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Research article

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

Chun Sheng Goh [a], *, Birka Wicke [a], André Faaij [b], David Neil Bird [c], Hannes Schwaiger [c], Martin Junginger [a]

[a] Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3854 CS, Utrecht, The Netherlands
[b] University of Groningen, Blauwborgje 6, P.O. Box, 9700 AE, Groningen, The Netherlands
[c] JOANNEUM RESEARCH Forschungsgesellschaft mbH, Elisabethstrasse 18/II, A-8010, Graz, Austria

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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.

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

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* Corresponding author.
E-mail addresses: c.s.goh@uu.nl, gohchunsheng@hotmail.com (C.S. Goh).

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production gap. For example, in Brazil, pasture degradation due to inefficient land use followed by land abandonment has driven further pasture expansion into forests (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.

2. Materials and methods

This analysis consists of five major steps with three extensions with the workflows shown in Fig. 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., 2016 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 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 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 2.3). The CSC-LUC was then distributed across time based on a pre-defined temporal dynamics (section 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 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 2.6–2.8). The data collection and processing was described in Box S1 (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 S1). For comparison, the method was tested with the inclusion of peat emission in section 2.7.

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. The analysis would be repeated with two spatial settings, i.e. on a global and a regional scale, 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 S1 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.

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

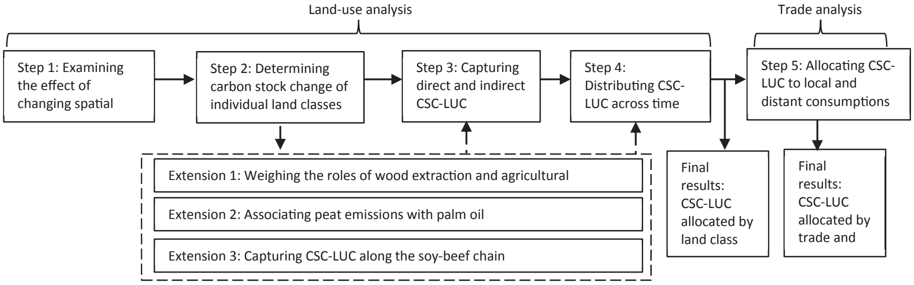


Fig. 1. Work flow of this study to allocate historical CSC-LUC to different drivers.

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 S2 (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 because 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., 2016). ‘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

$$\begin{aligned} \Delta A_{exp,x,t} &= 0 \\ \Delta A_{dis,x,t} &= \left|\Delta A_{x,t}\right| \end{aligned} \tag{1}$$

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.

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

$$\begin{aligned} \Delta A_{exp,UDL,t} &= 0 \\ \Delta A_{dis,UDL,t} &= A_{UDL,t-1} \end{aligned} \tag{2}$$

where.

X is the set of land classes;
‘F’ is ‘forest’; ‘D’ is ‘desert’; ‘OTH’ is ‘others’ (see also Table S2).

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:

$$\sum_{x} \Delta A_{x,t} = 0 \tag{3}$$

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 $\overline{C}_{x,t}$ every year to account for forest degradation.

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

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

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

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

Else

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

$$C_{loss,x,t} = A_{x,t-1}.\overline{C}_{x,t-1} - A_{x,t}.\overline{C}_{x,t} \tag{4}$$

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);
$\overline{C}_{x,t}$ is the average value of all carbon stock on one ha of x in a particular year (ktC/ha).

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., 2016). 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 S1). 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 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):

$$\Delta C_{exp,UDL,t} = \Delta A_{exp,UDL,t} \cdot \overline{C}_{F,t} \tag{5}$$

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

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

$$\Delta C_{exp,x,t} = C_{gain,x,t} - \frac{\Delta A_{exp,x,t}}{\Delta A_{converted,t}} \cdot \left(\sum_{x} C_{loss,x,t} - \Delta C_{exp,UDL,t} \right) \tag{6}$$

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).

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 and Chao, 2013; Purnomo, 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 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, Eq. (7) was employed to calculate total historical carbon stock change passed down by a land class:

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

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.

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

$$\Delta C_{direct\ historical,x,t} = 0 \tag{8}$$

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.

$$\Delta C_{historical\ pool} = \sum_{x} [\Delta C_{total\ historical,x,t} - \Delta C_{direct\ historical,x,t}] \tag{9}$$

Table 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.

$$\Delta C_{indirect\ historical,x,t} = \frac{\Delta A_{exp,x,t}}{\Delta A_{converted,t}} \cdot \Delta C_{historical\ pool} \tag{10}$$

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):

$$\Delta C_{combined,x,t} = \Delta C_{exp,x,t} \cdot h_0 + \Delta C_{direct\ historical,x,t} + \Delta C_{indirect\ historical,x,t} \tag{11}$$

$$\overline{\Delta C}_{combined,x,t} = \frac{\Delta C_{combined,x,t}}{P_{x,t}} \tag{12}$$

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).

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 S2 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 3.6). Crop-based liquid biofuel was an exception: biofuel was identified as a separate end-use (see Table S3), 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 Eqs. (13) and (14), respectively:

$$\Delta C_{combined\_domestic,x,t} = \overline{\Delta C}_{combined,x,t} \cdot D_{x,t} \tag{13}$$

$$\Delta C_{combined\_import,x,t} = \frac{\sum_r \overline{\Delta C}_{combined,x,r,t} \cdot E_{x,r,t}}{\sum_r E_{x,r,t}} \cdot I_{x,t} \tag{14}$$

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 S3), Eq. (13) and Eq. (14) were combined as Eq. (15):

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

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.

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., 2015). 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 S1), 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).

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.

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.

3. Results

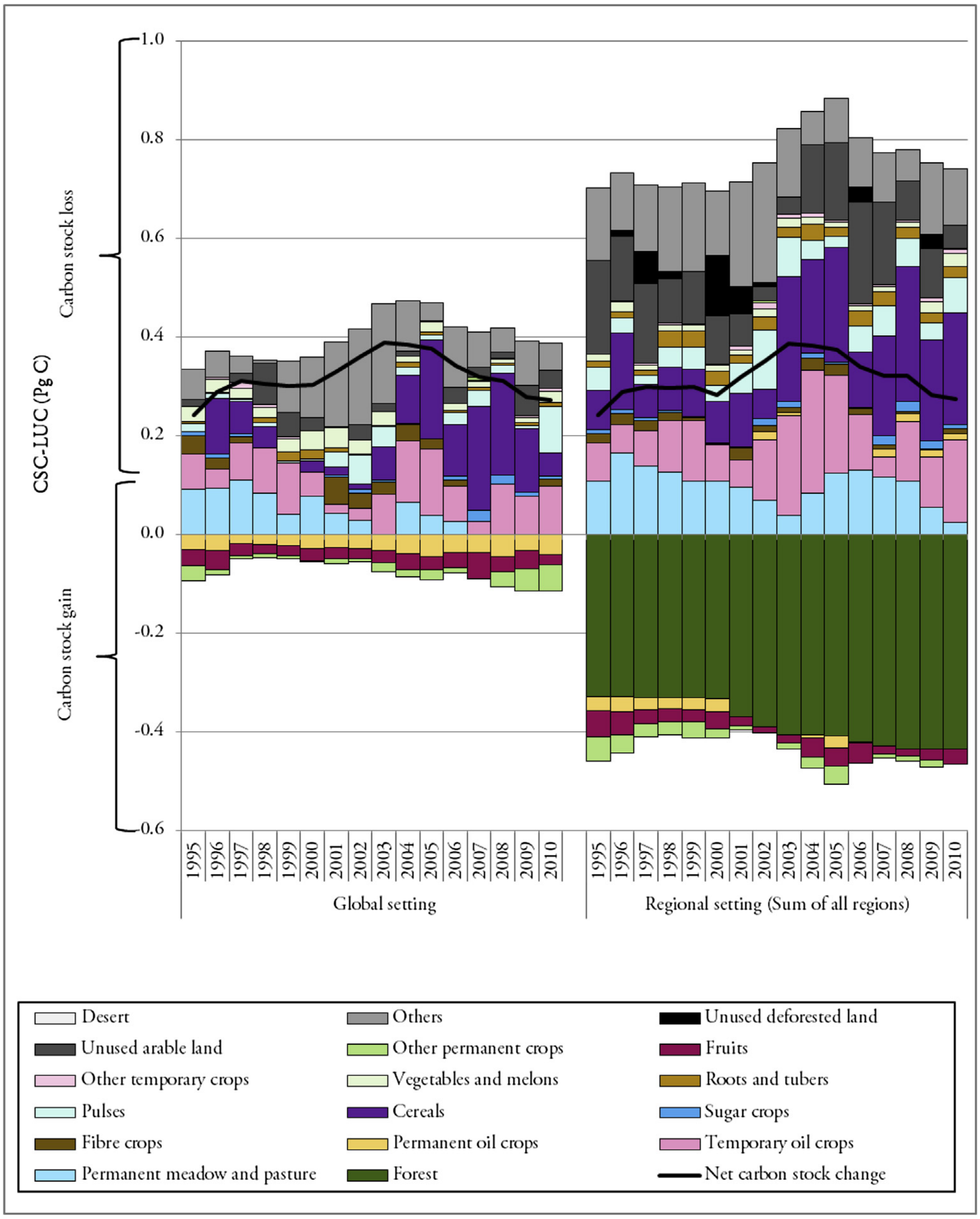
3.1. Allocation by land class

Fig. 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 (Fig. 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 (Fig. 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).

Fig. 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



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

Fig. 2. Time trend (1995–2010) of CSC-LUC allocated to land classes based on their expansion rates using the global and regional setting. Note: '+' and '-' represents carbon stock loss and gain respectively.

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.

3.2. Allocation by trade

Fig. 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

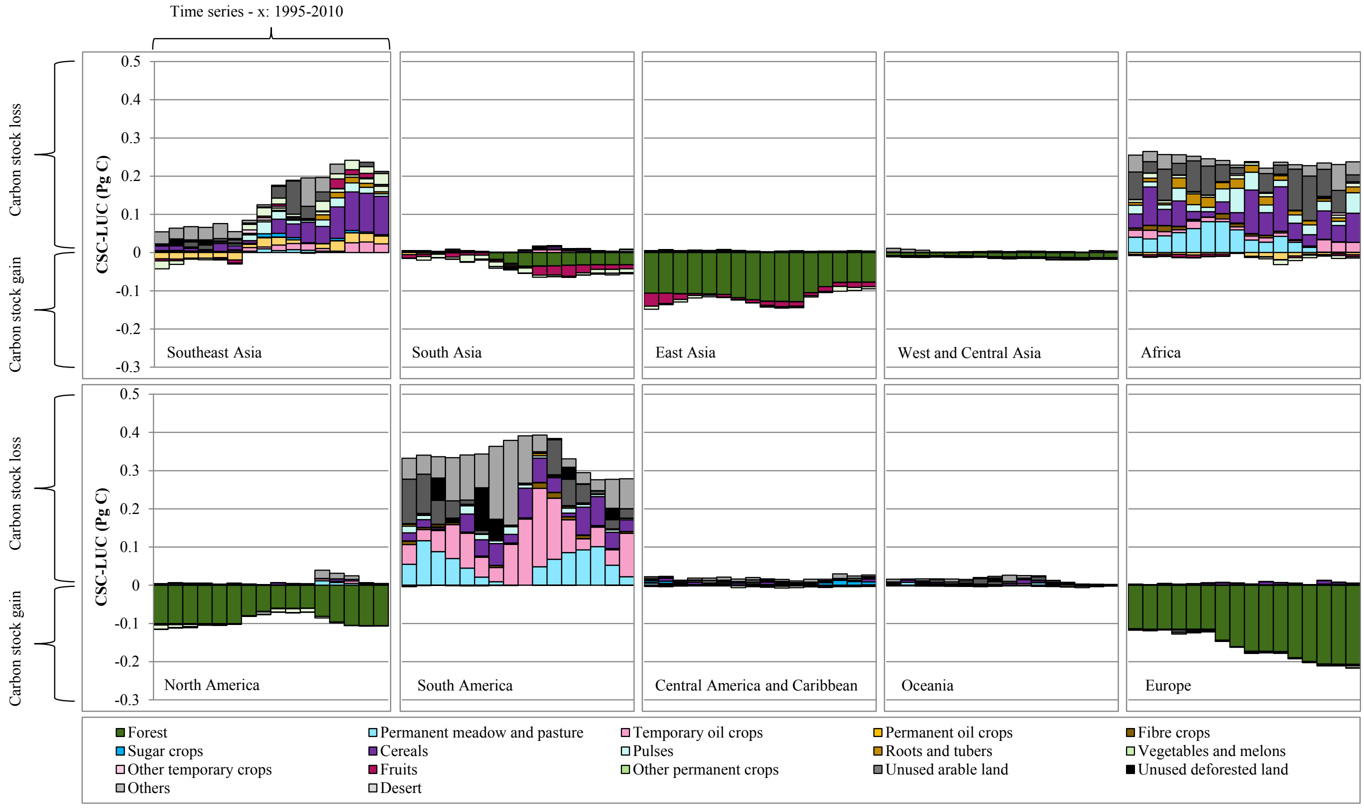


Fig. 3. Time trends (1995–2010) of CSC-LUC (y: Pg C) allocated to land classes based on their expansion rates using the regional setting.

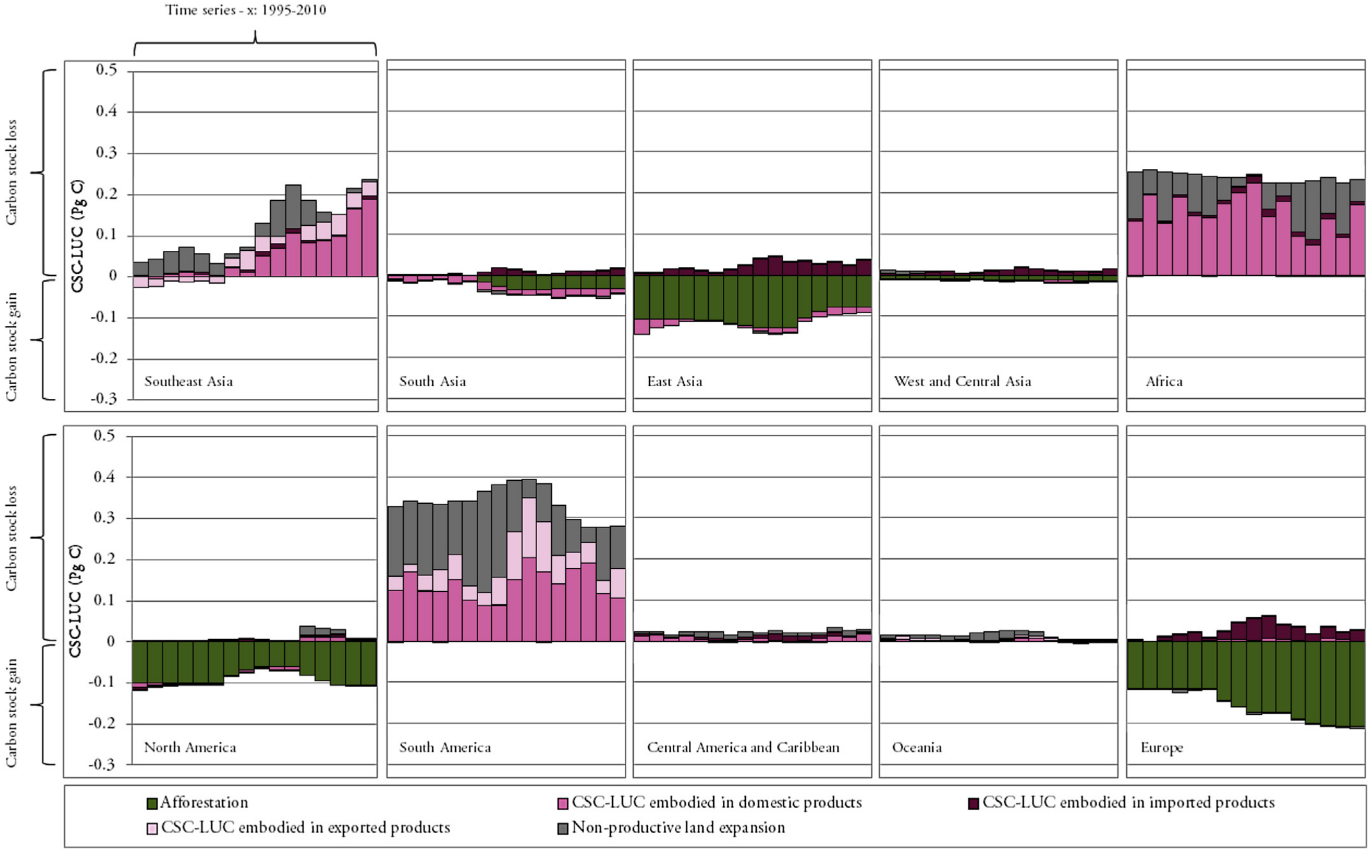


Fig. 4. Time trend (1995–2010) of CSC-LUC (y: Pg C) allocated to regional consumption with cross-border trade using the regional setting.

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.

3.3. Allocation by end-use

Fig. 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 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

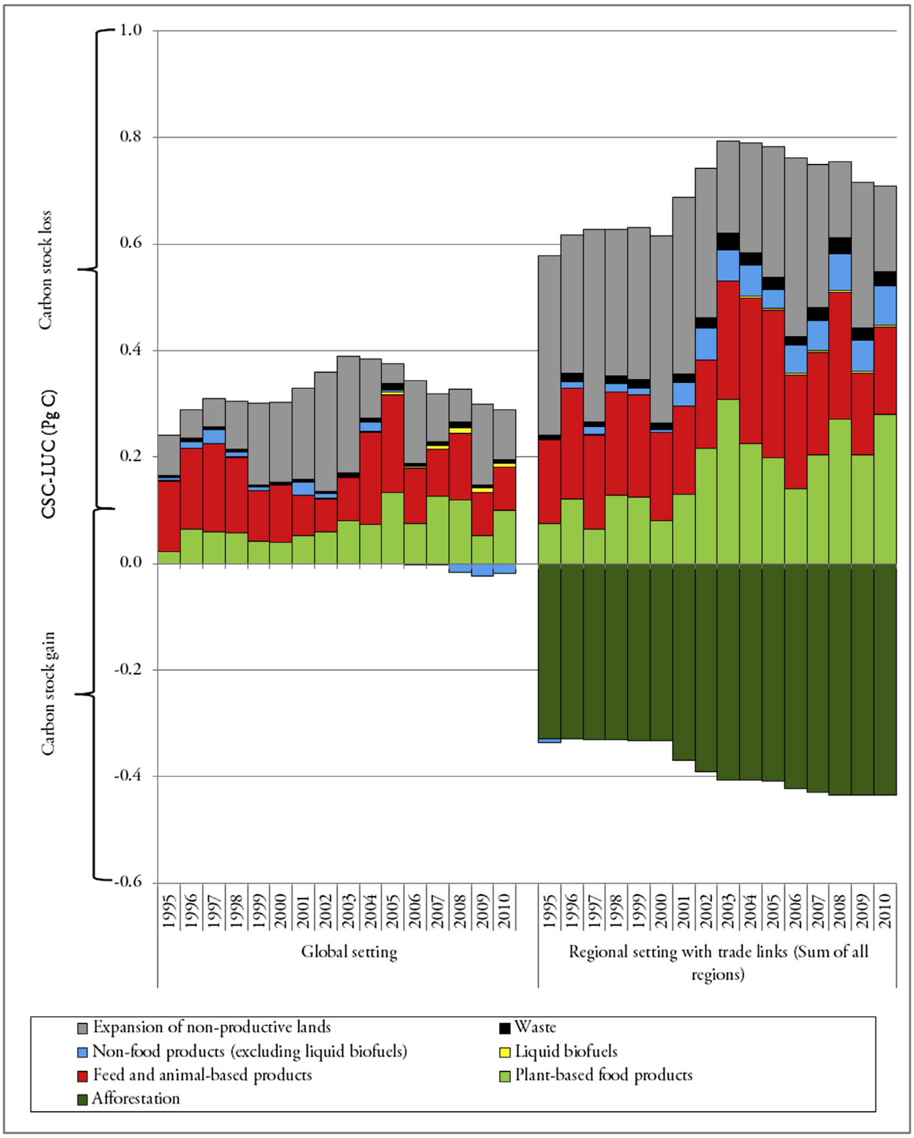


Fig. 5. Time trend (1995–2010) of CSC-LUC by regions and end-uses using the regional setting.

economically attractive.

Fig. 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 Fig. 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 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.

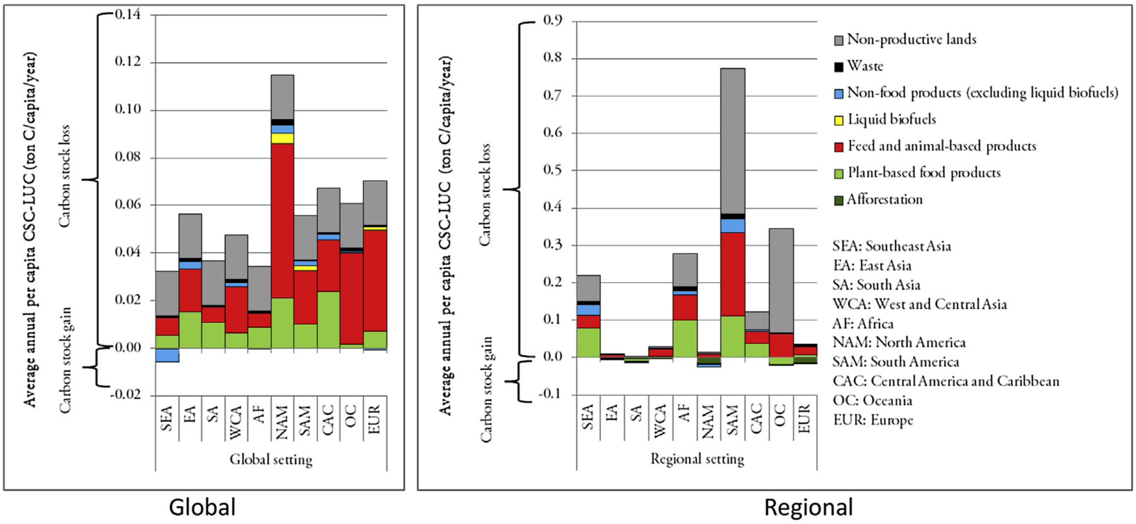
3.4. *Extension 1: allocation to wood products for the case of Southeast Asia*

Fig. 7 shows the results after re-adjustment of CSC-LUC using the two methods described in section 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 MtC/year and 3 MtC/year for method 1 and 2, respectively. In comparison, Henders et al. (2015) allocated about 20–90 MtC/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.

3.5. *Extension 2: allocation peat emission to permanent oil crops in Southeast Asia*

Fig. 8 illustrates how the addition of peat emission changed the results for 1995–2010. A top-up of about 50% of the CSC-LUC



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).

Fig. 6. Average annual per capita CSC-LUC by regions and end-uses using the global and regional setting for 1995–2010. Global Regional. 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).

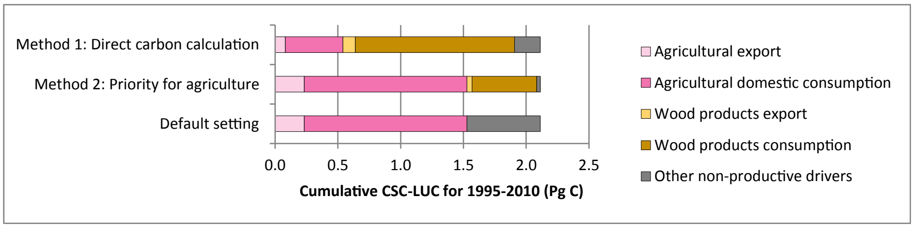


Fig. 7. Cumulative CSC-LUC re-allocated to agricultural product and wood products for the case of Southeast Asia in 1995–2010.

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.

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 S3. 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 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.

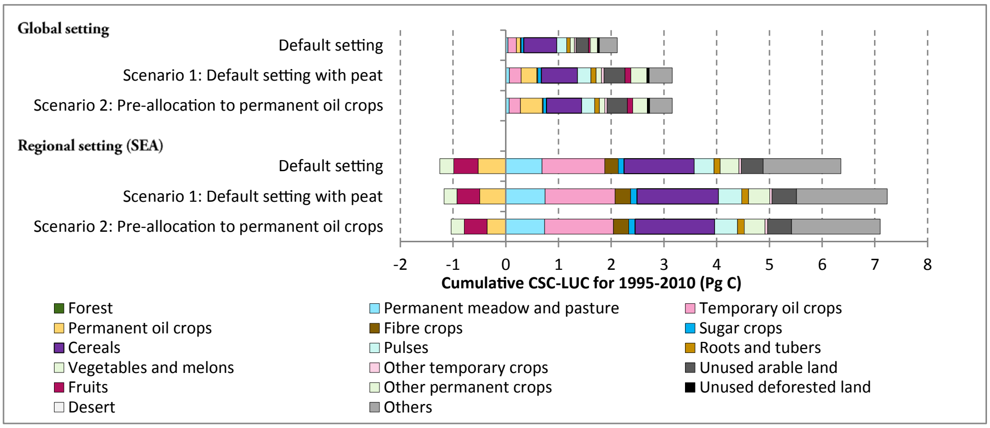
4. Discussions

4.1. *Methodological implications and limitations*

As described by Goh et al. (2016), 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.

4.1.1. *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



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

Fig. 8. Cumulative CSC-LUC allocated to different land classes in Southeast Asia adjusted with peat emissions for 1995–2010. Note: ‘+’ and ‘-’ represents carbon stock loss and gain respectively.

(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.

4.1.2. *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.

4.1.3. *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 generalized, 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.

4.1.4. *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.

4.1.5. *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.

4.1.6. *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 reexamine 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.

4.1.7. *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 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.

4.1.8. *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.

4.2. Data uncertainty

Data uncertainty is a major limitation for CSC-LUC studies. Ideally, data should be collected based on 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 (Qureshi 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.

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 have reiterated the outcome of the previous review (Goh et al., 2016), 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).

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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.2016.08.004.

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