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Review

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

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A B S T R A C T

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 carries out a meta-analysis of 12 existing studies, determines the different settings for the key functions embedded in consumption-based CSC-LUC studies and discussed their implications for policymaking. It identifies 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. This 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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1. Introduction

Carbon stock change as a consequence of land-use change (CSC-LUC) 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 socio-economic environment, new land-use policies or 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 is becoming 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 (Brandão et al., 2012; Creutzig et al., 2012). For example, it is possible to allocate certain CSC-LUC to vegetable oils in general assuming perfect substitutability (where the driver is the increased consumption of vegetable oils in general), while 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 differences in 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

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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.

2. Materials and methods

Two types of CSC-LUC approaches were defined. The *historical* approach (Fig. 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 (Fig. 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) (Fig. 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 Fig. 1B go in the opposite direction compared to Fig. 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.

2.1. Key functions

For communication, in this study the term 'function' is used to represent sets of methods, algorithms and parameters embedded in the methodological components illustrated in Fig. 1. Below are the eight key functions of consumption-based CSC-LUC studies identified based on the findings from existing reviews and studies[1] (see also Table S1 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).
- ***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 CSC-LUC. 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 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).
- ***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 1 shows their relevance to different methodological components. Based on these functions, the selected studies described in section 2.2 were reviewed and compared.

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 S1 (supplementary material). They were chosen because

[1] Brandão 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.

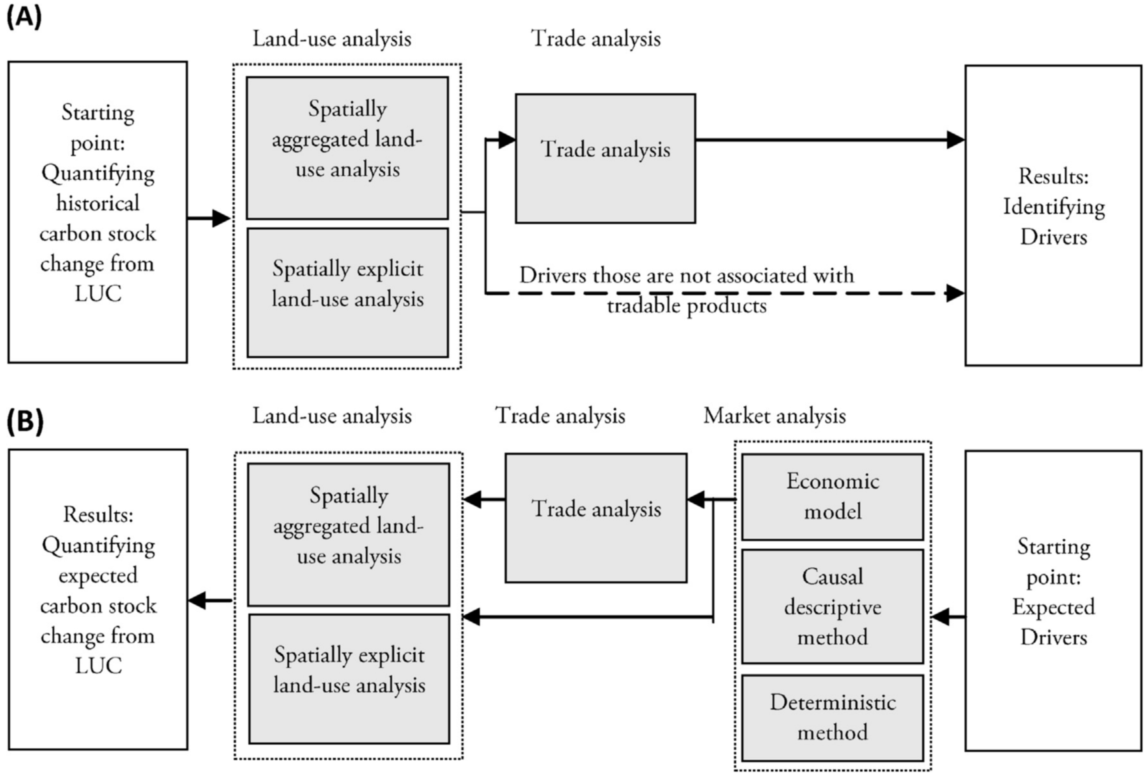


Fig. 1. Structures of (A) *historical* and (B) *projection* CSC-LUC approach (arrows indicate the direction of the workflow).

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.

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 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[2]), the indicators were further converted into the same unit (tCO_2/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 tCO_2/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

[2] gCO_2/MJ: gram carbon dioxide per megajoule; tC/tCPO: tonne carbon per tonne CPO.

Table 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	

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 Fig. S1 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. Results and discussions

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 Tables S3 and S4 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.[3]

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[4] (Romijn et al., 2013).

Land classification can also be done alternatively departing from the producer perspectives. Abood et al. (2014) classified land based on concessions granted by government, while Lee et al. (2013) 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.

3.2. 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. (2014) 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., 2016). One of

[3] 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).

[4] While FAO estimated 5 Mha of deforestation in Indonesia, other forest definitions made this estimate to be 18–27% higher.

Table 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) (Fig. S1).
	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		
Abood et al., 2014	Gross carbon dioxide emission from forest loss within industrial concessions in 2000–2010 (low)	1306.0	$MtCO_2$	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)	2345.0		
Lee et al., 2013 (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		
Harris et al., 2013 (Sumatera, Kalimantan, Papua)	Cumulative emission 2010–2050 expected to be caused by oil palm expansion (BAU)[a]	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
	Cumulative emission 2010–2050 expected to be caused by oil palm expansion (MRT)[a]	5.5		

	Cumulative emission 2010–2050 expected to be caused by oil palm expansion (RET)[a]	4.0		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 Fig. S1).
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).

[a] Business as usual (BAU), Moratorium on peat (MRT), Restoration of peat (RET).

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 biophysical 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. 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., 2013). 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.

3.4. 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., 2013) or (sub-)continents (e.g. Bauen et al., 2010). 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.

3.5. 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. (2014) (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. in press).

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. 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., 2014; Agus et al., 2013; Lee et al., 2013) 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).

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

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

No.	By land class	By product class	Full equation	Applications
(1)	$\frac{A_x}{A_{total}}$	$\frac{1}{P_x}$	$\overline{a}_x = a \cdot \frac{A_x}{A_{total}} \cdot \frac{1}{P_x}$	Used by some historical spatially aggregated studies (e.g. Saikku et al., 2012) based on share of land occupied.
(2)	$\frac{\Delta A_x}{\sum \Delta A_x}$		$\overline{a}_x = a \cdot \frac{\Delta A_x}{A_{total\ expansion}} \cdot \frac{1}{P_x}$	Used by some historical spatially aggregated studies (e.g. indirect LUC factor in Persson et al., 2014; Cuypers et al., 2013) based on contribution to land expansion.
(3)	–		$\overline{a}_x = \frac{a}{P_x}$	Can be applied on some historical spatially explicit studies (e.g. Agus et al., 2013) for estimating direct CSC-LUC.
(4)	–	$\frac{1}{P_x - P_{x,baseline}}$	$\overline{a}_x = \frac{a - a_{baseline}}{P_x - P_{x,baseline}}$	Used by projection studies.

Note:
x = the product(s) of interest.
$\overline{a}_x$ = 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).

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 3.9): 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).

3.7. 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 amortised 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., 2010) 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.

3.8. 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.

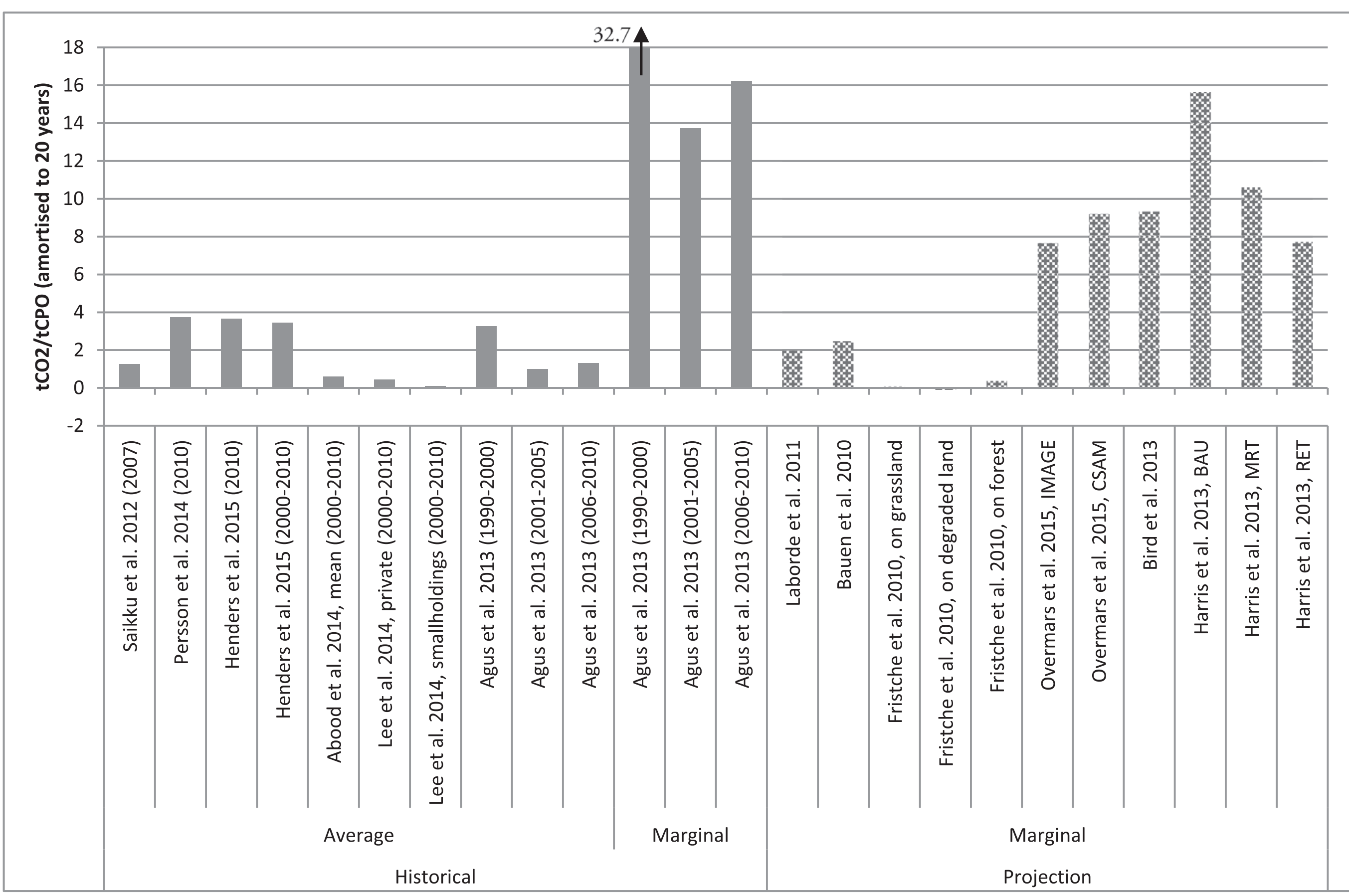
Second, trade flows can also occur at multiple orders - imported agricultural products may be re-exported. It is difficult to explicitly distinguish whether domestic products or imported products are (re-)exported. For example, Malaysia is not only a palm oil producer and exporter but also an importer (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., 2013). 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). 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 monitoring framework for (cross-sectorial) trade flows. 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., 2013).

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) (Fig. 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.



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

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

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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.
- 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.

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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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.08.055.

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