Modelling Indirect Land-Use Changes in Life Cycle Assessment

Jannick H Schmidt[1,*], Bo P Weidema[1], Miguel Brandão[2,3], Jürgen Reinhard[4],

[1] Aalborg University, The Danish Centre for Environmental Assessment, Skibbrogade 5, 1, 9000 Aalborg, Denmark
[2] International Life Cycle Academy, Passeig Pujades 1, 08003 Barcelona, Spain
[3] 2.-0 LCA consultants, Skibbrogade 5, 1, 9000 Aalborg, Denmark
[4] EMPA, Technology and Society Lab, Überlandstrasse 126, Dübendorf, Switzerland

[*] Corresponding author. E-mail: jannick@plan.aau.dk

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ABSTRACT
Around 9% of global CO_2 emissions originate from land-use change. Often, these emissions are not appropriately addressed in Life Cycle Assessment (LCA). The link between demand for crops in one region and impacts in other regions is referred to as indirect Land-use Changes (iLUC) and includes land-use changes (LUC), such as deforestation, and intensification. Existing models for iLUC most often operate with arbitrary amortisation periods to ascribe deforestation emissions over time, and the causal link between land occupation and deforestation is generally weakly established. This paper presents an iLUC model where amortisation is avoided by use of IPCC's Global Warming Potential (GWP). The causal link between demand for land and land-use changes is well established through markets for land. The presented iLUC model is applicable to all types of land, all crops and to all regions of the world.

Keywords: indirect land-use changes, land-use change, iLUC, intensification, consequential, attributional

Highlights

- The iLUC model is applicable to all land uses in all regions of the world.
- The model considers both land- use changes and intensification.
- The model is based on consistent life cycle inventory modelling principles.
- Consequential and attribution modelling assumptions can be applied in the model.

1. Introduction

According to Le Quéré et al. (2012), around 9% of global carbon emissions in 2011 originated from land-use change (LUC). Often, these emissions are not addressed in life cycle assessment (LCA) because the causal link between the use of land and deforestation is not well described and because there is a missing consensus on how to establish this link. Furthermore, several studies suggest that LUC and intensification of cropland may be caused by changes in demand for land. This paper proposes a new model and data for establishing the causal link between the use of land (LU) and the effects on LUC and intensification. This link is referred to here as indirect Land-use Changes (iLUC).

iLUC is defined here as the upstream LUC and intensification resulting from the LU elsewhere. Conversely, direct Land-Use Changes (dLUC) take place only in the same land as the LU. The upstream effects, i.e. deforestation and intensification, of occupying land in one region of the world and using it for a specific purpose are likely to take place in other parts of the world. The model is based on the assumption that current changes in demand for land cause current LUC. The market for land-tenure is defined here as a service that supplies capacity for production of biomass. The presented model is applicable to all regions of the world and to all types of land-use. The standard reference flow for the use of land, 'land-tenure', is the land's potential production capacity, measured as the potential Net Primary Production, NPP_0 (in unit kg carbon). This can readily be converted to occupation in units of hectare-years (ha yr), e.g. by use of data in Haberl et al. (2007). The concept is illustrated in Figure 1.

Distinction is made between different markets for land-tenure: land suitable for arable cropping, land suitable for forestry, land suitable for rangeland, and other land (barren,

deserts, ice caps etc.). The land-tenure market activity for arable land has four types of inputs: cropland already in use, transformation to cropland, cropland intensification and crop displacement. The total global observed LUCs (mainly based on FAO 2010) are assigned to different land-tenure markets, and the emissions related to LUC and intensification of cropland are based on IPCC (2006) and yield to fertiliser dose-response relationships. The inventory framework allows for the application of consequential and attributional modelling assumptions. Time-related effects are addressed by use of a time dependent version of the Global Warming Potential (GWP) index, as opposed to the amortisation approach, which is typically used in iLUC models.

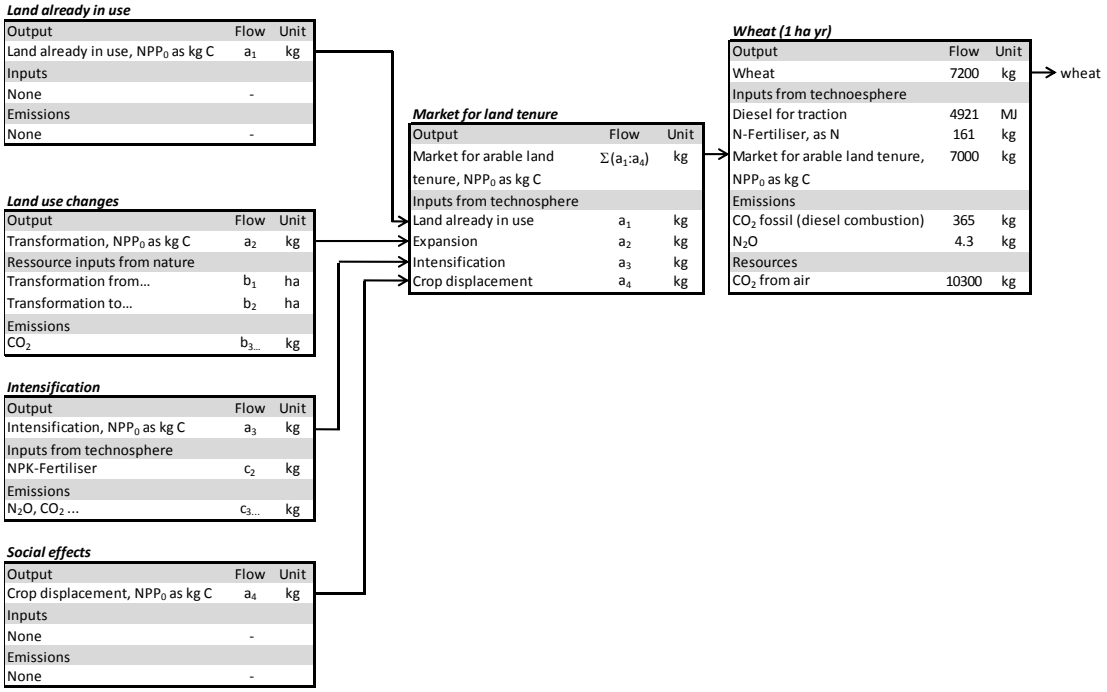

Figure 1. Inputs and outputs to and from the land-tenure market activity for arable land. In this example, the agricultural activity *wheat* has inputs from the market for land tenure activity which, in turn, has inputs from four different suppliers of biomass-production capacity. Each of these suppliers is associated with emissions. The sum of these emissions is referred to as iLUC emissions.

2. Methods

2.1 Goal and scope

The purpose of the presented iLUC model is to provide a life cycle inventory of the upstream consequences of LU. These consequences include both LUC and cropland intensification. The model is applicable to all types of land in all regions of the world for all types of crops, regardless of what they are used for: food, fuel, fibre, timber or other. The model is applicable to small-scale changes, i.e. changes that do not change the overall market trends (Weidema et al. 2009). An example of a large-scale change would be if the change under study required a considerable share of the remaining land available for arable cropping, so that the ratio between expansion and intensification would be affected. It should be noted that a large-scale change would require considerably large changes in demand for cropland, more than most current biofuel policies imply. Large-scale changes need to be analysed specifically by the use of scenario modelling. The model only includes long-term changes in supply caused by a change in demand. Hence, short-term effects on prices and subsequent price-elasticity effects are not included. This implies that reduced food consumption as a result of increased demand for cropland is not included.

2.2 Reference flow

The activities which include land-use clearly need a specified area in a specified period. This can be expressed in hectare-years (ha yr). An LCA market activity is defined for modelling purposes, referred to as 'market for land-tenure'. It comprises the inputs and outputs of the market for land-tenure that is the basis for the modelling of iLUC. An evident option for a reference flow of a land-tenure activity would be occupation of land (ha yr). However, this approach does not take into account that the potential production on 1 ha yr land in e.g. a dry temperate climate is significantly different from that in a wet tropical climate. This can be overcome by operating with a productivity-weighted occupation of land. In line with this, the use of the reference of potential Net Primary Production (NPP_0), measured in kg carbon can be used. Since the latter option provides a simple way to include land with different productivities, this is adopted. This is analogous to a production facility's capacity to produce a given product. It is up to the current production facility to utilise the capacity. For example, a 400 MW power plant has the capacity to produce 400 MW, but most often the installed capacity is not fully utilised. In the case of a land-using activity, it is up to the land-using activity to utilise the land's capacity to produce biomass. For productive land, the reference flow of the market for land-tenure activity is 'biomass production capacity, measured as NPP_0 in kg C ha^{-1} yr^{-1}. In the current study, data on global averages of NPP_0 are obtained from Haberl et al. (2007a). Detailed maps of NPP_0 are available from Haberl et al. (2007b).

2.3 Land-use classes and land-tenure markets

The iLUC model distinguishes land-use classes, which are characterised by the land cover, and land-tenure markets, which represent the potential use of the land independently of the actual land cover. Furthermore, the land-use classes are divided into i) land in use, which is maintained productive land, and ii) land not in use, which is not used for arable crops, wood or pasture. The included land-use classes and land-tenure markets are shown in Table 1. The land-use classes are based on a draft version of the Handbook on LCIA of Global Land-use within the framework of the UNEP/SETAC Life Cycle Initiative. This is also used in ecoinvent v3 (Weidema et al. 2011).

The relevant functions of land to be modelled are its ability to produce crops, e.g. food, feed and timber, and the provision of space for human structures, i.e. buildings, infrastructure and production facilities such as mines. When forests and human structures occupy land suitable for agriculture, it will have similar land-use related effects as when alternative crops are grown, because both types unable the use of land for its original crop purpose. Maps of potential biome classification in e.g. Del Grosso (2008) can be used to identify the potential use, i.e. which market the land belongs to, in a specific geographical location.

Table 1: Included land use classes and land tenure markets. The latter represents the potential use and is independent of the actual land cover.

Land use classes	**Description**
Land in use	
Cropland	Arable and permanent crops (FAOSTAT 2011)
Intensive forest	Productive intensive forest, mainly even-aged trees and clear cut (Weidema 2011)
Extensive forest	Productive extensive forest, mainly selective logging (Weidema 2011)
Pasture	Permanent meadows and pastures (FAOSTAT 2011)
Land not in use	
Primary forest	FAO (2010)
Secondary forest	Other naturally regenerated forest (FAO 2010)
Grassland	(Weidema 2011)
Land tenure markets	
Extensive forest land	Not fit for more intensive forestry (e.g. clear cutting and reforestation, species control etc.) because e.g. it is too hilly, too remote, or it is very infertile making intensive forestry uneconomic. Forests grown on extensive forestland are typically harvested after natural regrowth with mixed species.
Intensive forest land	Fit for intensive forestry but unfit for arable cropping because e.g. the soil is too rocky. Forest crops grown on intensive forestland may be managed as intensively or extensively. Intensive forestland may also be used for other uses, e.g. livestock grazing and extensive forestry.
Arable land	Fit for arable cropping (both annual and perennial crops), for intensive or extensive forestry, and pasture.
Grassland	Too dry for forestry and arable cropping. Grassland is most often used for grazing.

2.4 System boundaries and causalities

There are two types of land-use changes: direct land-use changes (dLUC) and indirect land-use changes (iLUC). dLUC are defined as the impacts occurring from land-use. These effects take place within the same LCA activity that uses (occupies) the land. iLUC are defined as the upstream consequences of the occupation of land, regardless of what is done with it. These effects have previously been called the competition effect (Lindeijer et al. 2001). Both dLUC and iLUC are illustrated in Figure 2. In Figure 2, area “a” is occupied by the product under study. Two situations are shown: on the left, the product under study is not demanded/produced, and on the right the product is demanded/produced. The situation in the right side clearly requires some land occupation (“a”) in the country where the product is produced. This is illustrated as a_{after}. The difference between a_{before} and a_{after} illustrates the dLUC. Often the dLUC only involves crop change on existing cropland. The associated emissions are often insignificant. However, drainage of organic soils - which is included under dLUC – may be significant in terms of GHG-emissions. This paper only focusses on dLUC.

The right side of Figure 2 illustrates a situation where ‘a’ is transformed, resulting in a reduction of net output of the land in the affected country from 10t to 9t. To compensate for this reduction, new production capacity is needed, which implies the transformation from b_{before} to b_{after}. b_{before} represents a situation where the land is not in use. The transformation of the area b often involves deforestation, and this is what is referred to as iLUC. In this example, iLUC is illustrated as transformation of land only; as described later in this paper, iLUC also include intensification and crop displacement.

The main assumption of the model is that the current use of land reflects the current demand for land, and that LUC are caused by changes in demand for land. This assumption is consistent with all other modelling in life cycle inventory, i.e. the demand for a product determines its production volume. The market for land is defined as a service that supplies capacity for production of biomass. This capacity can be obtained from the market, which has inputs from different suppliers, e.g. transformation of land and intensification.

The link between LCA activities that occupy land and the iLUC is established via the markets for land, and is modelled as upstream inputs to the product system. The upstream effects

related to the occupation of land are illustrated in Figure 2. All inputs to the market for land-tenure LCA activity are measured in kg NPP_0 (as kg C). This is explained further in section 2.5.

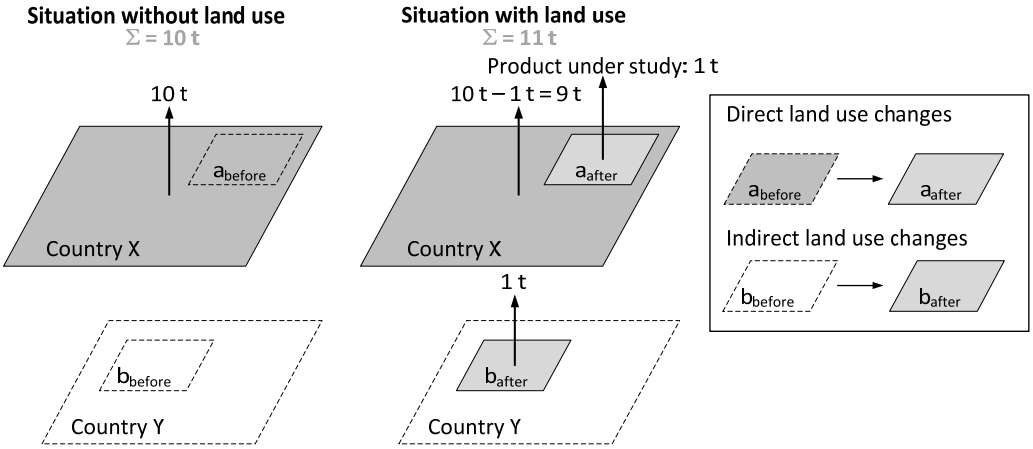

Figure 2: Direct and indirect LUC. The land under study is the area "a". Both direct and indirect LUC are accounted for.

As illustrated in Figure 1, the arable land-tenure market LCA activity has inputs of cropland already in use, cropland expansion, intensification, and crop displacement. The LCA activity '*Land already in use*' is not associated with any inputs or emissions because this land's production capacity is already established, and because maintenance of this capacity is inventoried as emissions ascribed to the agricultural activity that occupies 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). The concept illustrated for arable land in Figure 1 is generalised and expanded to cover all four land-tenure markets and their principal inputs in Figure 3. In Figure 3, boxes represent LCA activities (or processes), and flows are represented by arrows. Capital letters are used for names of activities and small letters are used for flows. The names of activities and flows in Figure 3 are used in the inventory section (section 2.5).

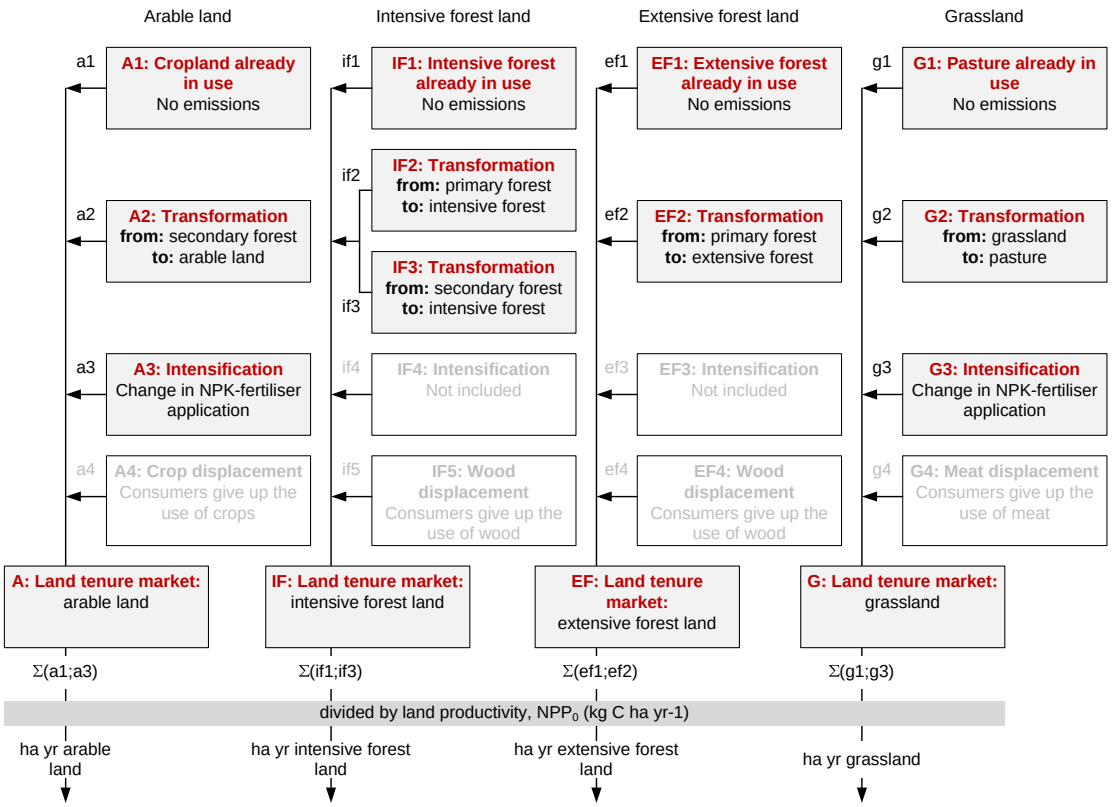

Figure 3: Illustration of the causal chain from occupation of land to all upstream effects (iLUC). The white boxes and grey text represent activities and flows which are not included in the iLUC model, and the in- and outflows of these activities are assumed to be zero.

2.5 Life cycle inventory data

As illustrated in Figure 3, the inventory includes three types of activities to be inventoried: land already in use, transformation and intensification. All types of activities in Figure 3 represent land or land substitutes (capacity for growing biomass). It has been assumed that displacement activities (A4, IF5, EF4 and G4 in Figure 3) are not affected as a consequence of changes in demand for land. It should be noted that this assumption is only valid in the long term and for small scale changes which do not change the overall market for land. For short-term and large-scale changes, land prices are affected, and displacement (or substitution effects) will occur.

'Land already in use' activities (A1, IF1, EF1 and G1) are characterised by having only output of capacity for biomass production, and no inputs or emissions. The outputs of these activities are calculated based on the area and productivity of existing land in Table 2. The data on existing land-use in Table 2 is based on FAOSTAT (2013) and FAO (2010).

Land transformation activities (A2, IF2&3, EF2 and G2) involve transformation of land and emissions of CO_2 and N_2O associated with land transformation (most often deforestation). The annual increment of land added to existing productive land is shown in Table 2. When acquiring new land, the source land can be identified using different approaches. One approach is using a land-use transition matrix (e.g. FAO 2000; Schmidt et al. 2012a,b). However, the identified land-use transition matrices do not take into account the potential use of the land being changed (land-tenure market) and the timber removal before the land is transformed into agricultural land, and they reflect actual land-use cycles rather than the effects of changing the demand for a specific land-tenure market. Therefore, these data are found to be inadequate for the current study. Another related, but not complete, and fully balanced, approach is to use detailed observed changes (e.g. Cederberg et al. 2011). The same disadvantages of this approach as those mentioned above apply to this method. Therefore, we

chose to allocate observed global land-use changes to the demand for the different markets for land-tenure based on logical arguments.

According to FAO (2010) the total gross deforestation 2000-2010 is 13 Mha yr^{-1}, of which 4.19 Mha yr^{-1} is primary forest. The remaining 8.81 Mha yr^{-1} is loss of productive and non-productive forest. According to FAO (2010), the loss of forest is caused by demand for land for other purposes such as agriculture and infrastructure as well as forest fires etc.

It has been assumed that the 13 Mha of gross deforestation takes place on arable land. The reason for that is that if it was on forest land, the land class would have remained forest, demand for arable land would not have taken place, and since range land is too dry for forest, this cannot be affected. The annual new area of cropland is also identified based on FAOSTAT (2013) at the country level and as the sum of all countries with a positive net change of 'Arable land and permanent crops' where the net change is identified as the trend from 2000 to 2010. The area is identified as 8.63 Mha, which is considerably lower than the 13 Mha. The discrepancy may be explained by statistical differences and by the fact that cropland may not always be established immediately after deforestation.

It has been assumed that the loss of primary forest is caused by forestry, i.e. it is the demand for wood that causes the step from primary forest to secondary forest/extensive/intensive forest. Based on FAO (2000, table 46-2), it can be derived that when primary forest is turned into productive forest, this is distributed as 92% to disturbed forest (long fallow), i.e. extensive forest and 8% to plantation, i.e. intensive forest. Hence, it is assumed that 3.86 Mha of primary forests are transformed to extensive forest and 0.38 Mha to intensive forest. Furthermore, it has been assumed that extensive forest has been established on extensive forest land and that intensive forest is established on intensive forestland. It has been assumed that the only established new extensive forest on extensive forestland is the 3.86 Mha primary forests. According to FAO (2010, p 90 and 94) the annual area of planted forest is 4.93 Mha and 76% hereof is productive forest. Based on this, it has been assumed that the annual establishment of new intensive forest is 3.75 Mha. 0.38 Mha takes place in primary forest and the remaining 3.37 Mha is assumed to take place in secondary forest.

The annual new area of pasture is identified at the country level and as the sum of all countries with a positive net change of 'Permanent meadows and pastures' in FAOSTAT (2013) where the net change is identified as the trend from 2000 to 2010. The area is identified as 4.59 Mha.

CO_2 emissions are determined based on the change in carbon stock of the involved land-use types (see Table 3). Note, that arable land does not involve transformation of primary forest – only transformation of secondary forest. The transformation of primary forest is assumed to be caused by the demand for forest products only. Hereby, it is also assumed that there are no wood by-products from transformation of land to cropland. As deforestation is modelled as accelerated deforestation, only the GHG-emissions are considered (see section 2.6). In Life Cycle Impact Assessment (LCIA), timing of non-GHG emissions are usually not considered, hence these can be left out.

Table 2: Area and productivity of existing land in use and creation of new land. The productivity is based on Haberl et al. (2007a). Land not in use and build-up land (estimated) are also included to have a total area that adds up to the world's total land area.

Land use class	**Existing land** Area (million ha)	**Existing land** NPP_0 (kg C ha-1)	**Land tenure market**	**New land** Area per year (million ha yr-1)	**New land** NPP_0 (kg C ha-1)
Cropland	1,527	6,110	Arable land	13.0	6,940
Intensive forest	201	7,200	Intensive forestland	3.75	7,200
Extensive forest	931	7,200	Extensive forestland	3.86	7,200
Pasture	3,357	4,860	Grassland	4.59	4,860
Build-up land	325				
Primary forest	1,102				
Secondary forest	1,799				
Grassland/other wooded land/other	3,769				
Total	**13,011**				

Intensification is included for cropland and pasture (A3, G3). It is likely that the output of existing forests can be increased. However, no statistical data documenting the global trends and means for that have been identified. Therefore, this is currently not included in the iLUC model. The outputs of A3 and G3 are determined based on the growth in intensification relative to expansion. For cropland, the proportion is 63% intensification and 37% expansion (see description below), and for pasture the proportion is 89% intensification and 11% expansion (determined based on relative change in stock density and relative change in gross pasture area from FAOSTAT 2013). Intensification of cropland is inventoried by first identifying which crops and where intensification takes place. Available time series data from 2000 to 2010 on the global production and harvested area of 154 different crops have been collated from FAOSTAT (2013). Based on this information the yields of different crops can be calculated. The average annual change in yield is determined from the slope of a linear regression line of the yields in 2000 to 2010. To calculate an average figure on the change in crop production from changes in yield, the average annual yield changes in % has been multiplied with the current crop production in 2010. This figure gives a good picture of the average change in annual crop quantity. In Table 4, the changes in yields from 2000 to 2010 are shown for the crops for which yields have increased the most. Some crops contain a relatively large share of water and hence 1 tonne/ha yr yield increase for such a crop cannot be compared with a 1 tonne/ha yr yield increase for a crop with low water content. Therefore, the production of all crops has been converted into production of dry matter (DM). This conversion is mainly based on the dry matter contents of crops in Møller et al. (2005).

Intensification is modelled based on the three most important crops and on pasture in the most important countries; for crops see the top three rows in Table 4. A similar identification of the most important countries where pasture intensification takes place has been made. However, since statistical data for pasture yields are not available, cattle densities on permanent meadows and pastures have been used as an indicator. Data have been extracted from FAOSTAT (2013). Based on this approach, it has been identified that Brazil was responsible for 32% of the increase in cattle (measured as stock, heads) due to pasture intensification in the period from 2000-2010.

The only included means of intensification is additional NKP fertiliser. For the included crops and countries the relevant crop yield response functions to additional fertiliser use are identified. These functions are differentiated with respect to fertiliser so that a function of kg dm crop per kg NKP is established. Subsequently, for the current fertiliser level for the each

crop and country an inventory can be established. This principle is further described in Schmidt (2008). The current level of fertiliser for different crops in different countries is based on total national fertiliser use (IFA 2013) which is distributed over all crops in each country (FAOSTAT 2013) based on general figures on fertiliser use by crop in different countries (FAO et al. 2002). The current (2007) fertiliser use level in maize in USA, rice in India, and wheat in China are estimated as 174, 101, and 182 kg N ha^{-1} yr^{-1} respectively. Since pastures in Brazil are fertilised at low rates (~4 kg NKP ha^{-1}) (Cederberg et al. 2009), it is assumed that intensification takes place on pasture which only receives excretions by grazing animals. For Brazil this has been estimated as 28 kg N ha^{-1} yr^{-1}. The yield-to-fertiliser dose-response relationship for maize is based on Johnson and Raun (2003), rice is based on Mehdi et al. (2008), wheat is based on Mehdi et al. (2008), and pasture is based on Sun et al. (2008). The dry matter yield (y) in tonnes as a function of N-fertiliser (N) in kg N for maize, rice, wheat and pasture are determined as in equation (1).

Equation (1)

$$y_{maize}(N) = -0.000060N^2+0.0259N+4.87$$
$$y_{rice}(N) = -0.000020N^2+0.0211N+1.31$$
$$y_{wheat}(N) = -0.0000020N^2+0.0100N+0.962$$
$$y_{pasture}(N) = -0.000010N^2+0.0120N+7.88$$

In order to convert the reference flow of the intensification activities to NPP_0 measured in kg C, a carbon content of biomass at ~50% (IPCC 2006, table 4.3), and a ratio of NPP_0 relative to harvested C (NPP_h minus residues not removed, i.e. 30% of NPP_h) at 2.95 is used (Harberl et al. 2007, table 2). The field emissions related to N-application are modelled based on IPCC (2006, chapter 6) tier 1. The applied N-fertiliser mix is determined by the trends of fertiliser consumption from 2000 to 2010 in the modelled countries; crop intensification (USA, India and China) and pasture intensification (Brazil). The data on fertiliser consumption are obtained from IFA (2013). LCI data for the production of fertiliser are based on ecoinvent v.2.2 (ecoinvent 2010).

Table 3: Carbon stocks in land use categories used in the iLUC model. Carbon stocks are based on IPCC (2006, chapter 4, 5 and 6): forests represent tropical regions, extensive and secondary forests are represented by an average of primary forest and intensive forests, and grassland represents average of tropical and sub-tropical scrubland/steppe. Unit: t C/ha.

Land use type	**Above ground carbon**	**Below ground carbon**
Land in use		
Cropland	6.3	64.7 (61% of initial land = secondary forest)
Intensive forest	70.5	26.1
Extensive forest	106	39.1
Pasture	4.09	11.8 (100% of initial land = grassland)
Land not in use		
Primary forest	141	52.2
Secondary forest	106	39.1
Grassland	25.2	11.8

Table 4: Calculated average annual increase in crop production from intensification for the world (million tonne DM) based on 2000-2010. For each crop the relative contribution to yield increase by the most significant country is specified.

Crop	**Production** (million t dm)	**Share**	**Most significant country**
Maize	13.0	25%	USA (36%)
Rice, paddy	7.49	14%	India (20%)
Wheat	6.59	13%	China (27%)
Sugar cane	4.50	9%	Brazil (62%)
Oil palm fruit	2.04	4%	Malaysia (87%)
Cassava	1.82	3%	Thailand (18%)
Seed cotton	1.54	3%	India (51%)
Sugar beet	1.53	3%	Russia (25%)
Rapeseed	1.41	3%	Canada (22%)
Barley	1.31	2%	Russia (23%)
Other crops	16.8	21%	-
Total	**58.0**	**100%**	

Table 5: Inventory data for the four land tenure activities and their upstream inputs.

Flows	Arable land	Intensive forest land	Extensive forest land	Grassland
Output, NPP_0 as million t C				
Land already in use	a1=9330	if1=1447	ef1=6703	g1=16315
Transformation	a2=90.2	if2=2.74	ef2=27.8	g2=22.3
		if3=24.2		
Intensification	a3=151			g3=188
Land use change, million ha				
From primary forest		0.38	3.86	
From secondary forest	13.0	3.37		
From grassland				4.59
To cropland	13.0			
To intensive forest		3.75		
To extensive forest			3.86	
To pasture				4.59
Flows related to intensification, million t				
Fertiliser: Ammonia, as N	2.55			3.84
Fertiliser: Urea, as N	10.5			2.41
Fertiliser: Ammonium nitrate, as N	1.90			5.00
Fertiliser: Calcium ammonium nitrate, as N	0.00619			0.115
Fertiliser: Ammonium sulphate, as N	0.0605			0.210
Emission to air: Ammonia	1.79			1.38
Emission to air: Dinitrogen monoxide	0.329			0.241
Emission to air: Nitrogen oxides	0.0824			0.0600
Emission to water: Nitrate	21.1			15.4
Emissions related to transformation, million t				
CO_2 (accelerated)	3,534	733	681	355
CO_2-eq. (time dependent GWP100)	26.9	5.59	5.19	2.71

2.6 Avoiding amortisation, time perspectives of land-use changes and implications for LCIA

When the occupation of land implies deforestation, a critical methodological choice arises: the period over which the deforestation emissions should be 'amortised' or allocated. The current model does not operate with amortisation. If only expansion is considered, occupation of 1 ha during 1 year is associated with 1 ha deforestation. After this period, the land is given over to other crops, which can then be grown without deforestation. Hence, the occupation of 1 ha yr is modelled as 1 ha deforestation in year 0 and -1 ha deforestation in year 1. The principle is illustrated in Figure 4, from which it can be seen that the net emissions from LUC are zero. Emissions from LUC can be regarded as moving emissions forth in time, i.e. the net effect of the transformation of 1 ha from forest to arable and subsequent occupation in 1 year in Figure 4 is that an emission occurs in year t_1 instead of t_2. A similar approach as the one described above is proposed by Kløverpris and Mueller (2013).

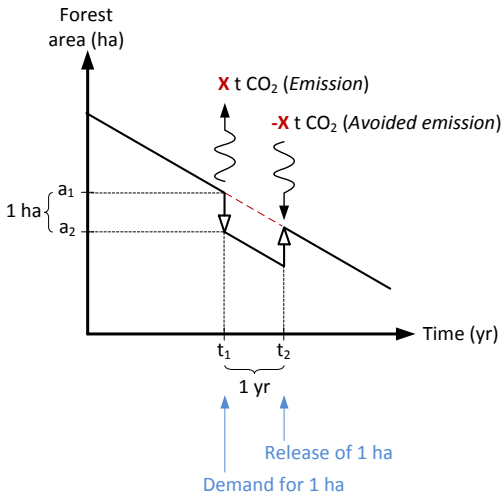

Figure 4: Effect of land-use changes on the timing of emissions.

The modelling of the net effect of causing emissions in year t_1 instead of t_2 relies on the assumption that current deforestation will not affect the total area that will be deforested – only the timing of intermediate deforestation activities will be affected. Hence, it is assumed that the downward slope of the curve in Figure 4 will flatten out (or maybe even start to have a positive slope) at some time, and that this minimum extent of forest will not be affected by current demand for land. The argument for this assumption is that the total 'acceptable' loss of forest, and correspondingly remaining forest, relies on the political will to protect forests. At a certain level, the willingness to pay for forest protection exceeds the potential returns of transforming the forest into productive land. The assumption that the minimum extent of forests will not be affected by current demand for land may be subject to uncertainties. It could be argued that e.g. the current demand for biofuels is pushing the minimum extent of forests downwards. In this case, these effects should be added to the current modelling of iLUC.

Furthermore, the effect of causing emissions in year t_1 instead of t_2 is only present as long as a net deforestation/expansion of arable land takes place. Once the expansion of arable land stops, the effect of deforestation shall be modelled without the avoided emissions at time t_2 in Figure 4, and the regeneration time shall be taken into account instead.

Other LUC models generally use another method to overcome the problem of non-proportionality between occupation (ha yr) and transformation of land (ha), i.e. most often an *amortisation period* is used. This is the number of years that the X t CO_2 emissions in year t_1 in Figure 4 should be divided by in order to represent the emissions that can be 'attributed' to one year. Some standards argue in a retrospective way, e.g. PAS2050 (2011, p 11) which uses a 20-year amortisation period prior to the Carbon Footprint (CF) assessment. The GHG-protocol (WRI&WBCSD 2011) uses a similar approach. It should be noted that applying an amortisation period without addressing the problem in a similar manner to Figure 4 introduces arbitrary assumptions, inconsistencies and odd cause-effect relationships, e.g. the PAS2050 implicitly assumes that LUC taking place up to 20 years prior to the assessment are caused by the current demand for arable crops. Some LCA and CF standards address a similar problem regarding the timing of emissions and temporary storage of carbon in products. For example, PAS2050 (2011) uses 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 when characterising the different emissions that is commonly adopted when using the Global Warming Potential (GWP) index. Similar approaches for the modelling of carbon stored in products are reported in the ILCD Handbook (JRC 2010, p 229-230), a JRC report (Brandão and Levasseur), Brandão et al.

(2013), Brandão (2012) and the GHG-protocol (WRI&WBCSD 2011). The lack of addressing the problem of LUC as equivalent to the delay/acceleration of emissions causes inconsistencies in PAS2050, as well as in the other standards. Delayed emissions caused by carbon stored in products are modelled using a 100-year time horizon, whereas accelerated emissions caused by LUC are modelled using a 20-year time horizon.

The common way in which emissions are dealt in LCIA is that the timing of the emissions has no effect, e.g. 1 kg CO_2 in year t_1 has the same effects as if it was emitted in t_2. In the current study, the Bern Carbon Cycle (IPCC 2007), which represents the fate of a CO_2 pulse emission and which is used to calculate the Global Warming Potential (GWP), is used to calculate the climate change effects associated with accelerating deforestation. A similar approach is proposed by Kløverpris and Mueller (2013) and Müller-Wenk and Brandão (2010). 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 by equation (2):

Equation 2

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

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 (3) (IPCC 2007, p 210).

Equation 3

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

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

When applying the GWP method for determining the relative importance of different emissions and timing of emissions several problems arise in addressing the impacts that the impact indicator (CO_2-eq) is assumed to represent:

- operating with only one time horizon is problematic since some impacts relate to the long-term effects of GHG-emissions in the atmosphere (such as rise of sea levels) and some are related to more immediate effects of GHG-emissions (such as increased frequency of extreme weather conditions)
- all radiative-forcing effects from emissions after the chosen time horizon are omitted

Therefore, we propose to operate with more than one time horizon.

2.7 Consequential and attributional modelling of the land-tenure activity

The model enables for operating with consequential and attributional modelling assumptions. The main difference between the two approaches is that while attributional modelling includes the average of all suppliers to a market for land, consequential modelling excludes constrained suppliers (Weidema et al 2009; Schmidt 2008). Therefore, the difference is that the consequential inventory only includes inputs of expansion and intensification (a2, if2&3, ef2 and g2&3 in Figure 3), whereas the attributional inventory also includes inputs from land already in use (a1, if1, ef1 and g1).

The differences in the consequential and the attributional approaches to the land-tenure activity can be interpreted as:

- Consequential: The output of the land-tenure market is the ***annual change*** in the land's capacity to produce products, i.e. the annual change in NPP_0.
- Attributional: The output of the land-tenure market is the land's ***annual total*** capacity to produce products, i.e. the annual total NPP_0 of land in use.

Generally, it is recommended to use the consequential modelling approach of the iLUC model because this represents the effects of demanding an area of land during a certain period of time compared to not demanding this land.

3. Results

Table 6 summarises a range of examples of results on GHG-emissions calculated with the iLUC model. The GHG-emissions are highest for arable land, followed by grassland and then intensive and extensive forestland. The reason why arable and grassland are higher is that these markets involve intensification which induces a higher impact than LUC. Note that this is valid for GHG-emissions. If biodiversity impacts were included, the LUC would be the most significant contribution. For arable land and grassland the distribution between the contribution from LUC and intensification are 15% / 85% and 2% / 98% respectively.

Table 6: GHG-emissions (GWP100) for the occupation of 1 ha yr of different land-tenure markets in different countries. The results are shown when applying the consequential modelling assumption. The NPP_0 are obtained from Harberl et al. (2007b).

Country/Region	**NPP_0, kg C ha^{-1} yr^{-1}**	**Market for land tenure (kg CO_2-eq. ha^{-1} yr^{-1})**			
		Arable land	**Intensive forestland**	**Extensive forestland**	**Grassland**
World average	6,110	4,592	1,491	1,343	3,116
Argentina (Pampas)	7,000	-	-	-	4,488
Baltics	7,000	5,261	1,449	1,306	-
Brazil Central (Cerrado)	9,000	6,764	1,864	1,679	-
Brazil North (Amazonas)	11,000	8,268	2,278	2,053	-
Brazil South (Pampas)	7,000	-	-	-	4,488
Canada	5,000	3,758	1,035	933	-
Canada South central (Praire)	4,000	-	-	-	2,564
France	7,000	5,261	1,449	1,306	-
France (Alp highlands)	5,000	-	-	-	3,205
Malaysia&Indonesia	11,000	8,268	2,278	2,053	-
Russia	5,000	3,758	1,035	933	
USA east	7,000	5,261	1,449	1,306	-
USA mid	5,000	3,758	1,035	933	-
USA Central (Praire)	5,000	-	-	-	3,205

Table 7 shows the global warming results for both consequential and attributional modelling approaches for the four land-tenure markets. The results in the table can be used directly in life cycle inventories. It appears that the results when using the attributional modelling assumption are significantly lower than those of the consequential one.

Table 7: GHG-emissions for the four land tenure markets. Results are shown as kg CO_2-eq. (GWP100) per NPP_0 (kg C) and per global average hectare-year. Global average potential productivity from Table 2 are used for the conversion of results per ha yr (see bottom line of current table). clca=consequential; alca=attributional.

Land tenure market	**Arable land**		**Intensive forest land**		**Extensive forest land**		**Grassland**	
Average potential productivity, NPP_0 (kg C ha-1)	6,110		7,200		7,200		4,860	
Modelling	clca	alca	clca	alca	clca	alca	clca	alca
GHG-emissions per NPP_0 as kg C	0.756	0.019	0.207	0.00379	0.187	0.00077	0.641	0.00816
GHG-emissions per ha yr (global average)	4,619	116	1,490	27	1,346	6	3,115	40
Productivity of land NPP_0 (kg C ha-1)	6,110	6,110	7,200	7,200	7,200	7,200	4,860	4,860

4. Discussion and Conclusions

This paper presents a model of iLUC, which: a) includes effects on deforestation and intensification, b) avoids allocation of deforestation (amortisation), c) is applicable to any land-use type in any location, and d) can handle both consequential- and attributional-modelling assumptions. The model is based on consistent LCA modelling principles, and to a large extent it is compatible with ecoinvent v3 (Weidema et al. 2011).

The results show significant iLUC effects on global warming: crops with yields 5-7 t/ha-yr grown on average-yielding land are associated with iLUC effects ranging from 1 to 1.5 kg CO_2-eq./kg crop.

The major uncertainties in the model are a) the market for land is assumed to be global, b) the determination of NPP_0 based on Haberl et al. (2007a,b) is relative coarse-grained, so 10-15% uncertainty is associated with reading maps which only show intervals, c) the determination of the relative distribution of inputs of expansion and intensification to the land-tenure market is associated with uncertainties since it is based on indirect estimation methods, d) the modelling of intensification through additional use of NPK fertiliser as the only affected mean of intensification, e) the dose-response effects of crop/pasture yields relative to additional fertiliser use are also associated with uncertainties, and f) intensification of forestry is not included.

Despite the uncertainties listed above, the model results are regarded as being within reasonable uncertainty intervals. We highlight that the model is open for improved data input at almost any level. This suggests that the presented model can be seen as a proposal for solving the conceptual challenges with the modelling of iLUC, and that future improvements of the model will focus on improving input data.

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