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A framework for modelling indirect land use changes in Life Cycle Assessment

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ABSTRACT

Around 9% of global CO_2 emissions originate from land use changes. Often, these emissions are not appropriately addressed in Life Cycle Assessment. The link between demand for crops in one region and impacts in other regions is referred to here as indirect land use change (iLUC) and includes deforestation, intensification and reduced consumption. Existing models for iLUC tend to ignore intensification and reduced consumption, they most often operate with arbitrary amortisation periods to allocate deforestation emissions over time, and the causal link between land occupation and deforestation is generally weakly established. This paper presents the conceptual framework required for a consistent modelling of iLUC in Life Cycle Assessment. It reports on a novel and biophysical iLUC model, in which amortisation is avoided by using discounted Global Warming Potentials (GWPs). The causal link between demand for land and land use changes is established through markets for land's production capacity. The iLUC model presented is generally applicable to all land use types, crops and regions of the world in typical LCA decision-making contexts focusing on the long-term effects of small-scale changes. The model's strengths and weaknesses are discussed.

1. Introduction

Approximately 9% of global carbon emissions in 2011 originated from land use changes (LUC) (Le Quéré et al., 2012). Often, these emissions are not addressed in Life Cycle Assessment (LCA) because the causal link between land use and deforestation is not well understood and because there is a lack of consensus on how to establish this link. Given that a significant part of global GHG emissions has traditionally been excluded from LCA, their inclusion may significantly change the results for some products. Furthermore, increased demand for crops is met not only by deforestation but also through cropland intensification and reduced consumption at other consumers.

Several attempts to estimate LUC emissions in LCA have been done. As demonstrated in Section 1.1, the variability of results of these studies is significant. We assess that this is mainly due to the absence of a common framework for determining the indirect effect of land use via LCA modelling. The main purpose of this paper is to provide a conceptual framework for this as a basis for a novel biophysical model. An example of the operationalization of the model is provided in Schmidt and Muñoz (2014, chapter 3.5) where the model is quantified with inventory data. Further, examples of the use of the model on agri-food products are available in Dalgaard et al. (2014) and Schmidt (2015). The new model divides the causal link from land use to its effects into manageable building blocks. Each of these blocks is flexible for inclusion of different modelling assumptions and data inputs, and is open for adaptation to new scientific evidence. The model is generally applicable to all land use types (cropland, grassland, forest and other) and to all regions of the world. The model only addresses long-term changes in supply caused by changes in demand. Hence, short-term effects on prices and subsequent price-elasticity effects are not included.

There are two types of land use changes: direct land use changes (dLUC) and indirect land use changes (iLUC). Both dLUC and iLUC are caused by the use or occupation of land; land use (LU). In this paper, dLUC are defined as those changes that occur on the same land as the land use, while iLUC are defined as the upstream life cycle consequences of the land use, regardless of the purpose of the land use. Examples of dLUC include changes in soil carbon content due to a certain cultivation practice, while examples of iLUC can be

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deforestation and cropland intensification that take place somewhere else than the land use. iLUC effects have previously been referred to as competition effects (Lindeijer et al., 2001).

1.1. Approaches for estimating iLUC

Several methods have been developed for estimating iLUC and associated GHG emissions. Although, the purpose of this paper is not a detailed comparison of our method with other models that have been developed for the same purpose, an overview of existing approaches and models is provided below.

Three types of iLUC models can be identified: biophysical, economic, and rule-based.

There are several biophysical models with different degrees of complexity (e.g. Bird et al., 2013; Audsley et al., 2009; Cederberg et al., 2011). The biophysical models can be characterised by their attempt to establish a link between the demand for land/crops and deforestation/intensification with the use of physical data on crop yields, and statistical data on deforestation and land use changes. For example, Audsley et al. (2009) identify one of the driving factors of LUC as commercial agriculture. Based on this, the share of global annual GHG emissions from land use changes that is caused by agriculture is evenly distributed on all agricultural lands on a hectare basis. This method resulted in a single emissions factor for agricultural land, i.e. 1.43 t CO_2-eq./hectare of agricultural land used. The model presented in this paper is a further development of this class of models.

Economic models are many and include Leip et al. (2010) (which uses the CAPRI model), Searchinger et al. (2008) (which uses the FAPRI model) and models using the several other partial- or general-equilibrium models available (GTAP, FAPRI-CARD, AGLINK-COSIMO, LEITAP, IMPACT, etc.). The different models were originally developed for different applications but have all been used for the purpose of estimating iLUC (see Edwards et al., 2010). Common to all the economic models is that they establish a link between demand for land/crops and deforestation/intensification/reduced consumption by using partial or general economic-equilibrium models. The economic models consider factors like land price, maps of land suitability, proximity to infrastructure and existing cultivation. These models normally consider that any land expansion first displaces abandoned or fallow cropland and grassland, before forests are converted.

The rule-based models include PAS 2050 (2011), the PEF-guide (European Commission, 2012), the GHG-protocol (WRI/WBCSD, 2011). The LUC models in those standards/guidelines can be characterised by being based on normative rules rather than on causalities. The models are typically referred to as dLUC where the focus is on the historical land cover of the specific plot of occupied land during the last 20 years. Usually LUC is amortised over an (arbitrary) period of 20 years.

1.2. Uncertainties of existing models

The level of uncertainty of all models is high, which is reflected in the high variability of iLUC estimates per MJ biofuel from the different models, from significant reductions in climate impacts (−150 g CO_2-eq./MJ, e.g. corn ethanol and rapeseed biodiesel from Lywood, 2008) to significant increases (150 g CO_2-eq./MJ, e.g. soybean biodiesel from Lywood, 2008, GTAP, LEITAP, FAPRI, Searchinger et al., 2008 and Dumortier et al., 2009). A major reason for this significant variation is the lacking common basis of the models – even at the conceptual level. The identified major differences between the models are:

- They operate with different causal relationships from the demand for land or crops to deforestation,
- They adopt different geographical boundaries (the rule-based models tend to be very narrowly associated with the specific field where the studied crop is grown – whereas the economic models and some biophysical models operate with global effects mediated through global markets for land),
- They handle temporal issues differently (e.g. amortisation of LUC),
- Some models take into account the productivity of the land under study while others do not,
- Not all models consider crop intensification and reduced consumption, and
- Some models consider crop and biofuel life cycle inventories as part of iLUC effects, e.g. substitutions caused by by-products.

It cannot *a priori* be determined if biophysical or economic models will result in the lowest overall uncertainty, since this depends on the quality of the input data that each model requires and the uncertainty of the causal relationships. Generally, economic models are more complex and thus have more data and relationships, but the uncertainty on these may in the end exceed those of the coarser, but simpler, biophysical models. We therefore believe that both types of models have a role to play. In this paper, we focus our contribution on the biophysical models.

2. Methods

2.1. Definitions and classifications

2.1.1. Definition of the function of land in iLUC modelling

Indirect land use changes can be estimated in different ways. Most of the existing models (biophysical, economic and rule-based) are crop and country-specific, i.e. iLUC depends on the production of a specific amount of a given crop (or biofuel) in a specific country. Since the same plot of land, with the same inherent properties, can be occupied by different crops (or for other purposes than crop production), we argue that this is not a desirable approach. Instead, we define land as a factor of production; Land is needed to cultivate crops, land is needed for operating an open-pit mine, for physically supporting residential areas, etc. Obviously, land occupation by human activities may also change the eco-system services supported by the land, such as erosion protection, carbon sequestration, water reservoirs, and biodiversity support. However, in an LCA context, changes in eco-system services are measured as impacts from the human occupation, rather than being part of the production function, unless the change in eco-system services is part of the purpose of the land occupation. When defining land as a factor of production, all land using activities in an LCA product system need to have inputs of this factor. Since the marginal use of land is for biomass production (food, fibre, fuel etc.), because biomass production is the least competitive use of land compared to other purposes (such as residential, industry, infrastructure, raw material extraction, recreation etc.), the use of land in general can be measured in terms of the land's potential for biomass production, which allows including the efficiency of the land use in the assessment, in parallel to other forms of capital utilization. This can be compared with wind power production; in a less windy region more wind capacity needs to be installed in order to generate the same amount of electricity as in a more windy area. In the same manner, more land is needed to produce the same amounts of crops in a region with lower potential biomass production than in a more fertile region.

In iLUC models, the underlying mechanism that causes effects outside the occupied land is via crop displacements (Schmidt, 2008; Kløverpris et al., 2008). Therefore, despite the fact that land may be used for something else than biomass production, the resulting effect will most often be on biomass production anyway. E.g. the iLUC effects of a residential area on potential or previous arable land would include provision somewhere else of the biomass production displaced by the residential area. Land's capacity for biomass production can be measured in different units, and this is further described in Section 2.3.

2.1.2. Life cycle inventory modelling approach

In life cycle inventory, there are different modelling approaches. The two main approaches, consequential and attributional, are defined in the UNEP/SETAC Shonan Guidance Principles (Sonnemann and Vigon, 2011, p 132–133): The consequential approach is a "*System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.*" Conversely, the attributional approach is a "*System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.*" Since several normative rules are thus possible for attributional modelling, we have adopted the approach of ecoinvent v3 (Weidema et al., 2013), where the average supply mix is used for the relevant land markets.

Our proposed modelling of iLUC allows both consequential and attributional modelling assumptions. In the consequential model, the inventoried system represents a change in demand for a defined unit of land use, whereas in the attributional model the system represents the average of all global land use effects (this is further described in Section 2.2.2 and 2.7).

2.1.3. Direct land use changes (dLUC) and indirect land use changes (iLUC)

This paper focusses only on iLUC. Both dLUC and iLUC are illustrated in Fig. 1. In this example, iLUC is illustrated as transformation of land only; as described later in this paper, iLUC may also include intensification and reduced consumption (social effects). In Fig. 1, the area "a" is occupied by the product under study. Two situations are shown: on the left, the product under study is not produced, and on the right, the product is produced. The situation in the right side clearly requires some land use ("a_{after}") in the country where the product is produced. The difference between a_{before} and a_{after} illustrates the dLUC, i.e. the impact on the area "a". Often the dLUC only involves a crop change on the existing cropland. The emissions associated with this are often insignificant. However, drainage of organic soils – which is included under dLUC – may be significant in terms of GHG emissions. The right side of Fig. 1 illustrates a situation where 'a_{after}' supplies the product under study, and consequently that the remaining output from country "x" is 1 t less than before (10 t minus 9 t). To compensate for this reduction, new production capacity is needed, which implies the transformation from b_{before} to b_{after} in country Y. b_{before} represents a situation where the land is not in production. What is referred to as iLUC is the transformation of the area "b", which will in most cases involve deforestation. That deforestation will be involved can be justified by looking at the time series from 2000 to 2010 for change in forest extent (from FAO, 2010) and arable land (data from FAOSTAT, 2014) for all countries in the world, from which it can be observed that change in arable land is negatively correlated with change in forest extent by −0.96 ha forest per ha arable land. Note that the definition of forest in FAO (2010, p 209) includes "*Land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10 percent…*" The tendency of cropland expansion from forests is supported by a range of studies (e.g. Gibbs et al., 2010). It is important to note that conversion of land from primary forest to cropland is often a complex process involving several steps from selective logging, heavy logging, slash and burn practices, to cultivation by smallholders etc. over a long period of time. In the proposed framework, we assume that the supply that meets a change in demand for land (e.g. cropland) can be represented as a combination of different land use transformations (e.g. from secondary forest to cropland and from fallow land to cropland, see Fig. 3). Our proposed framework does not include any of the intermediate steps in the conversion process, since we assume that the sum of all land use changes induced by a change in demand for cropland can be adequately represented by a combination of different transformation activities as referred to above.

2.1.4. Market for land or biomass provision

As described in Section 2.1.1, the function of land is defined as the capacity for biomass production. When identifying how this capacity is provided (e.g. by deforestation), it is crucial to know where, when and how this takes place. The identification of these system boundaries can be facilitated by observing the *market* for the biomass production capacity, or just 'the market for land'. The concept of using markets in life cycle inventory is described in Weidema (2003) and Weidema et al. (2013). Market activities are separate activities/processes between the supplying and using transforming activities. The output of a market activity for a product is the consumption mix of that product. For example, the specific electricity mix in a country is the output of the electricity market activity for that country. By including market considerations it is possible to distinguish the flexible, unconstrained supply

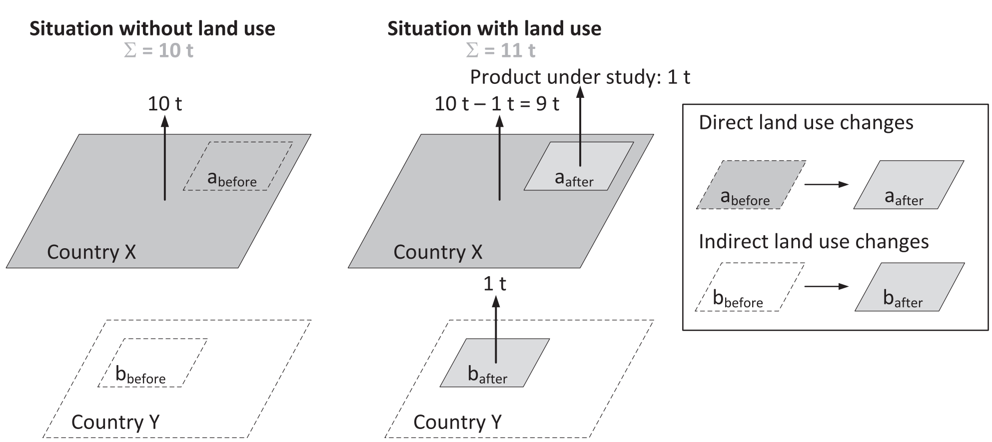

Fig. 1. Direct and indirect land use changes. The land under study is the area "a". The shaded squares represent land in use.

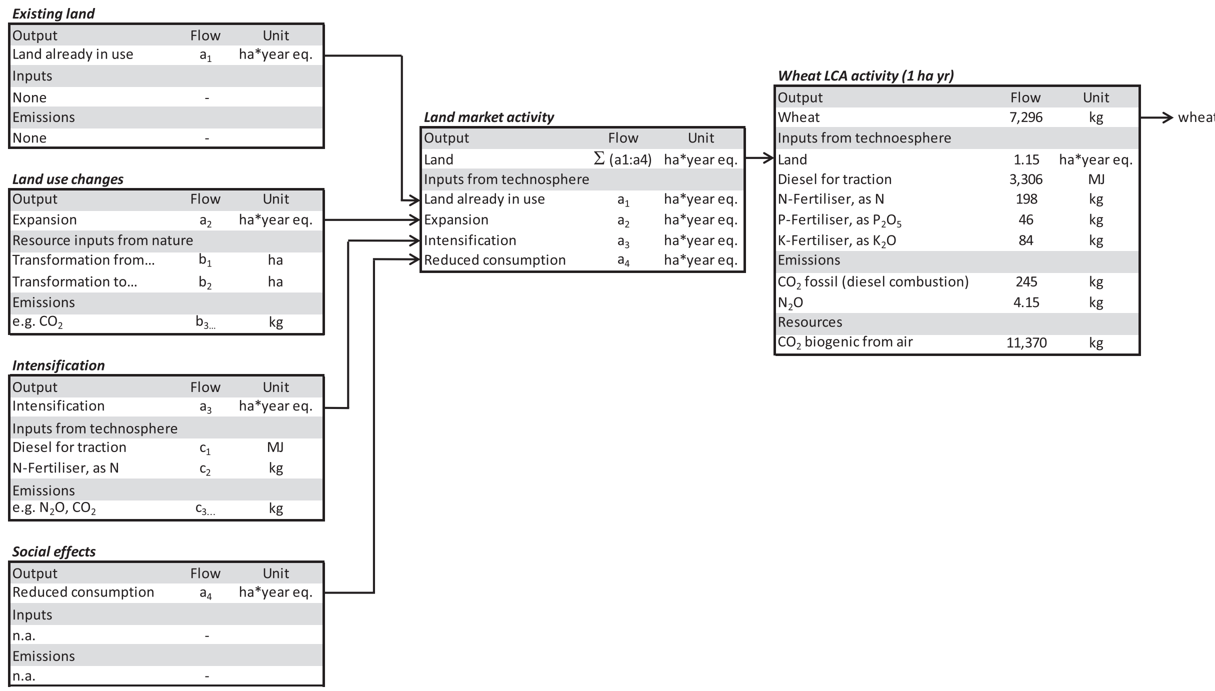

Fig. 2. Inputs and outputs to and from the land market activity for arable land. In this example, the agricultural activity *wheat* has inputs from the market for land, which in turn has inputs from four conceptually different suppliers of biomass production capacity. Each of these suppliers is associated with emissions. The sum of these emissions is referred to as iLUC emissions. The inventory data for wheat are taken from Dalgaard and Schmidt (2012). The unit of the flow of 'land' is productivity weighted hectare years (ha*year-equivalents); this unit is further explained in Section 2.3.

(used in consequential modelling), from the general average supply (used in attributional modelling). The 'market for land' LCA activity is placed between the LCA activities where biomass production capacity is "produced", i.e. where land use changes, intensification, and reduced consumption are taking place, and the LCA activity that occupies land. This is illustrated in Fig. 2. Note that the 'market for land' activity has inputs from all possible suppliers of biomass production capacity.

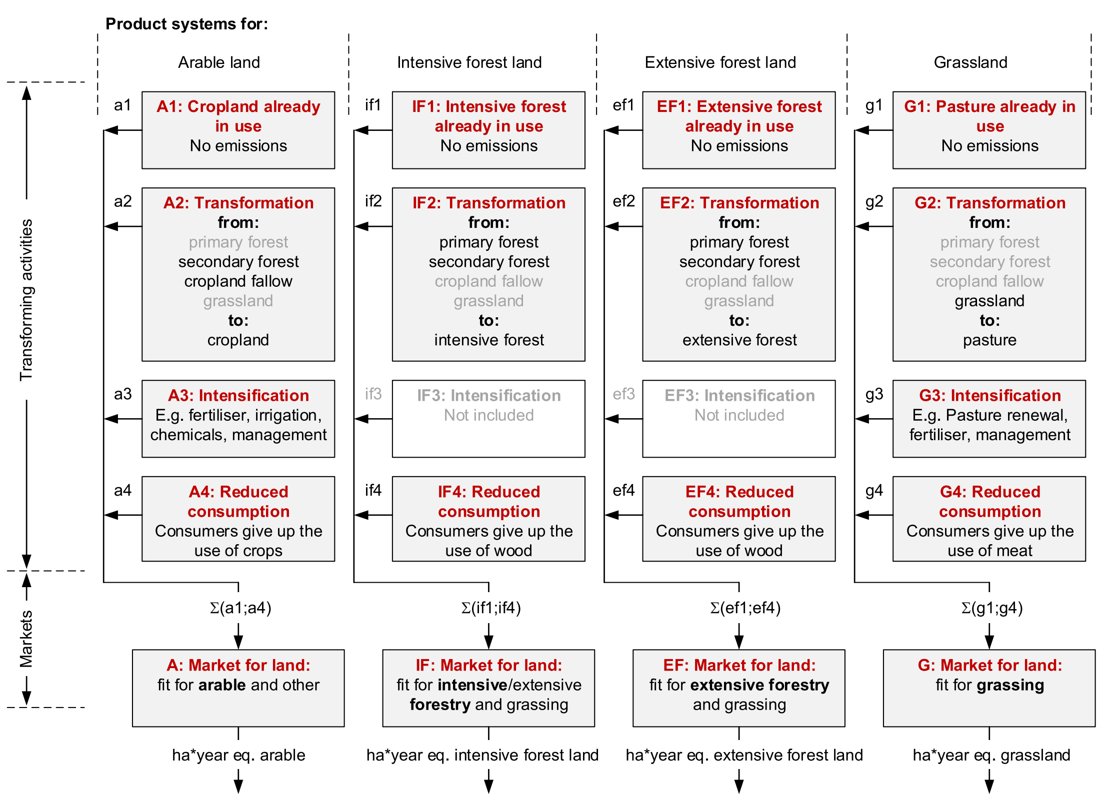

Fig. 3. Illustration of the involved activities in the product systems for the different markets for land, i.e. the causal chain from land use (the outputs in the bottom) to all upstream effects (iLUC). The white boxes and grey text represent activities and flows which are assumed to be zero, and therefore not included in the iLUC model.

2.2. Basic causality of iLUC

The main assumption of the model is that the current use of land is reflected in the current demand for land, and that land use changes are caused by changes in demand for land (land use). Clearly, there are some intermediate steps in the causal chain from land use to land use changes. A crop displaced by another crop will need to be produced somewhere else. This effect is described in Schmidt (2008) and Kløverpris et al. (2008). The fact that iLUC is taking place can be observed from the simple mass balance in Fig. 1; if the iLUC effects are not taken into account then it is implicitly assumed that the displaced crop is compensated without causing any effects (which is clearly not possible).

2.2.1. Generic or specific modelling of crops and locations

The economic models (and some biophysical models) address iLUC (the compensation of the imbalance of 1 tonne in Fig. 1) by attempting to capture all crop displacements at the specific crop and country level (including intensification of specific crops). The models identify the affected crops by price and price elasticity information, and specific crop markets are assumed, i.e. rapeseed displaced in one country is compensated with the same quantity of rapeseed produced somewhere else or, if it additionally includes elasticities of substitution, with the quantity of another crop that produces an equivalent amount of vegetable oil. In this way, the iLUC effect becomes crop- and country-specific, i.e. the iLUC effect from 1 tonne of barley in the US will be different from 1 tonne of barley in the EU, even though the barley is cultivated with similar yields and on land with similar potential productivity. The difference is caused by the import/export share of crops in each country, the price elasticity of each crop and the likelihood of intensification of each crop in each country. Since elasticity data are generally associated with high uncertainties and since the assumption of crop-specific markets is questionable (because many crops are substitutable), the complex crop- and country-specific modelling in the economic models may potentially yield more uncertainty in results compared to a situation where the link from land use to land use change is established based on a global and crop-generic approach, i.e. an approach where the place of occupation and the type of crop occupying the land does not influence the size of the iLUC. Our default assumption is that the markets for land are global. However, the model framework is open for segmenting the markets further if this can be justified, e.g. because of international trade agreements etc. Currently, we have not identified data to support an assumption of more local land markets. Although one could think of examples such as North Korea, which are not integrated in the world market, the countries where the majority of the land use changes are taking place (Brazil, Indonesia etc.) are fully integrated in the supply of globally traded land-using products. It should be noted that some geographical differentiation is considered in our model, since the land's potential productivity is taken into account − this is described further in Section 2.3.

In conclusion, we have decided not to include specific crop displacements in specific countries in the framework of the iLUC model. The causality is instead established by defining the required input (capacity for biomass production) to the land using activities, and then modelling how this demand for capacity is met on the global market.

2.2.2. Suppliers of capacity for biomass production

Conceptually, 'capacity for biomass production' is supplied from four different sources:

1. Productive land already in use.
2. Transformation of 'land not in use' to 'land in use' (e.g. cropland).
3. Intensification of land already in use.
4. Reduction in consumption of products/activities that require land.

The four sources listed above are also illustrated in Fig. 2. The default assumption in LCA is that long-term marginal supply is fully elastic, i.e. that demand for one unit product will in the long-term lead to supply of one more unit product, without affecting other customers of the product (Weidema, 2003). This assumption is justified when markets are competitive and unconstrained (i.e. where there are no market imperfections and no absolute shortages or obligations with respect to supply of production factors, so that production factors are fully elastic in the long-term) and individual suppliers are price-takers (which means that they cannot influence the market price) so that the long-term market prices are determined by the long-term marginal production costs (which implies that long-term market prices, as opposed to short-term prices, are not affected by demand). When applied to the inventory of iLUC, this assumption implies that a marginal change in demand for land will not have any long-term effects on commodity prices and supplies of land-using products. This is confirmed by the food commodity prices that over very long time series have not increased relative to the general consumer index. Recent short time price hikes for food products can largely be explained by changes in fuel prices and speculation in commodity futures (Baffes and Dennis, 2013; Cooke and Robles, 2009). Land and arable biomass production capacity from land transformation (source 2 above) is currently not constrained, as can be seen from the fact that the arable land area is still increasing. Even in the absence of changes in commodity prices, the global use of fertiliser has been increasing over time, indicating that some farmers are not yet operating at an economic optimal fertilisation level, and that part of the increase in commodity output can therefore still come from intensification on land already in use (source 3 above). Due to the absence of any clear tendencies in long-term changes in historical real price index for food 1961−2014 (FAO, 2015), we recommend, as a default assumption, to not include reduction in consumption (source 4 above) in the iLUC model framework. The stated price assumption is only valid for the typical LCA decision-making contexts, focusing on the long-term effects of small-scale changes. For short-term changes, land prices are likely to be affected, and downstream effects in consumptions may occur, and should be considered. This is also true in the case of non-marginal, large-scale changes that affect the current market conditions for 'capacity for biomass production', e.g. if an absolute constraint is encountered for additional production. It is important to note that the latter is relevant if i) the productivity of marginal land decreases, and ii) if a larger share of farmers operate at an economically-optimal level of fertilizer use, then the marginal production costs of land-based production increase with increased production, which would lead to increases in food prices and, consequently, reduced consumption. This issue should be addressed, at least in an uncertainty analysis, when populating the model framework with data.

The attributional version of the model is obtained by including inputs of all suppliers (1, 2, 3 and possible 4 above) to the market for 'capacity for biomass production'. The consequential version of the model is obtained by including the additional unconstrained supply only, i.e. only inputs from suppliers 2, 3 and possible 4 above are included in the market, since the land already in use cannot provide the additional change in production capacity required by the consequential model.

2.3. Unit of measurement of 'capacity for biomass production'; reference flow

As described in Section 2.1.1, the function of land is defined as capacity for biomass production. Obviously, the capacity for

Table 1
Included markets for land. The markets represent the marginal potential uses of the land and are independent of the actual land cover.

Markets for land	Inputs to the markets	Description
Market for arable land (fit for arable and other)	• Cropland already in use • Transformation of land not in use to cropland • Intensification of cropland already in use	Fit for arable cropping (both annual and perennial crops), for intensive or extensive forestry, and pasture.
Market for intensive forest land (fit for intensive/extensive forestry and grazing)	• Intensive forest land already in use • Transformation of primary/secondary forest (>15% tree cover) to extensive forest	Fit for intensive forestry but unfit for arable cropping e.g. because the soil is too rocky. Forest crops grown on intensive forest land may be managed intensively or extensively. Intensive forest land may also be used for other uses, e.g. livestock grazing and extensive forestry.
Market for extensive forest land (fit for extensive forestry and grazing)	• Extensive forest land already in use • Transformation of primary forest (>15% tree cover) to extensive forest	Not fit for more intensive forestry (with clear cutting and reforestation, species control, etc.) e.g. because it is too hilly, too remote, or very infertile, making intensive forestry uneconomic. Forests grown on extensive forest lands are typically harvested after natural regrowth with mixed species.
Market for grassland (fit for grazing)	• Grassland already in use • Transformation of grassland not in use to grassland in use	Too dry for forestry and arable cropping. Grassland is most often used for grazing.
Market for barren land (not fit for biomass production)	• Barren land already in use • Transformation of barren land not in use to barren land in use	Too dry for any biomass production.

biomass production is directly related with land use in terms of hectare years (ha*year); e.g. it can be expected that the double amount of biomass can be produced on 2 ha*year compared to 1 ha*year. However regional differences in the land's productivity should also be addressed, e.g. 1 ha*year in a warm rain fed climate can be expected to produce more crops compared to 1 ha*year in a cold dry climate. When accounting for the land's productivity, it should be the potential and not the actual (harvested) productivity that should be considered, because the land under study is 'capacity'; the utilization of the capacity is something that is managed in the land using process (input of 'capacity for biomass production' in the wheat process in Fig. 2). E.g. a poorly managed cultivation system may have a lower utilization of a field's capacity for biomass production (i.e. lower yield) than a well-managed field. The iLUC effect of 1 ha*year poorly managed field and 1 ha*year well managed field in the same region is the same; but the iLUC effect per unit of crop is higher for the poorly managed system because it is associated with lower yields. Hence, the measurement of land's capacity for biomass production is expressed as productivity weighted hectare years (ha*year-eq.). Occupation of 1 ha*year land with average potential productivity is equal to 1 ha*year-eq.

It is proposed to use potential net primary production (NPP_0) (see Haberl et al., 2007a) to differentiate the potential productivity of land in different locations. According to Haberl et al. (2007a) the average NPP_0 for arable land is 6110 kg $C^*ha^{-1}{}^*year^{-1}$. The relative productivity (the productivity factor) can then be calculated as the NPP_0 of the region where land is occupied divided by the average 6110 kg $C^*ha^{-1}{}^*year^{-1}$. This productivity factor is then multiplied by the occupied ha*years to express the use of 'capacity for biomass production' in ha*year-equivalents. Global maps of NPP_0 are available in Haberl et al. (2007b).

2.4. Markets for land

Land occupation can take place on land with different potential uses. E.g. land use on land that can be used for arable cropping will cause crop-intensification and land use changes in regions where the cleared land can be used for arable cropping (also if the current land is used for something else than arable cropping). But if the land use takes place on land not suitable for arable cropping, the iLUC effects will be different, e.g. land use in the desert will probably not be associated with any iLUC, land use in forested land in hilly areas with rocky soil or land use in dry or cold areas where arable cropping or forestry cannot take place will again be associated with other iLUC effects. The land's potential use determines which market for land is used. It is proposed to operate with at least five markets for land, see Table 1.

2.5. Life cycle inventory framework for the product systems for land

Fig. 3 illustrates the framework or product system of four of the five markets for land mentioned in Table 1. The fifth 'Market for land (not fit for biomass production)' is not illustrated because the use of land from this market is not associated with any iLUC effects.

The market activities have inputs of the four principal suppliers of 'land' as listed in Section 2.2.2; 1) land already in use, 2) transformation of 'land not in use' to 'land in use', 3) intensification of land already in use, and 4) reduced consumption of land-using products. The LCA activities representing 'land already in use' are not associated with any inputs or emissions because this land's production capacity is already established and the maintenance of this capacity is already described as emissions in the agricultural/forestry activities that occupy the land. The only reason for including the input from 'Land already in use' is to be able to operate with an attributional scenario (see Section 2.7).

2.6. Temporal issues of land use changes, avoiding amortisation, and implications for the impact assessment

In the following, it is described how land occupation is linked to land transformation, i.e. the causal relationship between land use and deforestation. Some methods use 'amortisation' or allocation to create a relationship between land use and land transformation, but this is avoided in the current model. The problems related to amortisation are described later.

If only transformation of land is considered as a source of 'capacity for biomass production' (as illustrated in Fig. 1), occupation of 1 ha in 1 year is associated with 1 ha deforestation. After the one year of occupation, the land is given over to other crops (or other uses), which can then be grown without deforestation. Hence, the occupation of 1 ha*year can be modelled as 1 ha deforestation in year 0 and reduction of 1 ha deforestation in year 1 (see Fig. 4), so that the net effect of 1 ha*year of occupation is simply that deforestation is brought one year forward in time. In terms of emissions from deforestation, these are also shifted one year in time, i.e. the net effect of transforming 1 ha of forest to arable and subsequent

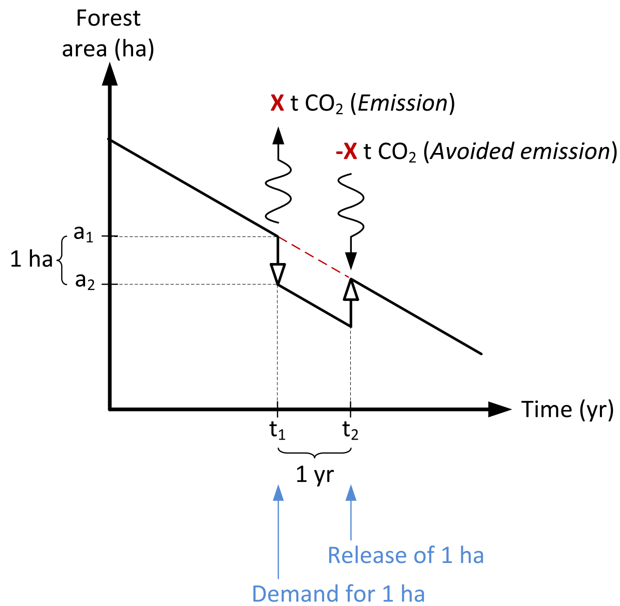

Fig. 4. Effect of land use changes on the timing of deforestation and associated CO_2 emissions.

occupation for 1 year is that land use emissions occur in year t_1 instead of t_2 while the aggregated net emissions are zero (Fig. 4). Kløverpris and Mueller (2013) propose a similar approach.

Modelling deforestation and associated emissions in year t_1 instead of t_2 does not include any effects on the total area that will be deforested in the long-term. It is obvious that the rate of forest loss will flatten out (or maybe even become an increase in forest area) at some time, at least when no unprotected forest area is left. Not including any long-term effects of the timing of the deforestation is equivalent to assuming that this minimum area of forest will not be affected by the current demand for land. An argument supporting this assumption is that the total 'acceptable' loss of forest, and thus the minimum area of forest, relies on the political will to protect forests. The assumption that the minimum area of forests will not be affected by current demand for land is subject to uncertainties. It could be argued that e.g. the current demand for e.g. biofuels is decreasing the potential minimum area of forests. In this case, these effects should be added to our current modelling of iLUC.

Furthermore, the validity of modelling land use changes as time-shifted deforestation is limited to the situations where there is a general net-deforestation (and net expansion of managed land). Once the expansion of managed land stops, land use changes must instead be modelled as delayed relaxation to natural areas. For this, relaxation times would need to be taken into account.

Other iLUC models generally use an *amortisation period* to overcome the problem of non-proportionality between occupation (ha*year) and transformation of land (ha). This is the number of years that the CO_2 emissions in year t_1 should be divided by to determine the emissions that can be 'attributed' to one year. Some standards use a retrospective approach, e.g. PAS 2050 (2011), which includes amortised land use change emissions from the previous 20 years in the Carbon Footprint (CF) of a product. The GHG-protocol (WRI and WBCSD, 2011) uses a similar approach. Applying an amortisation period, however, introduces arbitrary assumptions, inconsistencies and strange cause-effect relationships. For example, PAS2050 implicitly assumes that land use changes are taking place up to 20 years before a crop is produced. Not only is this an unlikely causality backwards in time, but it also introduces a temporal inconsistency with the way temporary storage of C in products is modelled in PAS2050, namely with a linear 100-year 'discounting' of GHG emissions, implying that 1 kg CO_2 emitted 90 years after the production of a product corresponds to 0.1 kg CO_2-eq. The argument for using a 100-year period for 'discounting' the emissions in PAS2050 is that it is consistent with the 100-year time horizon used to characterise greenhouse-gas emissions in the Global Warming Potential (GWP) index. Similar approaches for modelling C stored in products are reported in e.g. the ILCD Handbook (JRC, 2010), Brandão and Levasseur (2011), Brandão et al. (2013), and the GHG-protocol (WRI and WBCSD, 2011).

The timing of emissions is usually not included in life cycle impact assessment (LCIA): e.g. 1 kg CO_2 emitted in year t_1 has the same effects as if it was emitted in t_2. In the following, this is addressed with respect to GHG emissions. Similar changes to the LCIA framework should also be made for other impact categories, especially biodiversity and ecosystem services, which are usually referred to as significant impact categories with respect to land use changes. However, this is regarded as being out of scope of the current article. For GHG emissions we use the Bern Carbon Cycle (IPCC, 2007), which represents the fate of a CO_2 pulse emission and which is used to calculate the GWP, to calculate the climate change effects associated with shifting of deforestation in time. Kløverpris and Mueller (2013) and Müller-Wenk and Brandão (2010) propose a similar approach. According to IPCC (2007, table 2.14), the fraction of a CO_2 pulse present in the atmosphere as a function of time is expressed as:

$$\text{fraction}(t) = 0.217 + 0.259{*}\exp(-t/172.9) + 0.338{*}\exp(-t/18.51) + 0.186{*}\exp(-t/1.186) \tag{1}$$

The IPCC GWP (IPCC, 2007, p 210) is used for expressing the relative importance of different GHG emissions. Most often (or always) this is done relative to CO_2. The GWP is calculated as shown in Equation (2) (IPCC, 2007, p 210).

$$GWP_{i,\Delta t} = \frac{\int_{\Delta t}^{TH} RF_{i,\Delta t}(t-\Delta t)dt}{\int_{0}^{TH} RF_{CO_2,t=0}(t)dt} \tag{2}$$

where:

$GWP_{i,\,\Delta t}$ is the global warming potential for substance *i* emitted at time Δt relative to $t = 0$
TH is the applied time horizon
$RF_{i,\,\Delta t}$ is the radiative forcing for substance *i*, emitted at time Δt relative to $t = 0$
$RF_{CO2,t=0}$ is the radiative forcing for CO_2 emitted at time $t = 0$

2.7. Consequential and attributional modelling of iLUC

The model enables operating with consequential and attributional modelling assumptions (see Section 2.2.2). The main difference between the two approaches is that the attributional approach includes the average of all suppliers to a market for land, while the consequential approach excludes constrained suppliers (Schmidt, 2008; Weidema et al., 2009, 2013). Therefore, the consequential model includes only inputs from transformation, intensification and possibly reduced consumption. The included flows for the attributional and consequential modelling approaches are indicated in Table 2. The names of the flows are shown in Fig. 3.

The differences between these modelling approaches can be interpreted as:

- Consequential: The modelled effects represent a change in demand for land, i.e. the impacts from demanding a certain area of land in a certain period of time compared not to demanding this land.
- Attributional: The modelled effects represent the average effect of the demand for all land. Hence, the sum of all land use effects will add up to the current effects of deforestation and intensification.

Generally, consequential modelling is recommended for supporting decisions aimed at changing the amount of indirect land use and for comparing the indirect land use of different alternative products. Attributional modelling is recommended when it is desired to change the amount of indirect land use attributed to a specific product system, but without changing the overall indirect land use.

3. Discussion

This paper presents a model framework for capturing the indirect effects of land use in a consistent and comprehensive manner. The model is based on life cycle inventory modelling principles consistent with ISO 14040 and 14044 (ISO, 2006a,b) and physical causalities, and is compatible to a large extent with ecoinvent v3 (Weidema et al., 2013). The proposed new model overcomes a number of limitations of existing models. The model:

a) includes effects on both deforestation and intensification,
b) avoids amortisation of deforestation,
c) is applicable to any land use type in any location, and
d) it can support both consequential and attributional modelling assumptions.

The model framework addresses most of the issues that we consider relevant for performing a life cycle inventory of the effects of land use. It should be noted that only limited attention is given to life cycle impact assessment (LCIA), where only the implications with regard to GHG emissions are addressed. In the following the most important limitations and uncertainties are discussed.

Land markets are by default assumed to be global. The markets for land refer to the potential productivity of land. A change in demand for land, caused by land use, can be met through a combination of land transformation, land intensification and reduced consumption of land using crops (caused by price effects). Following the default long-term price assumption in LCA, it is recommended to not include the latter effect. This is in contradiction with some of the economic models, which take into account the (short-term) effects on prices caused by change in demand for land. When excluding these effects, the model can only be used for estimating the long-term effects of changing the demand for land. It should be noted that this default assumption is not valid if the marginal production costs of land-based production increase with increased production due to the lower productivity of marginal land, and if farmers generally reach a more economically-optimal level of fertiliser use. If this is the case, the prices and subsequent consumption of land-using crops will be affected by changes in demand for land. This issue should be addressed, at least in an uncertainty analysis, when populating the model framework with data.

The model is based on the assumption that current changes in demand for land cause current land use changes. The markets for land are defined here as providing the infrastructure service of “capacity for biomass production”. The standard reference flow for land use is the land's potential production capacity, measured as productivity weighted hectare years (ha*year-eq.), which is based on potential net primary production (NPP_0) in the considered region relative to the global average. Obviously, data on NPP_0 are associated with uncertainties and data sources may be too coarse to appropriately distinguish different regions, and not sufficiently detailed to grasp very local differences.

In this model, amortisation of land use change emissions to (an arbitrary) number of cropping years is avoided by considering the effect of land use changes as being the shifting of deforestation in time. The net-emissions from deforestation then become zero, but effects from GHG emissions are included by ‘discounting’ the emissions using a time-weighted version of the GWP method. The model does not include any effects on the total area that will be deforested in the long-term. The emissions from deforestation have been modelled as point emissions at the time of deforestation, while in reality they will occur over a period after deforestation. This implies that our model slightly overestimates the importance of the time shifting of GHG emissions compared to a model that would include the actual delay in emissions.

Table 2
Included flows in the attributional and consequential inventories. The flows refer to the flows illustrated in Fig. 3.

Markets for land	Consequential approach	Attributional approach
Market for land (fit for arable and other)	a2, a3, a4 (a1 = 0)	a1, a2, a3, a4
Market for land (fit for intensive/extensive forestry and grassing)	if2, if3, if4 (if1 = 0)	if1, if2, if3, if4
Market for land (fit for extensive forestry and grassing)	ef2, ef3, ef4 (ef1 = 0)	ef1, ef2, ef3, ef4
Market for land (fit for grassing)	g2, g3, g4 (g1 = 0)	g1, g2, g3, g4
Market for land (not fit for biomass production)	No iLUC effects	No iLUC effects

4. Conclusion

Without downplaying the uncertainties involved, the model framework provides a breakdown the relative complex and large issue of iLUC into smaller, more manageable pieces that can then be improved and refined separately. Once the model framework is populated with data, the breakdown of iLUC in smaller pieces enables for detailed uncertainty analysis, where the contribution to the overall uncertainty from each component can be evaluated.

The proposed model framework addresses consistently what previous models have addressed in less transparent and reproducible ways. For consistency with the basic assumption in LCA, the model only addresses long-term changes in supply caused by changes in demand. Hence, short-term effects on prices and subsequent price-elasticity effects are not included. Economic models have a different scope and model how markets balance in a relatively short-term after the introduction of a shock (change in land use). Thus, the two types of models may be seen as complementary rather than competing, even though they seemingly try to answer the same question.

With the proposed framework presented in this article, we argue that the iLUC discussion can move a step forward towards streamlined modelling and data improvements.

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