White Paper:
Consideration of land use change in ecoinvent version 3.3

Method, Implementation and Illustration

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Table of content

1 Introduction

Land use in the agroforestry sector is one main source for anthropogenic GHG emissions. Approximately 30% of all anthropogenic GHG emissions between 1989 and 1998 could be allocated to land use activities (Robledo and Blaser, 2008). Land use change (LUC), i.e. the transformation of one land use type to another, is responsible for approximately two thirds of those emissions (Robledo and Blaser, 2008). Therefore, the optimization of land use activities plays a key role in reducing greenhouse gas (GHG) emissions.

Until 2007, emissions from LUC were rarely integrated into LCA calculations. However, the possibility of using bioenergy as a climate change mitigation measure has sparked a discussion of how to integrate emissions associated with land use change into Life Cycle Assessment (Robledo-Abad et al., 2016) and had a major impact on the methods of calculation. As shown by Mc Manus and Taylor (2015), LCA publications addressing the key word "land use" has more than decupled during the last ten years. Bearing this in mind, a solid and up-to-date modelling has high priority, not only for the assessment of biofuels but for all land-using activities.

Ecoinvent has considered emissions from LUC already since 2007 or version 2.2 (Jungbluth et al. 2007). The first approach did not follow an overarching accounting method, focused exclusively on soybean and oil palm and did not consider all relevant carbon pools. In 2011 a more comprehensive approach was developed (Thomas Nemecek, Schnetzer, and Reinhard 2014). However, while the approach was applicable to all crops, it was only implemented for the above mentioned key crops due to time restrictions. The integration of a part of the World Food Life Cycle Inventory Database (WFLDB) in 2016 then offered the opportunity for the further extension of the 2011 LUC accounting method.

This main goal of this white paper is to elaborate the LUC accounting method applied to ecoinvent v3.3. We first elaborate the methodological basis and central components of the new ecoinvent LUC model. Next, we show its implementation in the ecoinvent database. We proceed with a brief discussion of methodological differences between the LUC accounting methods in ecoinvent version 2.2, 3.2. and 3.3 and an illustration for selected crops. We conclude with a summary of limitations and advantages of the present method.

2 Method

2.1 The WFLDB adapted Blonk tool

The ecoinvent v3.3 LUC approach follows the approach of the WFLDB adapted Blonk tool[1], a "Microsoft Excel tool developed to support the computation of LUC emissions based on the PAS2050-1/ENVIFOOD protocol approach" (Nemecek et al., 2015). This tool has been developed by Blonk Consultants in 2013 and has been reviewed and approved by the World Resource Institute (WRI) for use in the GHG Protocol. It has been modified[2] by the WFLDB consortium to comply with WFLDB's requirements.

Basically the tool answers <u>how much</u> of <u>which type</u> of LUC is attributed to <u>a given</u> crop in <u>any</u> country? It uses **land use statistics** and a **carbon inventories** to address this questions.

- First, the tool **uses statistical data** from FAOSTAT for crop production and natural land areas in all countries from 1991 to 2010, as well as from country climates and soils types. A time period of 20[3] years is used to determine expansion or contraction in crop and natural areas. The same time period is applied for the amortization of the emissions, which is aligned with PAS 2050-1 and FAO guides for feed supply chains (LEAP).
- Secondly, it provides all **carbon inventories** required for the assessment of the corresponding transformation and occupation impacts.

Both, allocation of LUC and the carbon inventories for land transformation and occupation are used for the ecoinvent v3.3 LUC model.

The WFLDB adapted Blonk tool offers three different approaches related to data availability of the user. "All these approaches are described in the PAS 2050-1 published by BSI, and are made operational in this tool using various IPCC data sources.

1. "Country known; land use unknown": To provide an estimate of the GHG emissions from land use change for a crop grown in a given country if previous land use is not known. This estimate is based on a number of reference scenarios for previous land use, combined with data from relative crop land expansions based on FAOSTAT data.

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[1] Latest edition is "WDLDB-adapted Blonk 2014 direct-land use change-assessment-tool_2016-06-09a.xlsx". Available upon request to Quantis.

[2] The most important modifications are: separation of carbon bound in vegetation (VEG) and the soil (SOC), differentiation between primary and secondary forest, addition of land tenure module compliant with ecoinvent, addition of «shared responsibility» allocation approach, inclusion of SOC-related emissions from peat drainage, Inclusion of carbon capture when relevant, addition of N_2O emissions related to SOC degradation, consolidation of all LUC flows into a single sub-process.

[3] The time period always amounts to 20 years and is independent of the crop cycle.

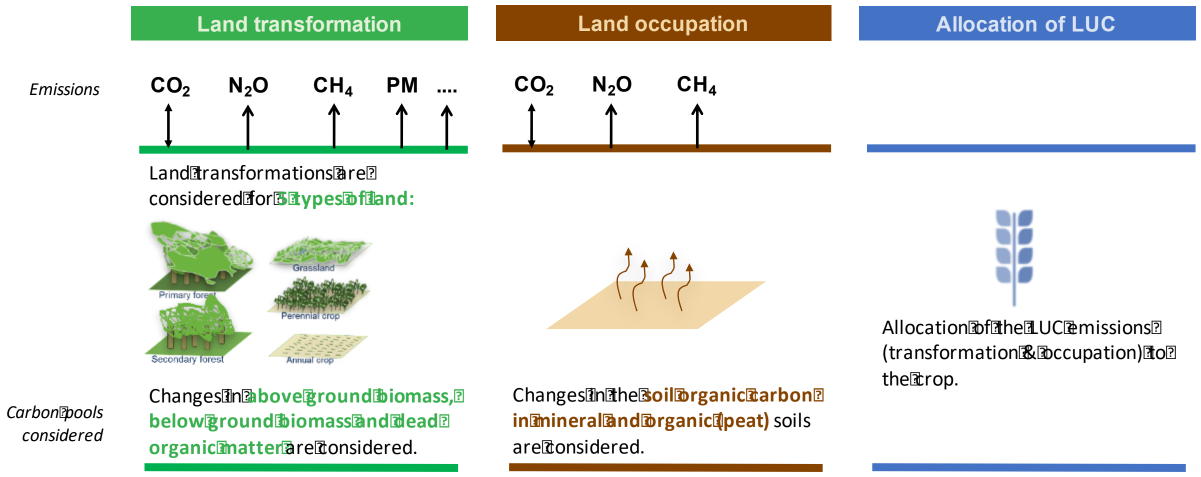
2. "Country & land use unknown": The calculation of an estimate of the GHG emissions from land use change when both the country of production and previous land is not known. A weighted average is determined based on FAO statistics, using the same methodology as in 1) for calculating the GHG emissions for each relevant country.
3. "Country & land use known": The calculation of GHG emissions of land use change when the previous land use is known."

The ecoinvent LUC model uses approach (1) for the calculation of the country-specific (local) land use change emissions and approach (2) for the computation of land use change emissions of crops with a GLO geography. Both approaches are country-centric, meaning that each country is treated as an autonomous island.

2.2 Application to ecoinvent v3.3

The consistent integration of greenhouse gas emissions associated with land use change in version 3.3 of the ecoinvent database is realized on the basis of mainly three components (see Figure 1).

- **Land transformation** activities model the transformation of 5 land types—primary forest, secondary forest, grassland, perennial land and annual land—to two land uses—annual or perennial crop. The transformation activities model the carbon stock changes in living and dead biomass (loss or accumulation of carbon dioxide).
- **Land occupation** activities model the changes in soil organic carbon, i.e., in mineral and organic soils (peat), which results from the occupation of already transformed land. Note, that land occupation does not refer to the elementary flow—inventoried for the purpose of biodiversity assessments—but exclusively refers to carbon related losses and gains resulting from the occupation of land which are modeled explicitly in the form of land use change activities.
- The **allocation of LUC** determines how transformation and occupation impacts are allocated to a specific crop.



Land transformations are considered for 5 types of land:

Changes in above ground biomass, below ground biomass and dead organic matter are considered.

Changes in the soil organic carbon in mineral and organic (peat) soils are considered.

Allocation of the LUC emissions (transformation & occupation) to the crop.

Figure 1: Central components of the ecoinvent LUC model.

In the following, we describe these components and their interaction in more detail.

2.2.1 Emissions associated with land transformation

The ecoinvent v3.3 LUC model considers the transformation of 5 land types—primary forest, secondary forest, grassland, perennial land and annual land— to two target land uses—annual or perennial crop. That is, 10 generic land transformation activities are distinguished. Figure 1 shows these land transformation activities modeled in ecoinvent v3.3.

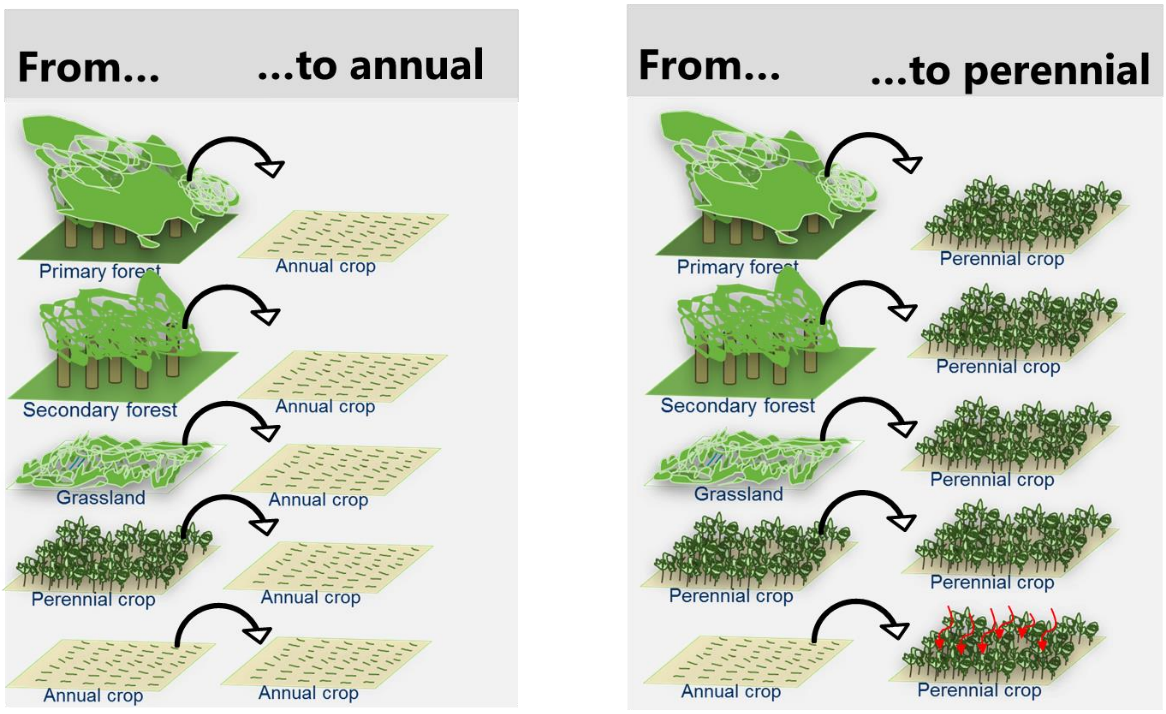


Figure 2: Land transformations considered in the ecoinvent v3.3 LUC approach. The red arrows indicate the accumulation of carbon due to the higher biomass carbon stock value of the new land use.

The generic activities are adapted to represent appropriately the carbon pools for each country of relevance.

Four kinds of carbon pools are considered: aboveground biomass (AGB), belowground biomass (BGB) dead organic matter (DOM) and soil organic carbon (SOC). Carbon stored in vegetation is denoted as VEG (vegetation carbon) and includes AGB and (when relevant) also BGB and DOM.

The values for carbon stocks in biomass (VEG) are taken from different sources.

- For primary and secondary forests, default carbon stock values are taken from the Global Forest Resource Assessment of the FAO (FAO, 2010). The vegetation carbon stock of forest in the reference situation is selected based on the country. Additionally, data on litter & dead wood is provided, and added to the reference carbon stock.
- For all other land transformations, carbon stock values are based (directly or indirectly) on the IPCC Agriculture, Forestry, and Other Land use (FOLU) report (IPCC, 2006). The carbon stock values for perennial crops are crop specific and are taken from Annex V to Directive 2009/28/EC (European Commision 2010).

The carbon pools of one and the same transformation activity vary across climate region. Therefore, the impact associated with the transformation of one hectare of primary forest will be different in Brazil than in Malaysia. Consequently, these transformation activities are always country-specific, i.e., they reflect the impact for a particular geography. Table 1 shows how changes in vegetational carbon pools are considered.

Table 1: Changes in carbon pools considered. Based on (Nemecek et al., 2015).

Carbon pools	**Land transformations**				
	From primary forest	From secondary forest	From grassland	From annual crop	From perennial crop
	Natural areas		Land already in use		
AGB	20% burned / 80 % emitted by decay		100 % emitted by decay. Net carbon capture may occur in certain cases (and is taken into account)		
BGB					
DOM			Ignored		

For land transformation from primary and secondary forest, it is assumed that 20% of the vegetation is burned. The remaining AGB, BGB and DOM is assumed to decay. In other words, 100% of the carbon stored in the vegetation is transferred into the atmosphere. This approach is in line with the default (tier 1) assumption of the IPCC (IPCC, 2006). The transformation activities also consider the interventions required for the clearing of the area—chainsaw and building machines.

No harvest or burning of biomass is considered for the land transformation from grassland. Instead, 100% of the carbon in vegetation is transferred into the atmosphere. DOM is considered negligible.

Likewise, no burning of biomass is considered for the transformation of perennial to annual cropland (Nemecek et al., 2015). The average difference in carbon stock is assumed to be transferred into the atmosphere as CO_2. However, the reverse transformation, i.e., the transformation from annual to perennial cropland, causes a re-accumulation of carbon.

2.2.2 *Emissions associated with land occupation*

Impacts recorded in the land use change activities result from changes in SOC. We distinguish between mineral and organic (peat) soils (Table 2).

Table 2: Changes in soil organic carbon pools considered. Based on (Nemecek et al., 2015).

Carbon pools	**Prior land use**				
	Primary forest	Secondary forest	Grassland	Annual crop	Perennial crop
	Natural areas		Land already in use		
SOC mineral	SOC changes are computed according to prior land use and management practice (IPCC, 2006). Net carbon capture may occur in certain cases (and is taken into account)				
SOC organic (peat)	Peat drainage emissions according to country-specific peatland cover (Joosten, 2010) and default emissions values (IPCC, 2013)				

The reference values for the soil organic carbon (SOC) stocks in mineral soils are based on country-specific soil and climate types and refer to (IPCC, 2006). Changes in SOC stocks in mineral soils are dependent on (i) the land use (perennial/tree crop, long term cultivated, paddy rice, etc.),(ii) the tillage practice (full, reduced, etc.) and (iii) the input level (low, medium, high without manure, etc.) (IPCC, 2006 Table 5.5 for cropland). For example, the transformation from annual to perennial cropland will, all other factor equal, increase the SOC stock, i.e., cause an accumulation of carbon dioxide. Furthermore, if the tillage intensity on cropland is reduced and the input level increases, accumulations in SOC stock will be even larger. Changes in management practices (tillage and input level) can occur without any land transformation, i.e., within the same land use category. However, these changes are only accounted for if there is a permanent change in management according to IPCC (Nemecek et al., 2015). In grassland systems, SOC can be increased by improving the management practice (nominally managed, moderately degraded, etc.) and the input (medium and high) (IPCC, 2006 Table 6.2 for grassland).

The annual emissions associated with organic soils are based on the average peatland cover in a particular country (Joosten, 2010) and default emission factors given by the (IPCC, 2013). Emissions associated with peat oxidation are carbon dioxide, methane and dinitrogen monoxide.

Losses in SOC are accompanied by mineralization of N, which in turn leads to emissions of N_2O. The emission factor for N_2O from mineralized N is 1%. The C:N ratio is taken from (IPCC, 2006) and amount to “15” for the conversion of forest or grassland to cropland and “11” for the conversion of cropland.

2.2.3 *Allocation of LUC*

The Allocation of LUC module determines how much of which type of LUC is attributed to a given crop in any country. The allocation of LUC happens on the basis of the area of land transformed per hectare of crop cultivated. In general, the WFLDB adapted Blonk tool offers two kinds of allocation paradigms. Both are country-specific (Nemecek et al., 2015).

1. Crop-specific approach (default): Allocates LUC to the crop of interest based on its **relative expansion** within a specific country and time period. In cases where the crop area in the country and its corresponding total land type area have increased in the considered time period, and if the area occupied by the natural ecosystem decreased during the same time period, the direct LUC is considered to be potentially relevant. Otherwise, LUC from a given land type is irrelevant to the life cycle inventory (Nemecek et al., 2015).
2. Shared-responsibility approach: Allocates LUC to the crop of interest based on its relative proportion of (total land) **area occupied**. In cases where the crop area in the country is greater than zero and if the area occupied by natural ecosystem decreased during the same time period, LUC impacts are potential relevant. That is, all crops carry the burden *in proportion to their occupied area*. As the expansion or decrease in area is not of relevance in this approach—only the occupied area counts—even crops with decreasing area will be assigned a LUC impacts.

Both allocation paradigms are implemented in ecoinvent v3.3 but, while only the crop-specific approach is "activated", ecoinvent could produce a database version with the shared-responsibility approach. A "parameter" is used to switch the amount of land use change allocated to each crop, i.e., either the proportion of relative expansion or the proportion of occupied area is used.

3 Implementation of the LUC model

3.1 Implementation for local crops

Figure 3 shows the general LUC structure in ecoinvent v3.3. There are five steps of modeling LUC and the corresponding activities and market datasets are described in the following sub-sections.

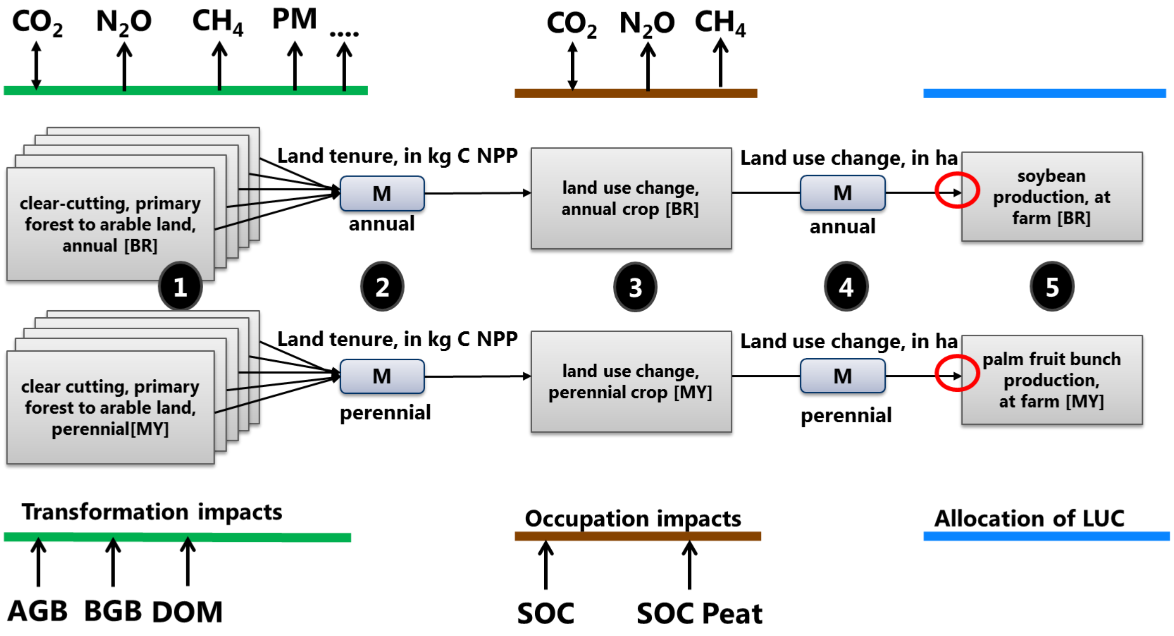


Figure 3: Land use change modeling structure associated with an annual and a perennial crop. Please, check the change report (Moreno-Ruiz et al., 2016) for a list of all activities and products created, classified by geography.

3.1.1 Activities modeling the component "Land transformation"

Country specific land transformation activities model all transformation impacts associated with the conversion of one type of land to another. All transformation activities produce land tenure measured in kg C net annual primary productivity (NPP) and not square meters. We introduced NPP in EI3.0 as a common currency to account for the annual productivity of land in different geographies and to account for the productivity added by intensification (which cannot be accounted for with an area based unit). The annual kg C NPP values are region-specific (with regions denoting sub-continental areas such like Eastern Asia, Southern Asia, etc.) and refer to Haberl et al. (2007). As all land transformation activities in a particular country rely on the same NPP value, the use of land tenure instead of m^2 does not cause any difference in area intensity among the land transformation activities, i.e., all land use change activities will, ultimately, link to the same area transformation, i.e., namely 500 m^2 per year (see Box 1).

BOX 1: Land tenure as an intermediate flow

The ecoinvent land transformation activities record all interventions associated with the provision of 1 kg C NPP/y in the given country. Consider the example of Hellland, a hot place with a low annual productivity of 0.2 kg C NPP/m^2 or an area intensity of 5 m^2/kg C NPP. Figure 4 illustrates, for this particular geography [HL], how the initial demand of 1 ha land use change, perennial crop translates into a final land transformation of 500m^2 on the basis of three operations. In order to provide one hectare of land use change, perennial crop in HL, 100 kg C NPP are required annually. For each country, the amount of land tenure input can be computed on the basis of two operations: an annualization by 20 years and the conversion to kg C NPP/y using the m^2/ kg C NPP, e.g. 5. The amount of final land transformation associated with the 100 kg C NPP can be computed by converting the annual kg C NPP to m^2 using the HL specific annual area intensity, i.e., 5 m^2/ kg C NPP. This results in the 500 m^2, i.e., 1/20th of the area of one hectare.

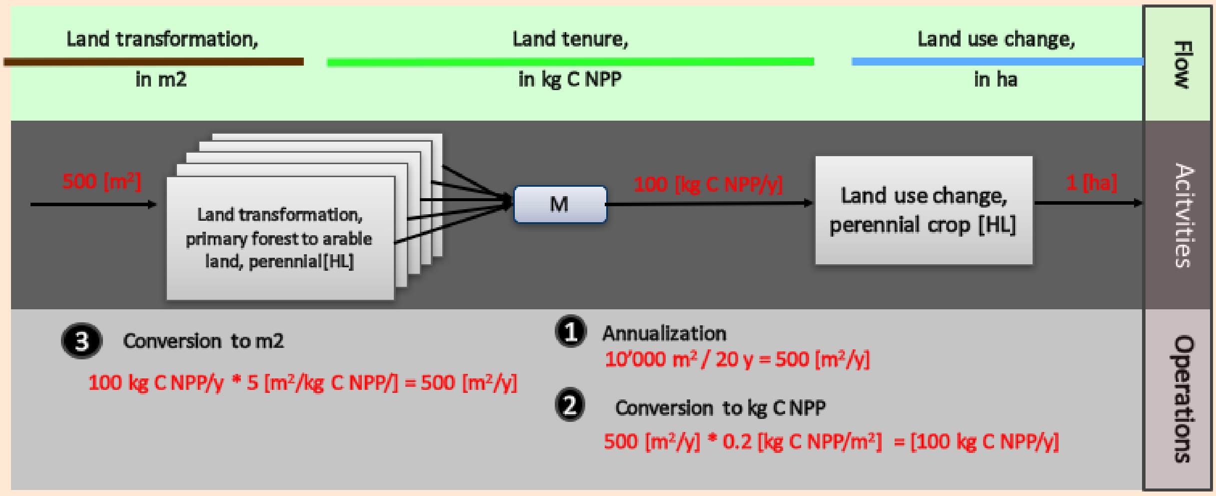


Figure 4: Artificial example for the transformation of a land use change flow [in ha] to the resulting land transformation flow [in m2] using land tenure as an intermediate flow [kg C NPP].

As all land transformation activities in a particular country rely on the same NPP value, the use of land tenure instead of m^2 does not cause any difference in area intensity among the land transformation activities. That is, the the supply of 1 ha of land use change will always result in 500 m^2 (10'000 m^2 / 20 y) of land transformation irrespective of the land use type (annual or perennial) and the country. The only varying component is the actual mix of land transformation required to supply the average ha of land use change. That is, the land tenure flow has, at least currently, no influence on the final land transformation. However, the use of land tenure might become relevant in the future for the consideration of intensification and difference in productivity between countries, e.g., in the framework of an iLUC model.

We distinguish between two land tenure products: land tenure, annual cropland and land tenure, perennial cropland in order to maintain the crop type based allocation of land use change impacts implemented in the WFLDB Blonk tool. With crop-type based allocation we refer to the fact that a perennial crop will only bear the impacts associated with the expansion of perennial crops and an annual crop will only bear the impacts associated with the transformation associated with annual crops.

Only the land transformations of relevance are modeled. For example, in Brazil the land transformations of grassland to annual or perennial land tenure has no relevance and is therefore not modeled. In Colombia, the land transformations of relevance are the transformation of perennial to perennial cropland and the transformation of annual to perennial cropland, while the transformation of primary and secondary forest and grassland is not of relevance.

Table 3 shows the exchange flow structure for all potential transformation activities modeling the production of land tenure, annual crops.

Table 3: Exchange flow structure for all transformation activities modeling the production of land tenure, annual crops. Each transforming activity produces one kg of land tenure, annual crops. "x" indicates if the exchange flow is considered in a particular land transformation activity.

Exchange flows	**Land transformations**				
From	Primary forest	Secondary forest	Grassland	Annual crop	Perennial crop
To	Annual crop				
Energy, gross calorific value, in biomass, …	x	x	x		x
Occupation, construction site	x	x	x		x
Transformation, from …	x	x	x	x	x
Transformation, to arable land, unspecified use	x	x	x	x	x
Diesel, burned in building machine	x	x			x
Power sawing	x	x			x
Carbon dioxide, from soil or biomass stock	x	x	x		x
Specific emissions from biomass burning (Nitrogen oxides, Propane, etc.)	x	x			

All land transformation activities include the elementary exchanges "Transformation, from …" and "Transformation, to …". For example, an activity modeling the transformation of primary forest to arable land would record: "Transformation, from forest, primary (non-use)" and "Transformation, to arable land, unspecified use". The productivity in kg per m^2 can be derived from the amount of land transformation needed to produce one kg of C NPP, i.e., the "Transformation, to …" flows recorded in the transformation activity. The transformation to annual crops does not cause any accumulation of biomass carbon because the carbon pools are typically lower than the other land use types. Therefore, the exchange flow "carbon dioxide, to soil or biomass stocks" is not considered.

Table 4 shows the exchange flow structure for all transformation activities modeling the production of land tenure, perennial crops.

Table 4: Exchange flow structure for all transformation activities modeling the production of land tenure, perennial crops. "x" indicates if an exchange flow is considered.

Exchange flows	**Land transformations**				
From	Primary forest	Secondary forest	Grassland	Annual crop	Perennial crop
To	Perennial crop				
Energy, gross calorific value, in biomass, primary forest	x		x		
Occupation, construction site	x		x		
Transformation, from …	x	x	x	x	x
Transformation, to permanent crop	x	x	x	x	x
Diesel, burned in building machine	x	x			
Power sawing					
Carbon dioxide, from soil or biomass stock	x	x	x		
Carbon dioxide, to soil or biomass stock			x	x	
Specific emissions from biomass burning (Nitrogen oxides, Propane, etc.)	x	x			

The transformation between "annual to annual land" and "perennial to perennial land" are always modelled explicitly but cause no LUC impacts. The only exchange flows recorded are "Transformation from annual (or perennial) cropland" and "Transformation to annual (or perennial) cropland".

The transformation of annual to perennial and the transformation of grassland to perennial crops can cause an accumulation of carbon in the form of vegetation. This accumulation is considered by means of the elementary exchange "carbon dioxide, **to** soil or biomass stock" which is assessed with a negative characterization factor of -1 in the LCIA methods of relevance.

3.1.2 Land tenure market

The country and crop type specific land tenure market mixes the available land tenure flows according to their production volume. The proportion of each land tenure flow represent the relative expansion of the particular crop category—annual or perennial cropland—into natural areas and land already in use obtained from the WFLDB adapted Blonk tool. The WFLDB Blonk tool uses statistical data from FAOSTAT for crop production and natural land areas in all countries from 1991 to 2010 to determine this expansion. The market produces a land tenure mix which represents the average land transformation impacts for a particular country and crop-type.

3.1.3 "Land use change" activities (3)

The country and crop type specific land use change activity uses the average (country and crop type specific) land-tenure mix as an input and adds the occupation impacts. That is, the loss/gain in soil organic carbon in mineral and organic (peat) soils associated with the country- specific land tenure mix.

The land use change activities represent the country and crop type- specific land transformation and occupation impacts on a per hectare basis. However, the impacts—associated with land transformation and occupation—actually refer to 500 m^2 or 1/20th of a hectare due to the amortization period of 20 years. This implies that the amount of land tenure input is always equivalent to 500 m^2. For example, dividing the amount of land tenure inputs in the land use change, perennial crop activity in Colombia (405.5 kg C NPP) by the NPP for South America (0.811 kg C NPP/m^2) yields exactly 500 m^2. That is, an output of 1 ha land use change always relates to land tenure inputs of 500m^2. The amortization in the land use change activity eases the allocation of land use impacts to a particular crop. The amount of land use change in ha required can be linked to crops by simply multiply the area requirement of a particular crop with the relative expansion of a particular crop.

Table 5 shows the exchange flow structure for the land use change activities.

Table 5: Exchange flow structure for all land use change activities. "x" indicates if an exchange flow is considered. (x) indicates the size of

Exchange flows	**Land use change, …**	
	…annual crop	…perennial crop
Energy, gross calorific value, in biomass	**(x)**	**(x)**
Land tenure, arable land, measured as carbon net primary productivity, annual crop	**x**	
Land tenure, arable land, measured as carbon net primary productivity, perennial crop		**x**
Methane, biogenic	**(x)**	**(x)**
Dinitrogen monoxide	**x**	**x**
Carbon dioxide, from soil or biomass stock	**x**	**x**
Carbon dioxide, to soil or biomass stock		**x**

For example, the land tenure flow in Colombia is mainly provided by the transformation of annual to perennial cropland. The corresponding gain in soil organic carbon is considered via the elementary exchange "carbon dioxide, to soil or biomass stock" in the respective land use change activity. The presence of methane emissions indicates that emissions from peat oxidation are considered.

3.1.4 "Land use change" markets (4)

A local market for land use change provides the country specific average land use change to all crops of relevance in the country, i.e., all crops in a country can link to this market. The market does not add any other data but simply acts as a connection between the average land use change activity of a particular country and crop type and any potential crop activity– two transforming activities can only link via a market.

3.1.5 Allocation of LUC (5)

The allocation of LUC to crop activities is realized by integrating the country and crop type specific market for land use change. Any crop whose area expanded during the last 20 years links to the respective local market in proportion to their relative change in area. A perennial crop (pears, sugarcane, palm fruit bunch, etc.) links to the perennial land use change market. An annual crop (soybean, wheat, etc.) links to the annual land use change market. For example, the area cultivated with soybeans in Brazil increased by 52%[4] from 1991-2010. Therefore, the cultivation of one hectare soybean in Brazil will consume 0.54 ha of the annual land use change market for Brazil. The area cultivated with oil palm in Malaysia increased by 56% from 1991-2010. Therefore, the cultivation of one hectare palm fruit bunches in Malaysia will consume 0.56 ha of the perennial land use change market for Malaysia. The WFLDB Blonk tool uses statistical data from FAOSTAT for the computation of the relative area expansion. If the relative change in area is zero or lower than zero, no land use change is assigned, i.e., the crop will not link to the local land use change market.

3.2 Implementation for global crops

Because LUC are country specific, crop activities with a global coverage cannot relate the LUC structure presented above. Instead, emissions from land use change associated with land transformation and occupation, both are added directly to the cop activity. The "Country & land use unknown" function of the WFLDB adapted Blonk tool is used to calculate GHG emissions from land use change when both the country of production and previous land is not known. The size of the emission depends on (i) the relative crop expansion in all countries of the crop during the last 20 years and (ii) the corresponding, country specific land transformations. The current results are based on the average FAOSTAT data (harvested area) of 2009-2011 and 1989-1991. The weighted average is used which takes into account relative difference in crop expansion into primary forest, secondary forest, grassland, perennial and annual land.

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[4] The relative expansion can be obtained by dividing the crop specific expansion in hectare during the last 20 years, e.g. 11.9 million ha for soybean, by the total crop area cultivated in 2010, e.g. 23 million ha.

4 Comparison with LUC accounting in EI2.2, EI3.2 and ecoinvent v3.3

4.1 Methodological differences

GHG emissions from LUC were already considered in EI2.2 for selected crop activities, i.e. soybean production in Brazil and palm fruit bunch production in Malaysia. However, as already highlighted in Nemecek et al. (2014), "the attribution of LUC followed no overarching method, focused only on the deforestation of rain forests and did not take account of all relevant carbon pools".

Consequently, the update to EI3.2 focused on the development of a coherent and consistent basis for the consideration of emissions from LUC. That is, a "reproducible method for the attribution of LUC to the relevant crop activities that allowed the consideration of all carbon pools for all relevant natural land transformations" (Nemecek et al., 2014). The new LUC modelling was applied to three crops: soybean and sugarcane production in Brazil and oil palm cultivation in Malaysia, since these datasets were present in the database and affected by the LUC according to the criteria set.

Table 6 contrasts the main differences between these and the present (v.3.3) approach.

Table 6: Integration of LUC emissions across ecoinvent version 2.2, 3.2 and 3.3.

	V2.2	**V3.2**	**V3.3**
Approach	Ad-hoc	(1) Determine relative crop expansion on the basis of FAOSTAT data (2) All of the "new" (expanded) land is related to a mix of land transformations, determined according to *specific studies.*	(1) Determine relative crop expansion on the basis of FAOSTAT data (2) All of the "new" (expanded) land is related to a mix of land transformations, determined on the basis of FAOSTAT data.
LUC allocation	Assumptions & Statistics	Specific studies / Assumptions	FAOSTAT data (country averages)
Analysis period	Inconsistent	20 years, 1990-2009 (three year average)	20 years, 1991-2010 (three year average)
Amortization period	Crop cycle (palm fruit bunch) 5 years (soybean)	20 years	20 years
Applied to	Soybean (BR) and Palm fruit bunch (MY)	Soybean (BR), Sugarcane (BR) and Palm fruit bunch (MY)	All crops with a non-Swiss geography. The detailed list of datasets with LUC can be found in the change report on the ecoinvent webpage (see table 10, page 34).
Carbon pools considered	AGB	AGB, BGB, DOM, SOC in mineral and organic (peat) soils	AGB, BGB, DOM, SOC in mineral and organic (peat) soils
Land transformations considered	Primary (rain) forest to arable land	Primary forest, secondary forest, shrubland and grassland to arable land.	Primary forest, secondary forest, grassland and perennial land to annual arable land. Primary forest, secondary forest, grassland and annual land to perennial crops according to FAOSTAT.
Source for carbon values	IPCC 2001	Relative crop expansion: FAOSTAT (2012).	Relative crop expansion: FAOSTAT (2012).

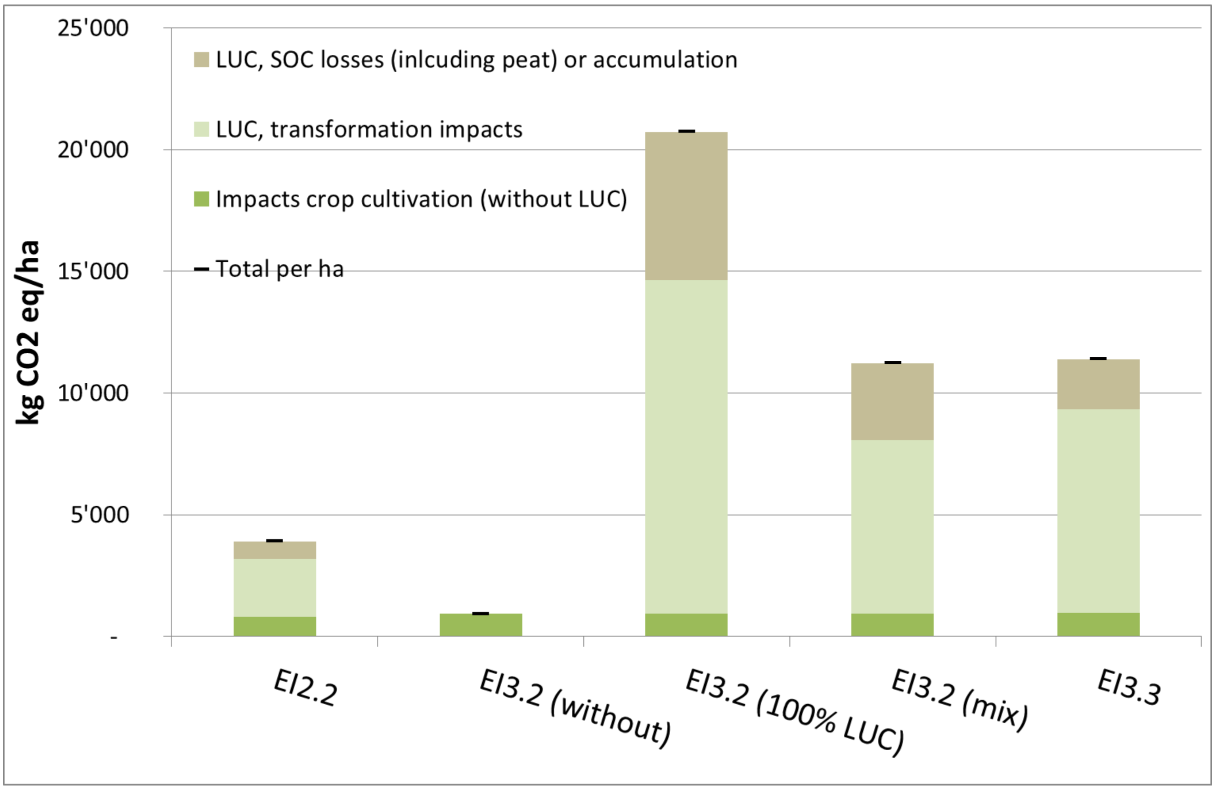
		Carbon stock values according (IPCC, 2006). Peat emissions and attribution according to (Page et al., 2011).	Carbon pools values according to (IPCC, 2006). Peat attribution according to average coverage in a particular country. Peat emissions according to (Joosten, 2010) and (IPCC, 2013). In addition, crop specific peat emissions are added for Malaysia according to (Page et al., 2011).

4.2 Illustrative Examples

The following analysis compares LUC impacts of selected crops across ecoinvent versions in order to highlight and discuss the detailed reasons for differences. We compare soybean, sugarcane and oil palm cultivation in version 2.2 (EI2.2), version 3.0-3.2[5] (EI3.2) and version 3.3 (ecoinvent v3.3). We assess environmental impacts using IPCC 2007 GWP100a.

4.2.1 Soybean production in Brazil

Figure 5 shows the climate impacts per hectare of soybean across version 2.2, version 3.2 and version 3.3 of the ecoinvent database.



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[5] The LUC accounting in EI3.0-EI3.2 did not change. Therefore, we don't make a detailed comparison between these versions but simple use the most recent version (EI3.2) as a basis for comparison.

Figure 5: Climate impacts (kg CO_2 eq/ha) of soybean cultivation in Brazil throughout different versions of ecoinvent. The increase in crop cultivation impacts from EI2.2 to EI3.2 is a result of updated emissions models.

Ecoinvent v2.2: In EI2.2, a 5 year period (1999–2004) was used to assess the LUC impacts associated with soybean (Jungbluth et al., 2007, p. 131). During this time period, the area cultivated with soybeans expanded by more than 8 million hectares. This represents the largest annual increment recorded to date. The corresponding LUC was calculated with 32% transformed from tropical rain forest, 52% transformed from shrubland and 16% transformed for annual cropland (Jungbluth et al., 2007, p. 131). Nevertheless, the LUC impacts are rather low in comparison with EI3.2 and 3.3, respectively. The reasons are twofold. First, the impacts associated with the transformation of shrubland were not considered, i.e. accounted for with zero. Second, the transformation of rainforest modeled by the activity "provision, stubbed land" did not consider BGB and DOM which typically contributes about half of the total carbon pool associated with primary forests.

Ecoinvent v3.2: In EI3.2, the average LUC was modelled by the market-based integration of two activities: soybean production without (without LUC) and soybean production with LUC (100% LUC). The former represents soybean production already cultivated 20 years ago, i.e. without LUC, while the latter activity represents soybean production on recently transformed land which was transformed during the last 20 years. 50% of the soybean area was already cultivated in 1990, whereas 50 % were added in the following 20 years, 12% at the expense of rain forest and 38 % at the expense of shrubland (Nemecek et al., 2014). The corresponding average (EI3.2 (mix)) impacts associated with soybean cultivation in Brazil can be calculated with 11'000 kg CO2 eq. The main reason for this increase in comparison with EI2.2, is the consistent inclusion of all carbon pools, i.e. the amount of C stored in AGB, BGB, DOM and SOC.

Ecoinvent v3.3: In ecoinvent v3.3, the impact of soybean cultivation amount to roughly 11'000 kg CO2 eq. The application of the WFLDB LUC methodology does not cause large changes even though the land transformations considered are different. In the present case, soybean production increased by 52%[6] during the last 20 years (1991-2010). According to FAOSTAT statistics, the expansion of annual crops affected mainly forest areas (65%), and already cultivated perennial land (6%)[7]. This causes large land transformation impacts of 8'300 kg CO_2 eq. per hectare but also losses in soil organic carbon stocks (2'000 kg CO_2 eq. per hectare).

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[6] The difference of 2% results from the fact that the WFLDB LUC methodology operates on a more recent time window (1991-2010) than the EI3.2 approach (1990-2009).

[7] The remaining 30% represents a transformation from annual to annual land.

4.2.2 Sugarcane production in Brazil

Figure 6 shows the climate impacts per hectare of sugarcane cultivated across version 2.2, version 3.2 and version 3.3 of the ecoinvent database.

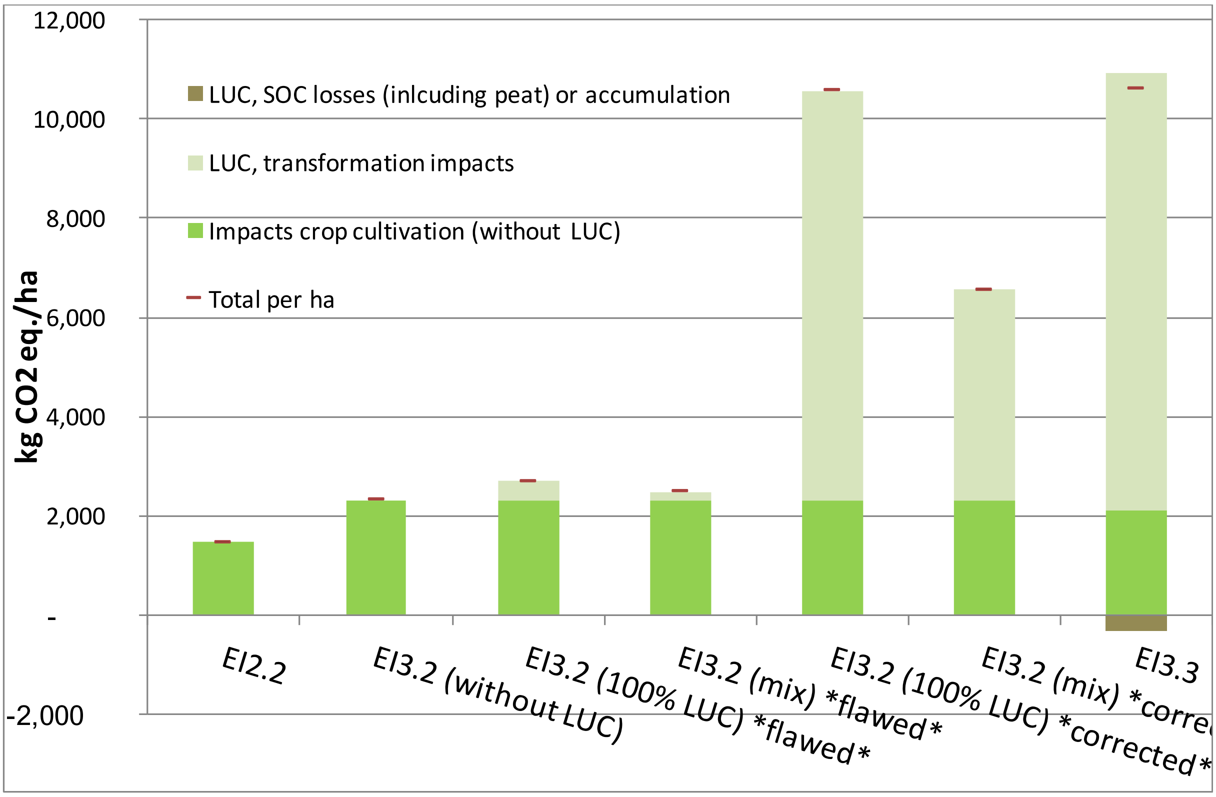

Figure 6: Climate impacts (kg CO$_2$ eq/ha) of sugarcane cultivation in Brazil throughout different versions of ecoinvent. The increase in crop cultivation impacts from EI2.2 to EI3.2 is a result of updated emissions models.

Ecoinvent v2.2: In EI2.2, 0.97% of the used land is calculated as transformed from shrubland (Jungbluth et al., 2007, p. 150) while the remainder is transformed from land already in use. Since no transformation impacts were assigned to shrubland, the LUC impacts of sugarcane cultivation in EI2.2 are zero.

Ecoinvent v3.2: In EI3.2, the average LUC is modelled by the market-based integration of two activities: sugarcane production without LUC and sugarcane production with 100% LUC. The latter activity models the LUC caused by the expansion of sugarcane cultivation of 51% during the last 20 years. In the absence of causal studies, this increase was assumed to be cultivated fully at the expense of shrubland (Nemecek et al., 2014). The appropriate integration of both activities via the local sugarcane market in Brazil represents the average (mix) of sugarcane production in Brazil. The annual production of sugarcane production in Brazil and the expansion of sugarcane during the last 20 years was used to determine the proportion from each sugarcane activity. However, the allocation of LUC was a factor 20 to low because the amortization was applied twice. Consequently, the LUC impacts of sugarcane was too low (EI3.2 (100% LUC) *flawed*) and likewise was the average mix representing sugarcane production in Brazil

(EI3.2 (mix) *flawed*). When correcting for this error, the average (mix) impacts of sugarcane production in Brazil amount to 7’000 kg CO_2 eq (EI3.2 (mix)). As mentioned above, this results from the assumption that the full increase in sugarcane cultivation during the last 20 years occurred at the expense of shrubland.

Ecoinvent v3.3: In ecoinvent v3.3, the average impact of sugarcane production in Brazil increases to 10’600 kg CO_2 eq. per hectare. In general, the reason for this increase can be attributed to the fact that the applied WFLDB LUC methodology is more conclusive than the former approach. Basically, it assigns LUC emissions on the basis of the (perennial) crop specific change in area and the country specific land transformations recorded during a 20 year time period. In the present case of Brazil, sugarcane production increased by 54%[8] during the last 20 years. The expansion of perennial crops affected mainly forest areas (primary and secondary, 83%) but also already cultivated annual cropland (15%) (FAOSTAT 2013). The former causes a large land transformation impact (8’800 kg CO_2 eq) while the latter causes a minor increases in SOC stocks, i.e. is responsible for the accumulation of SOC (-300 kg CO_2 eq). The release of SOC associated with the land transformation of forest areas is zero because the perennial land use will not affect the mineral SOC.

4.2.3 Oil palm production in Malaysia and Colombia

Figure 7 shows the climate impacts per hectare of oil palm cultivated in Malaysia across version 2.2, version 3.2 and version 3.3 of the ecoinvent database. It also shows the impacts of oil palm cultivation in Indonesia and Colombia for version 3.3.

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[8] The difference of 3% result from the fact that the WFLDB LUC methodology operates on a more recent time window.

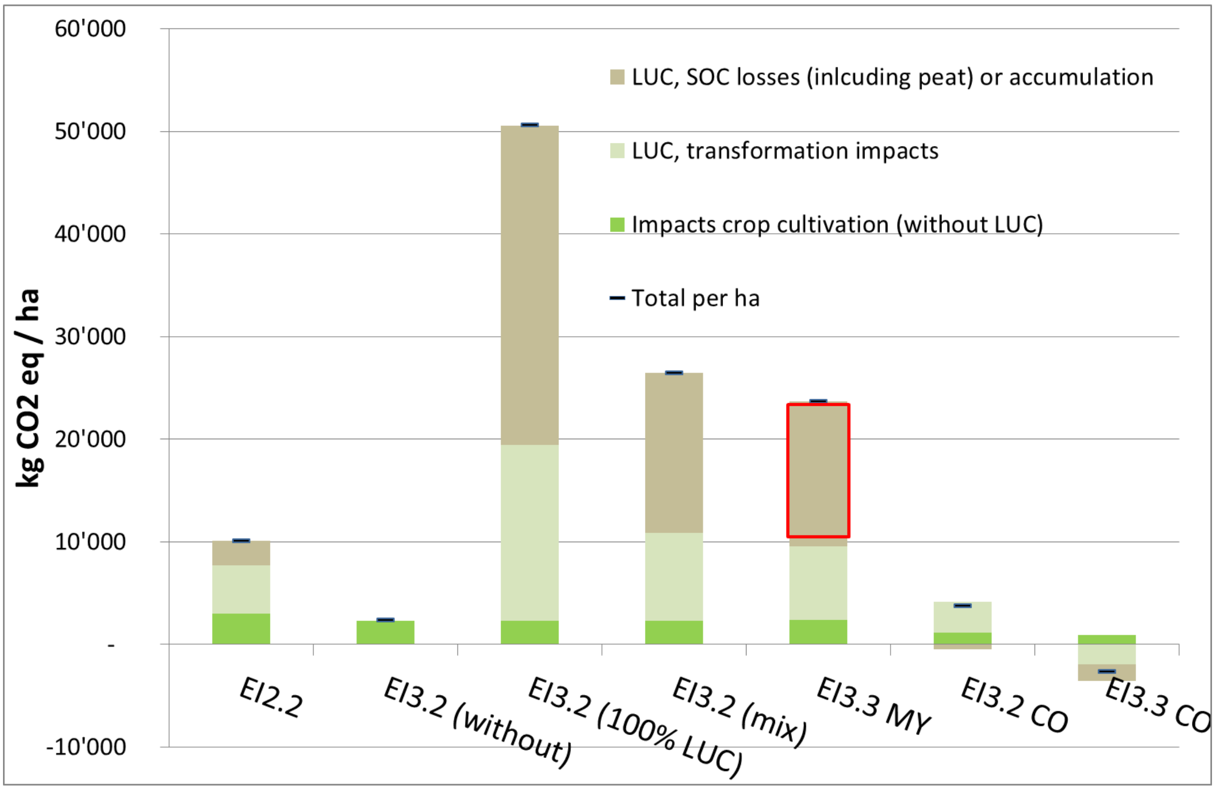

Figure 7: Climate impacts (kg CO_2 eq/ha) of oil palm cultivation in Malaysia throughout different versions of ecoinvent. The red square shows the emissions from peat oxidation which are added.

Ecoinvent v2.2 MY: In EI2.2, due to the large increase in oil palm cultivation, 100% of the area cultivated with oil palm in Malaysia was assumed to be transformed from tropical rain forest (Jungbluth et al., 2007, p. 88). The transformation from tropical rainforest is calculated with the process "provision, stubbed land, MY" which accounts for 119'000 kg CO_2 eq per hectare. The corresponding loss of SOC is calculated with 59'000 kg CO_2 emissions (Jungbluth et al., 2007, p. 88). The emissions from LUC are allocated over a time period of 25 years. The annualized emission from the transformation of primary forest amount to 4'800 kg, the annualized emissions from SOC to 2'400 kg CO_2 eq. per hectare. The total LUC impacts are rather low given the worst case assumption of 100% LUC from rain forest. The reason is mainly that emissions from peat oxidation were not considered. In addition, the transforming activity (provision, stubbed land, MY) did not consider BGB and DOM which typically holds about half of the total carbon stored in a primary forests.

Ecoinvent v3.2 MY: In EI3.2, the average LUC was modelled by the market-based integration of two activities: oil palm production without (without LUC) and oil palm production on land transformed within the past 20 years (100% LUC). 50% of the oil palm area was already cultivated in 1990, whereas 50 % were added in the following 20 years, 56% at the expense of primary forest (of which half is on peat land) and 44 % at the expense of perennial land which cause no LUC impacts (Nemecek et al., 2014). These land transformation were modeled according to Reinhard et al. (2007). The corresponding average (EI3.2 (mix)) impacts associated with oil palm cultivation in Malaysia can be calculated with 26'400 kg

CO_2 eq. The main reason for this increase in comparison with EI2.2, is the consistent inclusion of all transformation impacts, i.e. the loss of C stored in rain forests in the form of AGB, BGB, DOM which contributes with almost 8’500 kg CO_2 eq. per hectare, and all losses in SOC, i.e. particularly the oxidation of peat which contributes with almost 15’500 kg CO_2 eq. per hectare and year.

Ecoinvent v3.3 MY: In ecoinvent v3.3, the impact of oil palm cultivation in Malaysia amounts to roughly 24’000 kg CO_2 eq. per hectare. The area cultivated with oil palms in Malaysia increased by 56%[9]. With regard to land transformation, this expansion affected mainly perennial land (45%), secondary forest (42%), primary forest (11%) and annual cropland (2%). The average transformation impacts decrease to 7’200 kg CO_2 eq. per hectare, mainly because of the large proportion of secondary forest that wasn’t considered in EI3.2. With regard to land occupation, the sole application of the WFLDB LUC methodology would cause a large decrease of LUC climate impacts to roughly 10’000 kg. The LUC emission from SOC, i.e., mainly peat oxidation, would decrease significantly from almost 15’500 kg to 600 kg. This has two main reasons. First, the annual emission factor for wetlands used in the WFLDB adapted version of the Blonk tool is roughly 5 times lower than the emission factor given by Page et al. (2011). Secondly, peat emissions are computed as a country-average and not specifically for the area occupied by oil palm. Therefore, less than 3.5% of the overall land transformation affects peat land. However, Page et al. (2011, p. 18) indicates that the total area of oil palm plantations on peatland in Malaysia cover 0.53 million ha in 2010.[10] Assuming that all of the peat drainage happened during the focused time period, this means that roughly 23% of the overall land transformation in Malaysia affects peatland. As both, annual emission factor and the proportion of peatland affected by land transformations are specifically reflecting on oil palm cultivation in Malaysia, we use this information to complement the LUC impacts associated with the WDFLDB approach. Considering the annual emission factor of 106’000 kg CO_2 eq per ha and the expansion of oil palm during the last 20 years (56%) the annual peat emissions amount 14’000 kg CO_2 eq per ha. (see red rectangle in Figure 7).

Ecoinvent v3.3 CO: The oil palm plantation in Colombia shows a negative climate impact, i.e., -2’700 kg CO2 eq. Both, emissions from land transformation and emissions from SOC are negative. Although this might appear counterintuitive, other studies show the same result pattern (Castanheira et al., 2014; Castanheira and Freire, 2016). Oil palm cultivation in Colombia increased by 46% from 1991-2010. The land transformations are dominated by the transformation of annual to perennial cropland (72%) while the remainder (28%) represents transformation from perennial to perennial cropland which is accounted for with zero impacts. This land transformation pattern causes negative emissions because carbon stocks of oil palm plantation are generally higher than the carbon stock of the former, annual cropland. In

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[9] The difference of 6% results from the fact that the WFLDB LUC methodology operates on a more recent time window.

[10] And a “total area of 1.2 million ha are anticipated to be opened by the year 2020” (Page et al., 2011, p. 18).

addition, SOC impacts are negative because the mentioned transformation pattern increases SOC. However, it has to be kept in mind that replacing agricultural crops might cause indirect land use changes, which can increase the pressure on natural ecosystems indirectly.

5 Discussion

The requirements for the integration of emissions from LUC into a specific LCA study are quite different than the requirements for the integration into a background database. While the former has to use very specific LUC activities for the context under study, the latter primarily requires representative average LUC activities that facilitate a consistent consideration of emissions from LUC on a global scale. Overall, the main challenge for a background database such as ecoinvent is the integration of emissions from LUC across all land using activities with one consistent method. Even though the advancements shown in this article are a step in this direction, it's important to highlight some central starting points for the further improvement of the ecoinvent LUC accounting method:

- Allocate LUC not only to crop-producing but to all land-using activities: There is a need for a more comprehensive model that can be applied not only to crop producing but all kind of land using activities such as meat production, forestry, buildings and infrastructure. To date, emissions from LUC associated with agriculture are rather overestimated, simply because other drives are not considered appropriately.
- Country-centric perspective should be complemented with more change-oriented approaches: The country-centric perspective inherent to the present LUC model assigns emissions from LUC exclusively according to the LUC patterns within a country. That is, cause-effect relations are established exclusively within the boundary of a particular country[11]—a large loss of forests in country A can only be allocated to agricultural activities within country A[12]. However, the approach is not consistent with the change-oriented consequential system model since crop trade between countries and corresponding leakage cannot be considered.
- Complement the backward looking with a forward-looking approach: The current approach assigns LUC according to the past
- …

However, despite of these limitation, the consideration of LUC in a background database was never as consistent and complete than today. In this regard, the main advantage of the present approach is that it provides a framework and the data for consistently integrating LUC into all crop-producing activities. The modular structure facilitates a detailed tracing and analysis of the sources of emissions from LUC and can be easily switched on and off or adapted to the specific needs of the LCA practitioner. Furthermore, the structure allows the seamless integration of new LUC activities since new crop activities

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[11] Generally, cause-effect relations could be established on various scales, i.e., at the level of sites, city districts, counties, countries.

[12] The two available approaches—crop-specific and shared-responsibility—just take up a different stance of how country internal LUC patterns are allocated.

can immediately link to the existing activity for land use change (if other crops are already available for the country of the new crop activity).

6 Conclusion

The accounting of LUC has developed rapidly throughout the last decade. While largely ignored until 2007, it is now an integral part of many LCAs in the agricultural domain and increasingly considered in many background databases. However, the methodological developments have not converged so far, and the landscape of available accounting methods is still expanding, both in terms of data (improve temporal and spatial resolution) but also in terms of choices, i.e., more choices regarding the scale for establishing cause-effect relations (globe, country, county, plot–level) and the available allocation-paradigm (change-oriented or attributional and backward looking or forward looking). Ecoinvent will closely observe the further developments of this "landscape" in order to identify important elements for the improvement of LUC accounting throughout the database.

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8 Glossary

Direct and indirect land use change

“Direct and indirect LUC are often distinguished. Direct land use change can be defined as a change directly related to the history of the piece of land occupied. Indirect land use change can be defined as a change that appears in a different area than the direct land use as a direct consequence.” (Nemecek et al., 2015).

Above ground biomass (AGB)

“All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds, and foliage” (IPCC, 2006).

Below ground biomass (BGB)

“All biomass of live roots. Fine roots of less than (suggested) 2mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter” (IPCC, 2006).

Dead organic matter (DOM)

Consists of dead wood and litter.

Dead wood

“Includes all non-living woody biomass, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps, larger than or equal to 10cm in diameter (or the diameter specified by the country)” (IPCC, 2006) .

Litter

“Includes all non-living biomass with a size greater than the limit for soil organic matter (suggested 2mm) and less than the minimum diameter chosen for dead wood (e.g., 10cm), lying dead, in various states of decomposition above or within the mineral or organic soil” (IPCC, 2006).

Soil organic carbon (SOC)

“Organic carbon in mineral and organic soils (including peat) to a specified depth chosen by the country and applied consistently through the time series. Live fine roots of less than 2mm (or other value chosen by the country as diameter limit for below-ground biomass) are included with soil organic matter where they cannot be distinguished from it empirically.” (IPCC, 2006)