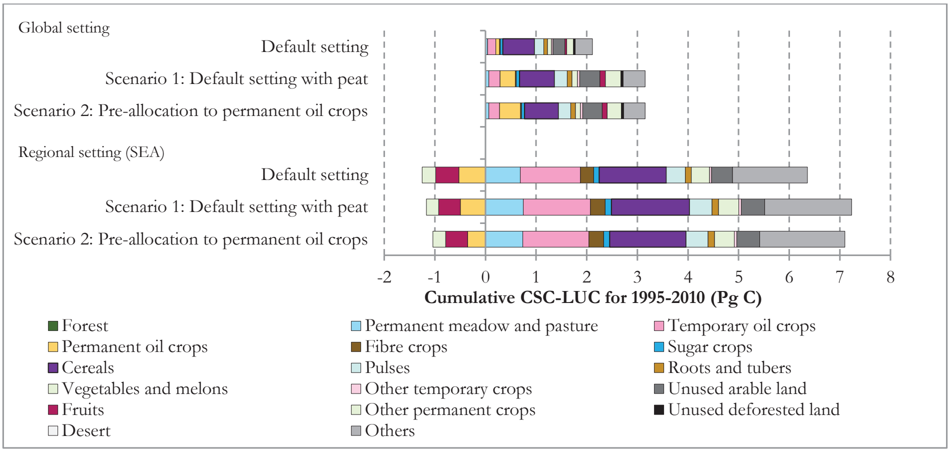
This review concluded that individual consumption-based CSC-LUC studies (i) only answer part of the question about CSC-LUC drivers, and (ii) have unique strengths and weaknesses, depending on the objectives and perspectives. Since the context can be very different, using quantitative results from a single study for accounting purposes in policymaking is not recommended; instead, policy implications can be better drawn by comparing different studies. Moreover, as the key assumptions and choices are often based on value judgement and this strongly affects the results, future research on linking CSC-LUC to consumption can be improved by being more transparent on the assumptions and choices made, and applying different settings in order to show how these assumptions affect the results. This will help improve interpretation of the results. Furthermore, as the major actors in driving the development of consumption-based CSC-LUC accounting are among the consumer countries (e.g. the development of default GHG values in the EU biofuel policies), the land-use dynamics involving non-agricultural and non-productive drivers (e.g. improper land-use practices like uncontrolled fire typically being the most important ones), which do not directly link to consumption, are generally not adequately addressed in current studies.



Note: '+' and '-' represents carbon stock loss and gain respectively

Figure 7-6. Time trend (1995-2010) of CSC-LUC allocated to land classes based on their expansion rates using the global and regional setting.

To cover the missing elements of non-agricultural and non-productive drivers, Chapter 4 aimed to supply alternative perspectives in viewing the drivers of CSC-LUC from both producer and consumer sides in quantitative manner. A method was developed to examine the effects of applying different methodological settings on the final CSC-LUC allocated to different drivers. Specifically, it was employed to quantify the relative role of additional demand for biomass compared to non-agricultural and non-productive drivers, as well as the changes in CSC-LUC allocation when propagating effects were considered. Through this method, historical CSC-LUC to agricultural expansions was allocated by land classes (products), trade, and end use. The key idea is examining the patterns and trends, particularly when the methodological settings are adjusted, instead of emphasizing the exact magnitude for accounting purpose. Three extensions were designed for wood products, palm oil and soy-beef chain to further explore the impact of adjusting the setting, i.e. employing different ways to address specific issues related to them.



Note: '+' and '-' represents carbon stock loss and gain respectively

Figure 7-7. Cumulative CSC-LUC allocated to different land classes in Southeast Asia adjusted with peat emissions for 1995-2010.

The study demonstrated that exact values of CSC-LUC at a single spatio-temporal point can be expected to change significantly with different methodological settings. One of the key results for the allocation of CSC-LUC by land classes using the global approach versus the regional approach was shown in Figure 7-6. One prominent example is that the cumulative CSC-LUC allocated to 'permanent oil crops' changed from 0.53 Pg C (billion tonne C) of carbon stock gain to 0.11 Pg C of carbon stock loss when spatial boundaries were changed from global to regional. From a global perspective on CSC-LUC, they outcompeted the other lesser productive, more land extensive and without carbon sequestration 'temporary oil crops' (which contribute to more direct and indirect CSC-LUC) such as soybean. When zooming into regional level, their advantage has disappeared because the expansions mainly occurred in regions with high carbon stock loss, particularly Southeast Asia. As an extension to the method, 'permanent oil crops' which consists of palm oil for the case of Southeast Asia was also further analysed for its links to peat emission (Figure 7-7). At global level, the advantage in terms of carbon stock gain of 'permanent oil crops' had shrunk significantly if peat loss was specifically pre-allocated to this land class, i.e. assuming that all carbon loss from peat loss is caused by the expansion of 'permanent oil crops'. This leads to the result that the carbon stock gain of this land class was 28% less compared to the value obtained without pre-allocation (i.e. the peat emission was distributed to all land classes). These findings reiterated the outcome in Chapter 3, where the values of CSC-LUC allocated to Indonesian palm oil using historical approach widely scattered in the range of 0.1 – 32.7 tCO_2/t CPO. This confirmed that that comparing drivers by exact values of CSC-LUC (e.g. in tonne C) at a single spatio-temporal point is highly uncertain, because they may change significantly with the methodological settings if different arguments or assumptions were employed.

This study also concluded that agricultural land degradation (reduction in productivity) and abandonment (left temporarily or permanently unused) are major (albeit indirect) drivers for CSC-LUC. This was clearly reflected by the large amount of CSC-LUC associated with the expansion of non-productive land as shown in Figure 7-6. This implies that a large carbon stock loss can be avoided while maintaining agricultural production if (i) better land-use practices are adopted to prevent further degradation and abandonment (i.e. inefficient agricultural expansion), and (ii) non-productive or under-utilised land resources are mobilised for productive use with sustainable practices.

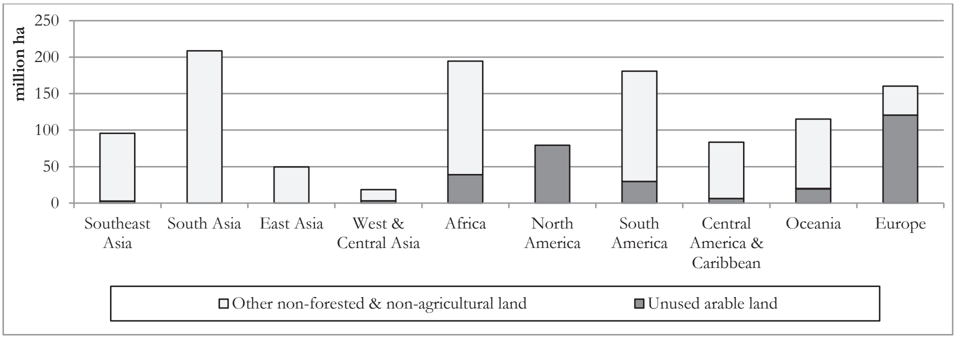
Overall, it is recommended that instead of focusing on only the consumer perspective, more detailed understanding of locally distinct land-use dynamics in the producing regions (especially the underlying causes of CSC-LUC which are not directly linked to increasing demand, e.g. uncontrolled fire) may reveal more meaningful solution to fulfil growing demand while preventing further carbon stock loss. This leads to the formulation of research question (iii) which is answered in the following sub-section.

iii. What are the land resources that can be potentially utilised to meet the additional biomass demand without causing undesired CSC-LUC, and what are the key factors for effective mobilisation of these land resources?

The conclusion from research question (ii) points to the need for more in-depth studies on non-productive land, as the expansion of this land class is regarded as a major driver for carbon stock changes from land use change (CSC-LUC). These non-productive lands may be utilised for future production to avoid further expansion into forests. In particular, land resources with low carbon stock that are currently under-utilised can be deemed potential future production sites without causing undesired CSC-LUC. Chapter 4, 5 and 6 contribute to the identification of these under-utilised low carbon (ULC) land resources and key factors to effectively mobilise them. In Chapter 4, using a global dataset, non-forested and non-agricultural area in different regions were quantified based on the level of utilisation, i.e. unused arable land, unused deforested land, desert and others. In Chapter 5 and 6, the different aspects of ULC land resources were further inspected in-depth. To maintain the continuity on oil palm and its expansion as a prominent example, analyses were made on regencies in Kalimantan (Indonesia), a major location for oil palm expansion, as case studies to answer this research question. Firstly, Chapter 5 reviewed the monitoring efforts for assessing ULC land resources in different domains like land cover or legal definition, and attempted to reconcile them for getting a more complete picture of ULC land. Specifically, various land area indicators (in terms of physical area) in different domains were identified, analysed and compared to obtain a more complete picture of available ULC land. Then, a narrative study was conducted in Chapter 6, coupled with literature review and desktop analysis, to assess the various factors for molising these lands for future production.

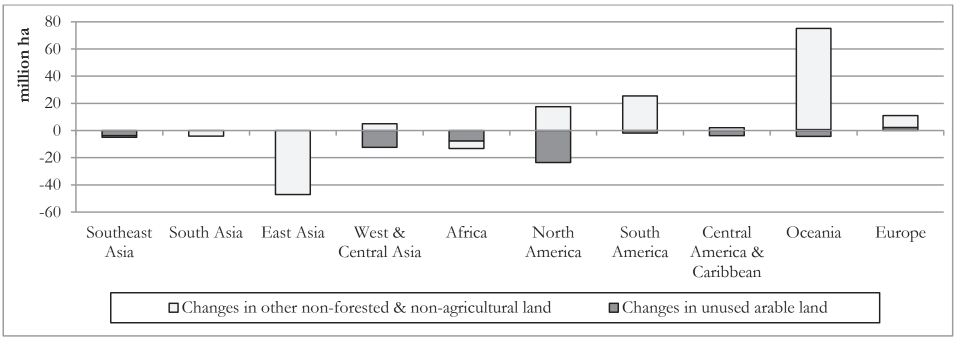
In Chapter 4, the ULC area is quantified for the different regions in the world. Figure 7-8 depicts the unused arable land and other non-forested & non-agricultural area across the world for the year 2010. The two most developed regions in the world, i.e. Europe and North America, have the most unused arable land (amounted to about 121 and 80 million ha, respectively). In terms of total ULC area, South Asia, Africa and South America are among the leaders. Nearly half of the global total ULC area (580 million ha out of 1,190 million ha) is located within these three regions. Figure 7-9 reveals that the changes in ULC area from 1995-2010 vary greatly from region to region. Oceania appeared to be the region with the largest growth, in contrast with East Asia which has the largest reduction in ULC area. The changes in North America and in a smaller scale in West & Central Asia and Central America & Caribbean is more complex, where the unused arable area has declined while the other non-forested and non-agricultural area has increased. While the findings summarised in the two aforementioned figures provide the global picture of ULC land, these results were highly aggregated and lack information to determine the potential of utilising these land resources. In particular, the non-forested & non-agricultural land may consist of a wide variety of land with distinctive characteristics. Due to the limiting global data, more in-depth studies on ULC land may only be performed on much smaller scales, such as at national, provincial or district level.

To explore in more details the characteristics of ULC land, a study was conducted on the case of Kalimantan as presented in Chapter 5. Kalimantan was selected for case study partly as a continuity to the Indonesian case study in Chapter 3, and also because of its rapid carbon stock loss. This study revealed that when quantifying ULC land area, a range of aspects have to be taken into account, not only with but also beyond the concern on actual carbon stock of the land (e.g. land ownership and legal classification). It is thus important to clarify the different ways of defining and quantifying ULC land. Available information which is relevant to ULC land were categorised into six monitoring domains. From an ecological perspective, *land cover* is a key indicator to distinguish land with high carbon stock. Meanwhile, information about *land suitability* is useful to evaluate the technical agricultural potential. For socio-economic aspects, *land occupancy* by small farmers provides an indication for local land-use. In addition, *land-use intensity* can be used to identify land that is used in lower intensity in terms of agricultural activities. The *legal classification and concessions* is another important aspect when land is legally classified as the official 'forest zone' or granted for agricultural activities (which may not be the same as the actual land cover and land-use). Finally, *land degradation* is also monitored as changes in land characteristics from environmental, technical and economic perspectives. As an example, Figure 7-10 illustrates the results from the *land suitability* monitoring domain, taking oil palm as an example for its suitability on low carbon land. The numbers can be quite different between one domain and another. For example, although the regency of Ketapang has nearly 1 Mha of low carbon land, only 0.6 Mha is deemed suitable for oil palm.



Notes: Unused arable land represents arable land that was not cultivated. Other non-forested and non-agricultural land represents land other than arable land that was not forested. Desert was excluded from the graph as it is deemed to have no potential for agricultural production, while unused deforested land was not shown because the area is insignificant at regional level.

Figure 7-8. ULC land area by region in 2010 (Source: Own calculation based on FAOSTAT 2014).



Notes: Unused arable land represents arable land that was not cultivated. Other non-forested and non-agricultural land represents land other than arable land that was not forested. Desert was excluded from the graph as it is deemed to have no potential for agricultural production, while unused deforested land was not shown because the area is insignificant at regional level.

Figure 7-9. Changes in ULC land area by region in 1995-2010 (Source: Own calculation based on FAOSTAT 2014).

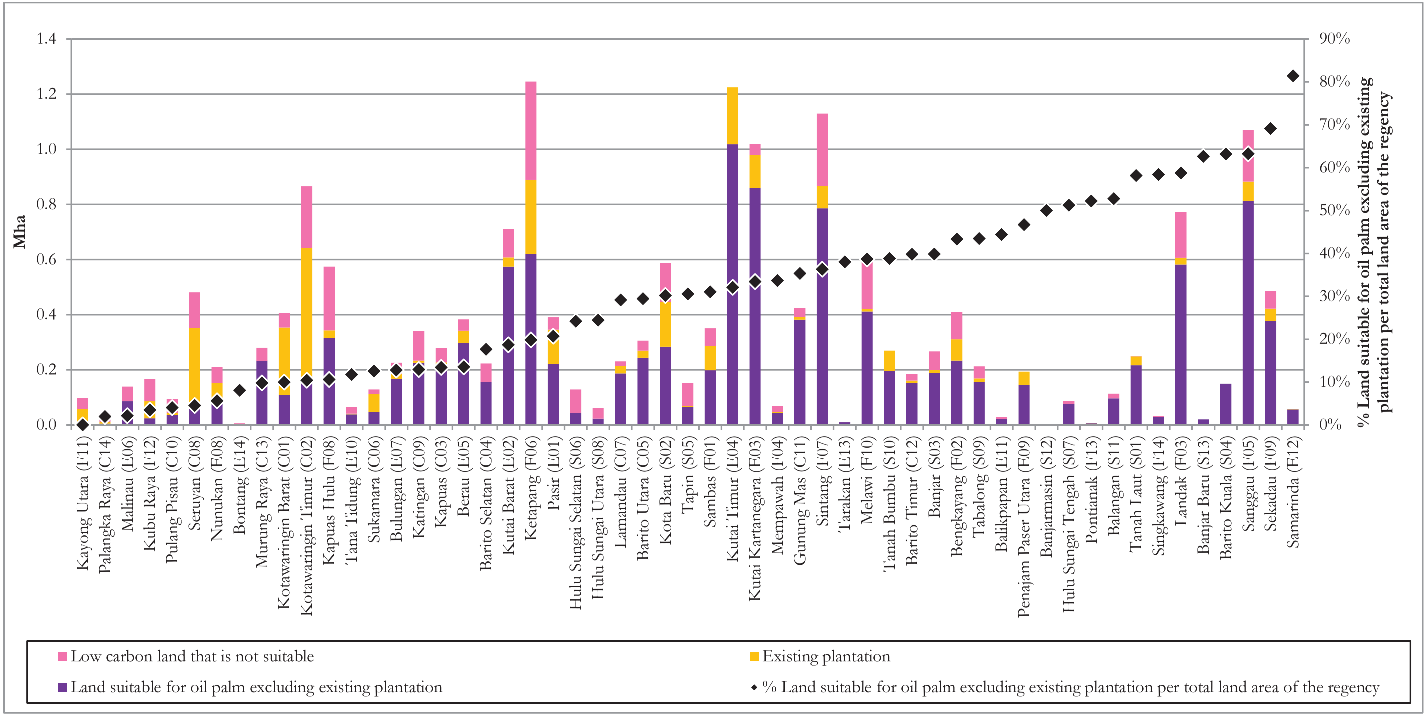
As ULC land can be quantified in different ways, using a single indicator to quantify ULC land may result in either an over-estimation (potentially inducing more unsustainable large-scale expansions) or under-estimation (potentially leaving a large area of land unused for decades). To address this shortcoming, the wealth of data collected, which represent the differences aspects of ULC land, can be employed complementarily to devise more appropriate land-use strategies (e.g. intensification of small farmers or large-scale expansion) at regency level to avoid potential CSC-LUC in the future. For example, large-scale establishments may need to be restricted in regencies with a high rate of land occupancy by small farmers, even if the regency has a substantial area of low carbon land. This was further confirmed in Chapter 6 where the small farmers may have different land-use preferences and not all can accept large-scale plantation. Furthermore, this may incur land disputes as land-use rights of small farmers were largely determined in a less formal way and difficult to be monitored. Instead, in the future, these regencies might prioritize a more diversified portfolio of agricultural activities, e.g. agro-forestry, which may be more suitable in environmental aspect. The regency of Seruyan is a prominent example with a low percentage of land remained suitable for oil palm and a large area of critical land. Meanwhile, the regency of Pulang Pisau has a substantial area of 'temporarily unused agricultural land' but a very limited area of 'low carbon land' – this implies that not all 'temporarily unused agricultural land' is ready for future exploitation. In this case, small-scale farming in combination with conservation that can contribute to replenishment of degraded land might be a better strategy. In comparison, several regencies in West Kalimantan like Sanggau, which have a large amount of low carbon land and land suitable for oil palm production, could be a better starting point to explore possibilities for large-scale establishment.

This study shows that by combining available data from different aspects, the assessment of ULC land resource can be significantly improved. However, a major limitation is that relying solely on estimates of physical area cannot provide a complete picture of 'real' land availability without considering a broader range of socio-economic factors (e.g. labour availability). For example, labour availability was mentioned in the interviews with local communities to be a major barrier for the mobilisation of ULC land for the case of Gunung Mas. Labour availability limits the 'real' potential of ULC land (i.e. land will remain under-utilised due to lack of labourers to carry out the intensification, thus it is not 'readily available'), but the physical land area indicators used in this study cannot tell much about this.

The conclusion in Chapter 5 shows that a more in-depth analysis of ULC land potential must also be performed in a broader context of socio-economic progress in individual regencies. To close this gap, the key factors for effective mobilisation of ULC land resources have to be first identified. This was demonstrated in Chapter 6 through a narrative study with field strips in Kalimantan, with the analysis of these factors through the lenses of different actors, i.e. indigenous communities, (trans)migrants, industry, government officials and civil society. Case studies were performed on four regencies with distinctive characteristics in Kalimantan: Gunung Mas, Kotawaringin Timur, Palangka Raya and Pulang Pisau. Oil palm was given a special focus as the major industrial crop in the area. Four types of factors – economic, agro-ecological, institutional and cultural factors - were identified. These factors cover the multiple aspects of ULC land, with some of these factors cannot be directly 'measured' in numbers (such as the condition of water management or risk of fire), while some can be quantitatively analysed to improve the estimation of ULC land that can be mobilised. As an example, based on the interviews, labour availability was identified by small farmers as a key barrier (lack of manpower) for mobilising ULC land, while large-scale plantation managers perceived this factor as an opportunity (with less risk of land conflicts). In order to better understand this factor, labour availability was further analysed to estimate the labour requirement if ULC land would be converted to oil palm cultivation under industrial management. The amount of ULC land that can be mobilised, specifically forecasted for the year of 2030, was found to be much lesser than the 15 Mha of the low carbon land available, reduced to only 11 Mha if all labourers are working in the agricultural sector, and 7 Mha if part of the labour force is diverted to non-agricultural sector. While the labour factor was quantitatively analysed, it also requires further qualitative understanding of the underlying causes of, in particular, labour mobility. For example, the transmigration policies in the past has have triggered large fluxes of labour movement into Kalimantan. This could have major impacts on the labour availability in the regencies but also social conflicts as already demonstrated in the past. Labour mobility policies like this have to be planned in a very careful way, especially taking into account the perspectives of local population to avoid unintended social conflicts.

This study proposed that, as a starting point, a comprehensive local assessment of the opportunities and barriers to utilising ULC land is needed to formulate practical and realistic land-use policies on a regency level for mobilising ULC land. In other words, the policies must be acceptable by the different stakeholders especially the local communities, economically viable for continuous implementation, and minimising the risk to the environment. Instead of focusing only on a single crop or end-use, this has to depart from analysing the specific conditions within individual regencies, especially considering the views of multiple land-use actors on different land-use options and business models. Therefore, it is crucial for future research to connect narrative studies on socio-economic aspects to quantitative land potential estimates which are based on environmental and agro-ecological factors.

The findings from Chapter 4, 5 and 6 can be combined as inputs to assess the land resources that can be potentially mobilised to meet the additional biomass demand without causing undesired CSC-LUC. Identifying the key factors for effective mobilisation of these land resources, as demonstrated in Chapter 6, can help deriving more realistic expectation, formulating tangible policies, and minimising unintended consequences. This is especially crucial for long-term successful implementation of policies for mobilising ULC land and avoid project failures (e.g. land abandonment due to discontinuity of financing or loss of interests from farmers).



*Suitability criteria are: low carbon land with elevation <1000m, soil depth >75cm, soil acidity < pH 7.3, slope <30%, water resource buffers >100m, and conservation buffer >1000m

Figure 7-10. Land suitability: Land suitable for oil palm in Kalimantan as identified by WRI (2012) in comparison to low carbon land and existing oil palm plantation identified by MoF (2015).

7.5 CONCLUSIONS AND RECOMMENDATIONS

This thesis has addressed key knowledge gaps of monitoring the BE in terms of biomass flows, land-use change, carbon impacts and future land resources. In particular, it answered questions on tracking the biomass flows for the BE, measuring the impacts of additional demand on CSC-LUC, and assessing land availability for future biomass production.

With the rapid growth of cross-sectorial biomass flows and cross-border trade, it is essential to monitor the BE across sectors from traditional agriculture to modern downstream activities that serve for a range of end-markets, such as bio-based products and energy, as well as across scales from local to global level, as the first step to understand the implication of creating new demand on global CSC-LUC. It was illustrated in Chapter 2 how different streams of biomass flow into and out of a country, and spread across multiple end-markets. To effectively monitor these flows, existing monitoring efforts can be harmonised to draw a more complete picture of the biomass flows for the BE. Combining these flows helps to clarify the consumption patterns in different end-markets in conjunction with the trends in cross-border trade.

Following that, this thesis attempted to assess the roles of biomass consumption in driving CSC-LUC. With such complex flows that involve a wide range of stakeholders, linking the additional demand from the expanding BE to global CSC-LUC is found to be complicated as described in Chapter 3. This largely depends on perspectives from multiple stakeholders which are framed by different (sometimes conflicting) interests. Attempts to superimpose a universal method for CSC-LUC accounting from place to place and over time are unlikely to work. Through developing alternative mechanisms to link CSC-LUC to these flows, Chapter 4 clearly showed that a small change in the methodological setting will lead to a substantial difference in the quantitative results on CSC-LUC that has a significant implication to policymaking. Nevertheless, despite the different angles used in interpreting the links of the BE to CSC-LUC, the increasing demand for biomass, and the often highly inefficient land-use practices are likely to be the key drivers for global CSC-LUC. In this regard, improving land management and productivity with efficient use of ULC land offers opportunities to close the demand gap while also reducing the CSC-LUC impacts.

To do so, the identification of ULC land resources and key factors to mobilise them is critical. As presented in Chapter 5, ULC land can be characterised in multiple aspects, such as land cover and legal classification. All these aspects have to be taken into account when quantifying the area that can be potentially used for future production. To effectively mobilise these land resources, a range of factors (from economic to cultural factors) has to be addressed, particularly from the different perspectives of various actors (from government to small farmers) as described in Chapter 6. There is no one best solution for all, but it depends on the local characteristics in agro-ecological and socio-economic aspects. Most importantly, the immediate and long-term objectives have to be clearly defined, especially in addressing unsustainable demand-driven expansion or inefficient local land-use practices. For example, there can be an urgency to prevent uncontrolled fire in one place to immediately reduce environmental impacts, while socio-economic benefits from using ULC land is a long-term consideration which cannot be neglected.

In conclusion, while measuring the impacts of the expanding BE on the consumption side is important, this thesis demonstrated that it is critical to also monitor from the producers' perspective, particularly in consideration of the detailed local context. In other words, monitoring of the BE can also serve for the formulation of localised strategies to answer questions on how the transition to the BE can be done in a sustainable way, considering the participation of a wide range of stakeholders across scales. The questions on 'how' and 'why' are equally important to 'what' and 'when' when it comes to designing a monitoring framework that covers both quantitative and qualitative information. These monitoring efforts provide a basis for deploying tailor-made land-use strategies in different places to address improper local land-use practices, while improving productivity for meeting additional demand from BE without compromising the environmental and socio-economic sustainability. This conclusion can be translated into three wider implications for future research on monitoring the BE:

i. **Cross-sector monitoring**: The concerns on sustainability for many developed countries relying on biomass imports are largely characterized by sectors. This is reflected in the disparity in sustainability standards for monitoring biofuel production in comparison to food and chemicals, leading to the situation where the e.g. certified vegetable oils are largely diverted to the biofuels market, and uncertified (or 'uncertifiable') vegetable oils to the other sectors. However, the share of vegetable oils produced sustainably in a producing region like Southeast Asia does not necessarily increase. This implies that monitoring of biomass needs to be performed across sectors to ensure that CSC-LUC is properly understood on the production side.

ii. **Landscape monitoring**: The overall impact of agricultural activities on CSC-LUC cannot be easily determined by types of crops, as it involves various non-agricultural and non-productive drivers. For example, uncontrolled fire resulting from land preparation can hardly be distinguished by type of crops as a range of actors are responsible for these. This implies that the entire landscape involving multiple land-uses and business models should be monitored all together.

iii. **Cross-scale monitoring**: Current monitoring activities on biomass flows, carbon impacts and land-use for both consumption and production sides are mostly carried out at national level. Some producing locations, like Kalimantan, were further examined on a spatially explicit scale. However, land-use patterns are also affected by aggregated effects from the distinctive socio-economic environment (e.g. institutional and cultural factors) within a smaller administrative unit (e.g. a state, a province, a regency or a district), which could have a dominating influence on the land-use dynamics within the unit's border. This implies that evaluation of a sustainable BE should be made across different scales to be able to incorporate both global changes and local variations.

However, one should acknowledge the lack of resources to maintain reasonably high quality and consistent monitoring in many places, especially in the sense of coherence between different monitoring activities. This is in part because there is still no widely shared vision on developing the BE between different groups or institutions that perform the monitoring work. Practically, insights from existing work may be combined to portray the multiple aspects of the BE and its implications on CSC-LUC, as demonstrated in this thesis for several cases. Integrating all the existing efforts could greatly improve the monitoring of BE. Several key recommendations for improving future monitoring, based on the findings of this thesis, are summarised below under two main aspects:

i. Optimising existing datasets and information

- **Reconciling available datasets:** Chapter 1 and 5 demonstrated how to put information from different sources together for the cases of the Netherlands (which relies heavily on import) and Indonesia (which relies heavily on export), respectively. Meanwhile, Chapter 4 illustrated the combination of different datasets for global analysis. It is recommended that these analyses are also conducted to set up a tailor-made monitoring system for other (groups of) countries (e.g. big countries like the US or China which act as both big producers and consumers) or local administrative units with distinctive characteristics. This will set examples and provide lessons to countries/local administration with similar setting to develop their own monitoring systems in the future.
- **Improving data quality and availability:** While there are various sources of information and reporting systems, their quality could be uneven especially in terms of reliability (e.g. non-transparency in methodology) and completeness (e.g. low monitoring frequencies) as revealed by Chapter 1, 4 and 5. In several cases, data is unavailable at all, and assumptions have to be made to fill in the data gap. For future research, it is therefore important to address these uncertainties. It is recommended to further improve the quality, availability and consistency of data from existing monitoring systems, especially for the key datasets like biomass flows and land cover maps. One example is to increase the spatio-temporal details, such as updating the land cover map more frequently (e.g. the spatially explicit maps are only available with an interval of 5 years for the case of Indonesia). The consistency between trade data from different reporting agencies is also another example for further refinement (e.g. the data from trade statistics from custom may not match the data collected from the industry).

ii. Measuring CSC-LUC and assessing ULC land resources in multiple contexts

- **Inspecting the relative role of underlying causes of CSC-LUC in different contexts:** Chapter 3 and 4 showed that the relative roles of different underlying causes of CSC-LUC in different contexts, such as varying scale in spatial and temporal dimensions or emphasizing individual end-markets, can be examined by adjusting the key functions of the methodology. Future research on CSC-LUC can further build on this by varying the setting of key functions in order to improve our still limited understanding of underlying causes of CSC-LUC.

For example, in the case of Indonesian palm oil demonstrated in this thesis, the priority is to conduct and compare analysis at both national and regency level which are the most relevant administrative units for land-use policies to better understand the relative roles of the drivers within the country and also the individual regencies. This has to be done with the consideration of various non-agricultural and non-productive drivers. With that, more targeted national and regency policies can be designed to tackle the real issues in different regencies.

- **Integrating approaches from different disciplines in mobilising ULC land resources as a means to tackle CSC-LUC:** As demonstrated in Chapter 5 and 6, quantitative studies (mostly focusing on environmental aspects) and qualitative studies (mostly focusing on socio-economic aspects) on ULC land were performed separately. While CSC-LUC is an issue that cross-cuts different aspects from climate change to agricultural economics, working in silos has resulted in individual studies painting incomplete pictures of the issues. Therefore, it is recommended that future monitoring should be performed in a more comprehensive way by reconciling the different approaches and combining insights on different aspects. For example, the narrative studies on socio-economic changes can be combined together with quantitative modelling of CSC-LUC to better explain the trends and the relative roles of different drivers, and provide directions to refine the modelling exercises (e.g. to include the consideration of various socio-economic factors like labour availability for mobilising ULC land resources).
- **Identifying the key factors for mobilising ULC land resources with inputs from different land-use actors:** In Chapter 6, cases in different regencies proved that mobilising of ULC land resources largely depends on not only global factors (e.g. changes in commodity prices) but also a range of locally distinctive factors (e.g. labour availability) and on the business model applied (e.g. small farmers perceive key factors such as labour availability very differently than large-scale plantation managers). This implies that future research on ULC land has to explicitly identify these factors for each specific case and prioritise the most critical ones. As a starting point, a comprehensive local assessment of the opportunities and barriers to utilising ULC land is needed to formulate practical and realistic land-use policies at a relevant administrative level for mobilising ULC land. In other words, the policies must be designed in a way that are acceptable by the different stakeholders especially the local communities, economically viable for continuous implementation, and minimising the risk to the environment. Instead of focusing only on a single crop or end-use, this has to depart from analysing the specific conditions within individual regencies, especially considering the views of multiple land-use actors on different land-use options and business models.

SAMENVATTING

De wereldwijde belangstelling voor de ontwikkeling van de 'bio-economy' (bio-economie, BE) en de 'bio-based economy' (biogebaseerde economie, BBE) is sinds het begin van de 21e eeuw aanzienlijk toegenomen (FAO 2016). De term BBE wordt gebruikt om economische activiteiten aan te duiden waarbij gebruik wordt gemaakt van biogebaseerde grondstoffen en producten voor non-food doeleinden, hetzij in ruwe vorm, hetzij als tussenproducten of eindproducten (hierna 'biomassa' genoemd) (FAO 2016). Dit concept valt binnen het ruimere BE-kader dat al het eindgebruik van biomassa omvat, met inbegrip van levensmiddelen en diervoeders. Omdat de BE en BBE dezelfde grondstoffen gebruiken, in het bijzonder landbouwproducten waarbij gebruik wordt gemaakt van landbouwgrond, zijn ze nauw met elkaar verbonden, evenals met de grotere thema's van voedselzekerheid, klimaatverandering en plattelandsontwikkeling (FAO 2016). Dit wordt tevens gekenmerkt door complexe sectoroverschrijdende (bijvoorbeeld vanuit de levensmiddelensector naar de energiesector) en grensoverschrijdende stromen van biomassa. In de periode van 1995 tot 2010 zijn de internationaal verhandelde volumes van landbouwproducten aanzienlijk toegenomen, namelijk van 7 naar 12 EJ, terwijl het aandeel van de verhandelde producten ten opzichte van het totaal aantal primaire landbouwproducten ook is gestegen, van 18% naar bijna 22% (FAOSTAT 2014).

Aangezien één van de gemeenschappelijke doelstellingen van de ontwikkeling van de BE is om de uitstoot van broeikasgassen door verbranding van fossiele grondstoffen te verminderen, is het cruciaal om toezicht te houden op de uitstoot van broeikasgassen die samenhangt met de wereldwijde toeleveringsketen van biomassa. Deze toeleveringsketen omvat de productie en verwerking van grondstoffen, transport en logistiek van multilaterale grensoverschrijdende handel en het eindverbruik in verschillende eindmarkten. Van deze componenten wordt de grootste bijdrage geleverd door de verandering van de koolstofvoorraad (*carbon stock change*, CSC) als gevolg van verandering in landgebruik (*land-use change*, LUC) (hierna 'CSC-LUC' genoemd). In de afgelopen decennia werd 8 tot 20% van de jaarlijkse wereldwijde antropogene CO_2-uitstoot in feite veroorzaakt door alle CSC-LUC (van der Werf et al. 2009, Bos et al. 2016).

Om inzicht te krijgen in de implicaties van het creëren van een nieuwe bedreiging van mondiale CSC-LUC, was het onderzoek in dit proefschrift gericht op de belangrijkste kennishiaten met betrekking tot het volgen van de biomassastromen voor de BE, het meten van de effecten van de extra bedreiging voor CSC-LUC en het beoordelen van landbeschikbaarheid voor de toekomstige productie van biomassa. Daartoe werden de volgende onderzoeksvragen geformuleerd en beantwoord:

i. Hoe kunnen de biomassastromen voor de groeiende bio-economie van productie tot consumptie op lokale en wereldwijde schaal worden gevolgd ('monitoring'), en wat zijn de patronen van de belangrijkste stromen?

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ii. Hoe kunnen de veranderingen in koolstofvoorraad door veranderingen in grondgebruik in verband met de extra vraag van de groeiende bio-economie worden gevolgd, en wat zijn de effecten van het toepassen van verschillende methodologische parameters vanuit verschillende perspectieven?

iii. Wat zijn de hulpbronnen die mogelijk kunnen worden gebruikt om aan de extra vraag naar biomassa te voldoen, zonder dat dit leidt tot ongewenste veranderingen in koolstofvoorraad als gevolg van veranderingen in grondgebruik, en wat zijn de belangrijkste factoren voor een effectieve inzet van deze hulpbronnen?

In de eerste plaats is het, gezien de snelle groei van sector- en grensoverschrijdende biomassastromen, essentieel om controle uit te oefenen op alle sectoren van de BE. Dit houdt specifiek in: van de traditionele landbouw tot moderne downstream-activiteiten die een reeks van eindmarkten bedienen, zoals biogebaseerde producten en energie, maar ook op lokale en mondiale schaal, om inzicht te krijgen in het effect van het creëren van nieuwe behoefte aan wereldwijde CSC-LUC. In hoofdstuk 2 wordt een methodologisch kader voorgesteld voor het in kaart brengen van de binnenlandse productie-consumptie en grensoverschrijdende handel, en het respectieve aandeel van duurzaam gecertificeerde biomassa, met als doel om de monitoring van de biomassastromen van de BE te verbeteren. Als voorbeeld vond een casestudie plaats van de situatie in Nederland voor de periode 2010-2011, waarbij de aandacht uitging naar drie relevante categorieën die een brede toepassing hebben, variërend van voedingsmiddelen en diervoeders tot grondstoffen en energie: (i) houtachtige biomassa, (ii) oliën en vetten, en (iii) koolhydraten. Hieruit bleek dat het verbruik van houtachtige biomassa voor energieopwekking was toegenomen tot 3,5 ton, inclusief 1,3 ton geïmporteerde houten pellets waarvan meer dan 85% was gecertificeerd. Verder werd ongeveer 0,6 ton oliën en vetten en 1,2 ton koolhydraten gebruikt voor de productie van vloeibare biobrandstoffen. Tevens kwam uit de casestudie naar voren dat meer dan 50% van houtige biomassa voor niet-energetische grondstoftoepassingen ofwel gecertificeerd was, ofwel verkregen uit gerecycleerde stromen. Sinds 2011 hebben gecertificeerde plantaardige oliën hun intrede gedaan in de Nederlandse levensmiddelensector, die goed zijn voor 7% van de totale consumptie van plantaardige oliën. Over het geheel genomen toont het onderzoek aan dat voor een effectief toezicht op deze stromen verschillende bestaande monitoringsinspanningen kunnen worden gecombineerd. Op die manier kan een vollediger beeld van de biomassastromen voor de BE worden verkregen, hoewel daarvoor wel een aantal methodologische uitdagingen, zoals inconsistenties in gegevensdefinities, opgelost dienen te worden. Dit draagt bij aan een beter inzicht in de consumptiepatronen in verschillende eindmarkten, in samenhang met de trends in de grensoverschrijdende handel.

Het is ingewikkeld gebleken om bij dergelijke complexe stromen met een breed scala aan belanghebbenden de extra vraag van de groeiende BE te koppelen aan mondiale CSC-LUC. In dit proefschrift is geprobeerd tot een beoordeling te komen van de invloed van de consumptie van biomassa op CSC-LUC (hoofdstuk 3). Uitgaande van het voorbeeld van palmolieproductie in Indonesië werd een meta-analyse van twaalf bestaande studies naar CSC-LUC uitgevoerd. Hieruit bleek dat er grote verschillen bestonden tussen de resultaten van de studie, grotendeels veroorzaakt door de verschillende interpretaties van het verband tussen directe causale factoren en onderliggende oorzaken van CSC-LUC. Op hun beurt waren deze het gevolg van verschillen in specifieke methoden, algoritmen en parameters die onderdeel uitmaakten van de methodologie. Voorbeelden zijn de manier waarop werd bepaald wat het verband is tussen ontbossing en oliepalm, en het opnemen van niet-agrarische en niet-productieve causale factoren in de berekening om het relatieve aandeel daarvan voor CSC-LUC te vergelijken met die van de consumptie van palmolie. Voor de geselecteerde historische studies en projectiestudies bevonden de geharmoniseerde kwantitatieve resultaten zich respectievelijk tussen 0,1-3,8 en -0,1-15,7 t CO_2/t ruwe palmolie. Geconstateerd werd dat CSC-LUC toegeschreven aan palmolie typisch lager was wanneer rekening werd gehouden met opstuwende effecten en niet-agrarische en niet-productieve causale factoren. De waarden varieerden ook, sterk afhankelijk van de marginale en gemiddelde allocatiemechanismen die werden toegepast. Hieruit blijkt dat de individuele analyses slechts antwoord geven op een deel van de vraagstelling over causale factoren van CSC-LUC en dat deze elk hun sterke en zwakke punten hebben. Omdat de context heel verschillend kan zijn, wordt de aanbeveling gedaan om voor berekeningen in het kader van beleidsvorming niet uit te gaan van kwantitatieve resultaten van één enkele studie. Voor het bepalen van de rol van verschillende causale factoren (bijvoorbeeld houtkap versus palmolie), of de relatieve bijdrage aan CSC-LUC vanuit regionaal en mondiaal perspectief, is verder onderzoek noodzakelijk.

Op dit moment is het houden van toezicht op CSC-LUC grotendeels afhankelijk van perspectieven die afkomstig zijn van meerdere stakeholders en ten dele voortvloeien uit verschillende (soms tegenstrijdige) belangen. Pogingen om op verschillende plaatsen en voor langere tijd een universele methode op te leggen voor het berekenen van CSC-LUC hebben waarschijnlijk geen kans van slagen. In hoofdstuk 4 werd onderzocht hoe een kleine verandering in de methodologische opzet de kwantitatieve resultaten kan beïnvloeden, door een methode te ontwikkelen voor het toewijzen van historische CSC-LUC aan agrarische uitbreidingen op basis van grondsoort (producten), handel en eindgebruik. Concreet werd onderzocht wat de relatieve rol is van agrarische uitbreiding als gevolg van een groeiende vraag in vergelijking met niet-agrarische en niet-productieve causale factoren, evenals de gevolgen daarvan in de regionale en mondiale context gezien de versterkende effecten. De analyse voor de periode van 1995 tot 2010 liet drie belangrijke trends zien: (i) degradatie en verlaten van landbouwgrond bleek een belangrijke (zij het indirecte) causale factor voor CSC-LUC te zijn, (ii) CSC-LUC werd versterkt door de groei van grensoverschrijdende handel, (iii) in de jaren 2000 is het gebruik voor niet-voedingsdoeleinden (met uitzondering van vloeibare biobrandstoffen) een belangrijke bijdrage aan CSC-LUC gaan leveren. De studie toonde aan dat de exacte waarden van CSC-LUC op een bepaald ruimtelijk-temporeel punt aanzienlijk kunnen verschillen afhankelijk van de toegepaste methodologie. CSC-LUC die werd toegeschreven aan ‘permanente oliehoudende gewassen’ veranderde bijvoorbeeld van 0,53 Pg C (miljard ton C) toename van de koolstofvoorraad in 0,11 Pg C afname van de koolstofvoorraad wanneer de geografische grenzen werden gewijzigd van wereldwijd naar regionaal.

Ondanks de verschillende invalshoeken voor de interpretatie van de verbanden tussen de BE en CSC-LUC, zijn het vaak zeer inefficiënte grondgebruik en de toenemende wereldwijde vraag naar biomassa waarschijnlijk de belangrijkste causale factoren voor wereldwijde CSC-LUC. Verbetering van het beheer en de productiviteit van landbouwgrond, in combinatie met een efficiënt gebruik van onderbenutte koolstofarme (*under-utilised low carbon*, ULC) landbouwgrond, biedt kansen om aan de toenemende vraag te voldoen en tegelijkertijd de effecten voor CSC-LUC te verminderen. Op basis van de situatie in Kalimantan in Indonesië, hét voorbeeld van ontbossing, werd in hoofdstuk 5 onderzoek gedaan naar ULC-gronden aan de hand van een analyse van gegevens en het formuleren van indicatoren uit verschillende monitoringsdomeinen: bodembedekking, geschiktheid van de grond, exploitatievorm van de grond, intensiteit van het grondgebruik, juridische kwalificatie en concessie, en degradatie van de grond. De analyse werd uitgevoerd op het niveau van het regentschap, de meest relevante instantie in de hiërarchie voor de implementatie van het beleid voor het gebruik van landbouwgrond. Hieruit bleek dat de indicatoren voor ULC-grond op het niveau van het regentschap sterk varieerden. Een regentschap kan bijvoorbeeld een aanzienlijk gebied 'tijdelijk ongebruikte landbouwgrond' hebben maar een slechts een beperkt gebied 'koolstofarme grond', wat impliceert dat niet alle 'tijdelijk ongebruikte landbouwgrond' geschikt of gereed is voor toekomstige exploitatie vanuit het oogpunt van de koolstofvoorraad. Dit toonde aan dat het gebruik van één enkele indicator om beschikbare ULC-gronden te kwantificeren riskant is, omdat dit zeer waarschijnlijk leidt tot over- of onderschatting. Om die reden werd in een casestudie verder onderzoek gedaan naar ULC-gronden, op basis van vier regentschappen. Daarbij werden alle indicatoren vergeleken, ondersteund door onderzoek van de relevante literatuur en van gegevens die door middel van open interviews werden verkregen. Deze informatie werd gebruikt om een schatting te maken van de oppervlakte van ULC-grond op basis van mogelijke strategieën voor grondgebruik. Zo kon bijvoorbeeld worden vastgesteld dat een regentschap over een grote oppervlakte ongebruikte koolstofarme grond beschikte die mogelijk geschikt was voor oliepalmexploitatie.

De belangrijkste beperking is echter dat fysieke schattingen geen compleet beeld van de 'werkelijke' beschikbaarheid van landbouwgrond kunnen bieden wanneer daarbij niet een breder scala van sociaaleconomische factoren in aanmerking wordt genomen (bijvoorbeeld de beschikbaarheid van arbeidskrachten). Om deze landbouwgronden effectief te kunnen mobiliseren, werden in hoofdstuk 6 de Kalimantan-casestudies verder onderzocht door de factoren vanuit de verschillende perspectieven van de verschillende actoren (van de overheid tot kleine boeren) nader in ogenschouw te nemen. De factoren werden globaal ingedeeld in economische, agro-ecologische, institutionele en culturele categorieën. Deze factoren werden afwisselend waargenomen als kansen en/of belemmeringen voor verschillende soorten grondgebruik (bijvoorbeeld oliepalm, rijstvelden of agrobosbouw) en voor verschillende businessmodellen, en deze visie kon variëren tussen regentschappen. In het algemeen werd oliepalm door de meeste ondervraagden beschouwd als een economische kans, omdat er geen andere, meer aantrekkelijke opties bestonden. Soms werd oliepalm echter ook als een beperkte mogelijkheid gezien, als gevolg van verschillende factoren zoals onvoldoende beschikbaarheid van arbeidskrachten vanwege een lage bevolkingsdichtheid. Deze economische factoren hingen samen met de agro-ecologische factoren, bijvoorbeeld bodemkwaliteit, die vaak als de reden voor lage economische aantrekkelijkheid werd beschouwd. Institutionele en culturele factoren zijn subtieler en complexer, en hangen samen met sociaal-politieke elementen in de hiërarchie van autoriteiten. Deze studie toont aan dat de mobilisatie van ULC-grond zich niet zou moeten concentreren op een enkel gewas of eindgebruik, maar dat een analyse van de specifieke omstandigheden binnen de afzonderlijke regentschappen als uitgangspunt zou moeten dienen, vooral gezien de verschillende standpunten van de grondgebruikactoren over mogelijke opties voor grondgebruik en bedrijfsmodellen. Zo heeft Gunung Mas potentieel voor een grootschalige aanpak, terwijl in Pulang Pisau oliepalm deel zou kunnen uitmaken van een kleinschalige, gemengde teelt van gewassen waarmee extra inkomsten kunnen worden gegenereerd. Er is niet één beste oplossing voor iedereen; dit hangt af van lokale agro-ecologische en sociaaleconomische aspecten. Het belangrijkste is dat de doelstellingen voor de korte en lange termijn duidelijk worden gedefinieerd, met name bij de aanpak van niet-duurzame, vraaggestuurde uitbreiding of van inefficiënte praktijken bij lokaal grondgebruik. Er kan bijvoorbeeld in een bepaald gebied een dringende noodzaak bestaan om ongecontroleerde branden zo snel mogelijk terug te dringen in verband met onwenselijke milieueffecten, terwijl de sociaaleconomische voordelen van het gebruik van ULC-grond daarentegen tot overwegingen leiden die van belang zijn voor de lange termijn en daarom niet kunnen worden genegeerd.

Samenvattend kan gesteld worden dat het van groot belang is om de effecten van de zich uitbreidende BE-markt te meten. In dit proefschrift wordt aangetoond dat het cruciaal is dit niet alleen aan de verbruikskant te monitoren, maar ook vanuit het perspectief van de producenten, vooral met inachtneming van de specifieke kenmerken van de lokale context. Met andere woorden, het monitoren van de BE kan ook dienen voor het formuleren van lokale strategieën voor het beantwoorden van vragen over hoe de transitie naar de BE op duurzame wijze kan geschieden, rekening houdend met de deelname van een breed scala van stakeholders op alle niveaus. Voor het ontwerpen van een monitoringskader dat zowel kwantitatieve als kwalitatieve informatie oplevert, zijn de vragen over het 'hoe' en 'waarom' even belangrijk als die over het 'wat' en 'waar'. Deze inspanningen rond monitoring vormen een basis voor de implementatie van toegesneden strategieën voor grondgebruik op verschillende plekken, om verkeerde lokale praktijken tegen te gaan en tegelijkertijd de productiviteit te verbeteren. Op die manier kan worden voldaan aan de additionele vraag vanuit de BE zonder daarbij afbreuk te doen aan de ecologische en sociaaleconomische duurzaamheid. Deze conclusie kan worden vertaald in drie bredere implicaties die onderwerp kunnen zijn voor toekomstig onderzoek naar monitoring van de BE:

i. **Sectoroverschrijdende monitoring**: De huidige duurzaamheidsproblematiek is sterk gekoppeld aan bepaalde sectoren, hetgeen weerspiegeld wordt in verschillen in duurzaamheidsnormen voor de controle op de productie van biobrandstoffen in vergelijking met die voor voedsel en chemicaliën. Om ervoor te zorgen dat alle biomassa duurzaam wordt geproduceerd, dient monitoring in en tussen alle sectoren plaats te vinden.

ii. **Landschapsmonitoring**: Het totale effect van agrarische activiteiten op CSC-LUC kan niet eenvoudigweg worden bepaald op basis van soorten gewassen, omdat het gaat om verschillende niet-agrarische en niet-productieve causale factoren. Om die reden dient het landschap als geheel te worden gemonitord, inclusief de verschillende soorten grondgebruik en bedrijfsmodellen.

iii. **Schaaloverschrijdende monitoring**: Hoewel de huidige toezichtactiviteiten vooral op nationaal niveau worden uitgevoerd, worden patronen van grondgebruik ook beïnvloed door de geaggregeerde effecten van de specifieke sociaaleconomische omgeving binnen een kleinere bestuurlijke eenheid, die een dominerende invloed op de dynamiek van grondgebruik kan hebben. Daarom dient monitoring op verschillende schaal plaats te vinden, om zowel wereldwijde veranderingen als lokale variaties in kaart te brengen.

Wel dient echter erkend te worden dat men op veel plaatsen over onvoldoende middelen beschikt om een goede en consistente monitoring te realiseren, vooral in de zin van samenhang tussen de verschillende activiteiten op dat gebied. Dit vloeit ten dele voort uit het feit dat er tussen verschillende groepen of instellingen die de monitoringswerkzaamheden uitvoeren nog steeds geen breed gedeelde visie op de ontwikkeling van de BE bestaat. In praktisch opzicht zouden inzichten uit bestaande activiteiten kunnen worden gecombineerd om de verschillende aspecten van de BE en de gevolgen daarvan op CSC-LUC in kaart te brengen, zoals in dit proefschrift voor een aantal casestudies is aangetoond. De integratie van alle bestaande inspanningen zou de monitoring van de BE sterk kunnen verbeteren. Een aantal belangrijke aanbevelingen voor het verbeteren van toekomstige monitoring, gebaseerd op de bevindingen van dit proefschrift, zijn hieronder samengevat in twee belangrijke aanbevelingen:

i. **Optimalisering van bestaande datasets en informatie**

- **Het combineren van beschikbare datasets:** Het verdient aanbeveling dat monitoringssystemen specifiek worden toegesneden op verschillende (groepen) landen (bijvoorbeeld grote landen zoals de VS of China die beide optreden als grote producenten en consumenten) of lokale bestuurlijke eenheden met specifieke kenmerken. Deze systemen kunnen vervolgens als voorbeeld dienen voor landen/lokale bestuurseenheden met een vergelijkbare achtergrond op basis waarvan zij in de toekomst hun eigen controlesystemen kunnen ontwikkelen.
- **Verbetering van de kwaliteit en beschikbaarheid van gegevens:** Er bestaan verschillende informatiebronnen en rapportagesystemen, die mogelijk niet van dezelfde kwaliteit zijn. Dit geldt in het bijzonder voor de betrouwbaarheid (bijvoorbeeld methodologisch niet transparant) en volledigheid (bijvoorbeeld lage controlefrequenties). De kwaliteit, beschikbaarheid en consistentie van gegevens van bestaande monitoringssystemen, met name voor belangrijke datasets als biomassastromen en kaarten van bodembedekking, dienen te worden verbeterd.

ii. **Meting van CSC-LUC en beoordeling van ULC-gronden in meerdere contexten**

- **Onderzoek van de relatieve rol van de onderliggende oorzaken van CSC-LUC in verschillende contexten:** In dit proefschrift wordt aangetoond dat de relatieve rol van verschillende onderliggende oorzaken van CSC-LUC in verschillende contexten kan worden onderzocht door belangrijke aspecten van de methodologie aan te passen. In toekomstig onderzoek zou dit kunnen worden uitgebreid naar verschillende andere contexten om ons nog steeds beperkte inzicht in onderliggende oorzaken van CSC-LUC te verbeteren.

- **Integratie van benaderingen uit verschillende disciplines om ULC-gronden te mobiliseren als een middel om CSC-LUC aan te pakken:** Omdat CSC-LUC een kwestie is die verschillende aspecten heeft, van klimaatverandering tot landbouweconomie, wordt aanbevolen toekomstige controles vollediger en op meer samenhangende wijze uit te voeren, en wel door de integratie van inzichten uit kwantitatieve studies (met name de milieuaspecten) en kwalitatieve studies (met name de sociaaleconomische aspecten) om zo een volledig beeld van de vraagstukken te verkrijgen.
- **Identificatie van de belangrijkste factoren voor het mobiliseren van ULC-gronden op basis van de input van de verschillende actoren van grondgebruik:** Een uitgebreide lokale beoordeling van de kansen en belemmeringen voor het gebruik van ULC-gronden is nodig om op een relevant bestuurlijk niveau een praktisch en realistisch beleid voor grondgebruik te kunnen formuleren, rekening houdend met de visie van meerdere actoren van grondgebruik op verschillende opties voor grondgebruik en bedrijfsmodellen. In toekomstig onderzoek naar ULC-gronden zouden voor elk specifiek geval de verschillende mobiliserende factoren expliciet geïdentificeerd moeten worden en de belangrijkste daarvan worden geprioriteerd.

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CURRICULUM VITAE

Chun Sheng Goh (also known as CS, and in Chinese 吴浚生), was born in Penang, Malaysia on the 20th of December, 1985. He graduated from the Universiti of Sains Malaysia, receiving both his B.Sc. (2009) and M.Sc. degree (2011) in Chemical Engineering. Over the course of his M.Sc. study, he specialised in the production of 2G biofuels from oil palm biomass (laboratory research), including a 3-month research visit at UHP 1 in France. He then won the Australian Endevour Research Fellowship and undertook a 6-month practicum at University of New South Wales in Australia. After completing his M.Sc., CS moved to the Netherlands where he worked as a researcher at Utrecht University, focusing on topics related to bio-economy, particularly on international trade, land-use and carbon impacts. Two notable projects are 'Monitoring of biomass and bioenergy trade flows in the Netherlands' with Netherlands Enterprise Agency (RVO) and 'Large-scale Investments in Food, Fibre, and Energy (LIFFE) Options for the Poor' with Centre of International Forestry Research (CIFOR). For the latter, he spent 4 months in Indonesia, mainly in Central Kalimantan, Bogor and Jakarta. In the same period of time, CS also played the role as the secretary of IEA Bioenergy Task 40, an international working group with the theme of 'Sustainable international bio-energy trade'. In addition to coordinating business meetings, he also managed dissemination activities (website, newsletters, publications, workshops and conferences). In July 2016, he returned to Malaysia and moved to a new position as Senior Executive (National Biomass Strategy) at Agensi Inovasi Malaysia.

CS is married with a son. He is fluent in English, Chinese (Mandarin, Min Nan/Hokkien, Cantonese) and Bahasa Malaysia. He can briefly communicate in Bahasa Indonesia and Dutch. CS can be reached by e-mail at gohchunsheng@hotmail.com.

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