A simple approach to land use change emissions for global crop commodities reflecting demand

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ABSTRACT

A development of the top down method for accounting for all direct and indirect land use change emissions (LUCE) is presented, which reflects the relative rates of global crop expansion. It uses crop production and area data from FAOSTAT to derive expansion rates, reflecting global demand. Crops that drive land use change more, e.g. soy thus receive a heavier burden than other. It is thus more equitable than the original top down method. Alternative sources of values for LUCE and connected agricultural area are addressed. It still represents a method with relatively low computational and data demands.

Keywords: greenhouse gas emissions, land use change, crops, top down, soy

1. Introduction

Greenhouse gas (GHG) emissions (GHGE) from land use change (LUC) have a large effect on life cycle assessments (LCA) of food production, especially from livestock products (e.g. Audsley et al., 2009, Leinonen et al., 2013, Leinonen et al., 2014, van Middelaar et al. 2013, Meul et al., 2012, Cederberg et al., 2011). The relative importance is even greater in life cycle based studies such as determining product carbon footprints or if calculating GHGE from national or regional food consumption.

Determining the GHGE from land use change (LUCE) is relatively straightforward if the history of the land parcels is well known and if the initial conditions of soil and biomass carbon densities are known. This is not, however, always the case, neither does this address the consequences of indirect LUCE.

Current approaches to determine direct LUC GHG emissions (direct LUCE) include the UK publically-available specification PAS 2050, which started with one method as (BSI, 2008), and was later revised in (BSI, 2011). In BSI (2008), the default position if land history was not known was to assume the worst case scenario of LUCE: deforestation. This was revised in BSI (2011) to apply the weighted average of direct LUCE from the originating country, although it did not specify exactly how this should be applied. If dealing with a major commodity, such as soy, the data requirements are potentially very high, given the large areas of land and multiple countries. The method is based on the premise that one land use is succeeded by another, e.g. forest to arable. It does not address land that may have been deforested, then abandoned and regenerated towards forest. Fearnside (1997) addressed this with the concept of "net committed emissions", which also requires much detailed data to be effectively applied. This approach was also used by Cederberg et al. (2011). These methods do not really address indirect LUC fully.

A radical alternative, the "top down" approach was developed by Audsley et al. (2009), revised by Vellinga et al. (2013) for the Dutch feed industry and compared with other approaches by van Middelaar et al. (2013). In the top down" approach, all global direct and indirect LUCE are applied uniformly to all economically connected agricultural land. The underlying principle is that commodity demand will be met by the world market, so that land expansion operates collectively in response to demand. LUC in one area may result from changed demand in any other, whether direct or indirect.

Data needs are relatively modest and can be derived mainly from FAOSTAT land use and production statistics. This is coupled with an estimate of global LUCE, of which several possible values exist. These differ in response to inclusion or not of emissions from source such as nitrogen transformations when soil C stocks are depleted. Values for total global LUCE range from 3.3 Gt CO_2e/year (DeFries, et al. 2002), through 4.94 Gt CO_2e/year (Audsley, et al., 2009) to 8.49 Gt CO_2e/year (Olivier, et al., 2005). Vellinga & Van Middelaar (2011) used 5.62 Gt CO_2e/year, as a result of averaging 14 different sources.

Another factor that affects the overall result is how much of the global agricultural area should be considered to be connected. Audsley, et al. (2009) used 3.47 Gha, whereas Vellinga & Van Middelaar (2011) estimated it as 4.9 Gha. Differences in the accounting procedure are evident.

A limitation of the original method is that all crops are considered to be "equally guilty" and carry the same burden per ha, whereas soy expansion by area exceeds other crops (e.g. 1.75 more than maize). In an attributional approach such as PAS2050, crops like soy typically have a high LUCE burden, while European wheat would have none. The reality is somewhere in between. This study presents an enhancement of the top down method, which addresses the relative expansion rates of global crop areas. It is thus still (a) relatively simple to apply, (b) responds to changes in commodity demands (hence reflecting economic drivers for LUC) and (c) avoids double counting. As before, indirect LUCE are also included.

2. Methods

Choices in the approach were compared that addressed calculating the rate of change of crop areas, calculating the global agricultural area and the global LUCE. The core feature, however, was including the rates of crop expansion.

Six measurements are considered in this study including the range (4.94, 5.62, 5.8 and 8.1 Gt CO_2e/year).

2.1. General approach

The world's top 25 crop commodities (by weight produced) were analyzed individually. All other crops were treated as one and grassland as another crop. The top 25 commodities accounted for 85% production on a fresh weight basis or 74% of cropped area. Production and crop area data came from FAOSTAT (2014).

2.2. Calculating land area changes

Annual rates of area expansion (ARE) for the top 25 crops were determined using time spans of 3, 5, 7, 10, 15 and 20 years, with the last year being 2010. 20 years is the period used by the IPPC and in PAS2050 used to capture the bulk of LUCE, although in reality, these may continue beyond 20 years.

Three approaches were tried by Dominguez (2013). The first was simple difference between the final year under scrutiny (A_F) and the initial year (A_i), Equation 1.

$$ARE = \frac{A_f - A_i}{T_f - T_i} \qquad \text{Equation 1}$$

The second used interval proposed in PAS2050-1:2012 interval, in which the average of three years is used in order to reduce fluctuations (Equation 2).

$$ARE = \frac{\left(A_{f-1} + A_f + A_{f+1}\right) - \left(A_{i-1} + A_i + A_{i+1}\right)}{3\left(T_f - T_i\right)} \qquad \text{Equation 2}$$

The third method was simple linear regression. Dominguez (2013) compared the three methods and found similar results, but regression has the advantage of including an estimate of uncertainty. Hence, it is the only method presented here.

The expansion of the other 137 smaller crops was simply derived by the difference between global harvested areas and those of the top 25 crops and treating them as one lumped crop.

The rate of expansion of grassland required screening out the area used by subsistence graziers, e.g. those in sub-Saharan Africa. Audsley et al. (2009) filtered out countries that did not fulfil the following three criteria. (1) Producing less than 0.5% of global production of meat from cattle, sheep and goats. (2) Importing less than 0.5% of globally produced meats. (3) Exporting 0.5% of globally produced meats. Hence, the area expansion of grass only included that from the countries that met all the 0.5% thresholds.

The sum of both crop and grass expansions gave the total annual net rate of expansion (ANRE) for a given period. This is the area that commercial agriculture varied annually, expanding or contracting according to global trends.

The next step is to obtain the proportion of each commodity $Ppt_{(ARE_c)_t}$ in the ANRE.

$$Ppt_{(ARE_c)_t} = \frac{(ARE_c)_t(100)}{ANRE_t} \qquad \text{Equation 3}$$

$(ARE_c)_t$ is the annual rate of expansion for a commodity c in a period t, $ANRE_t$ is the annual net rate of expansion in a period t.

2.3. Normalization

The question of dealing with declining crops areas was addressed through normalization. All expansion rates (as proportions of the total) were made positive by adding the smallest integer possible, i.e. 1. Each rate was then divided by the mean expansion rate to give the normalized values for each crop (NV_C), such that the sum of all expansion rates would still sum to the total. These normalized values were then used to scale the total estimate of LUCE for all crops. This was applied because the general trend for the cropped area is expansion and that some "responsibility" should be held by all major crops. The main effect was thus to cause all major crops to incur a portion of global LUCE.

2.4. Baseline emissions from land use change

The baseline emissions from land use change are the LUCE per unit of agricultural land as used by Audsley et al. (2009) and by Vellinga et al. (2013). Two terms are needed for the top down method: the global agricultural area to be considered (Table 1) and the global estimate of LUCE (Table 2). These represent estimates of cumulative LUCE from agriculture.

Table 1. Values used for global agricultural areas harvested

Value, Gha	Source
3.47	Audsley, et al. (2009)
4.90	Vellinga and Van Middelaar (2011)
2.88	Method here studied, includes grassland area from screening

Table 2. Values used for global land use change GHG emissions

Value, Gt CO_2e/year.	Source	Comments
3.30	DeFries, et al. 2002.	
4.94	Audsley, et al., 2009.	58% CO_2e from IPCC 2007 AR4 dedicated to commercial agriculture
5.62	Vellinga and Van Middelaar 2011.	
5.80	Vellinga and Van Middelaar 2011.	Including effects of soil degradation
8.10	Houghton, 2003.	Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000
8.49	Olivier, et al. 2005.	

The value of 1.42 t CO2e/ha derived by Audsley et al. (2009) is simply the result of dividing the global land use change GHG emissions (4.94) by the global agricultural areas harvested (3.47).

3. Results

3.1. Land use change 1990 to 2010

Crop areas expanded from 1990 to 2010 at an average rate of 7.0 Mha/year, with a considerably greater expansion rate from 2002 (Figure 1). The overall increase in cropped area was 12% of the 1990 value. In contrast, grassland expansion increased up to 1996 and declined to 2010, at 1% below the 1990 area. This is a net effect with some grassland being created from deforestation and some being lost to cropping. The overall agricultural expansion is clearly dominated by crops. Linear regression accounted for 86% of the variance in crop area expansion from 1990 to 2010 and 92% from 2001 to 2010.

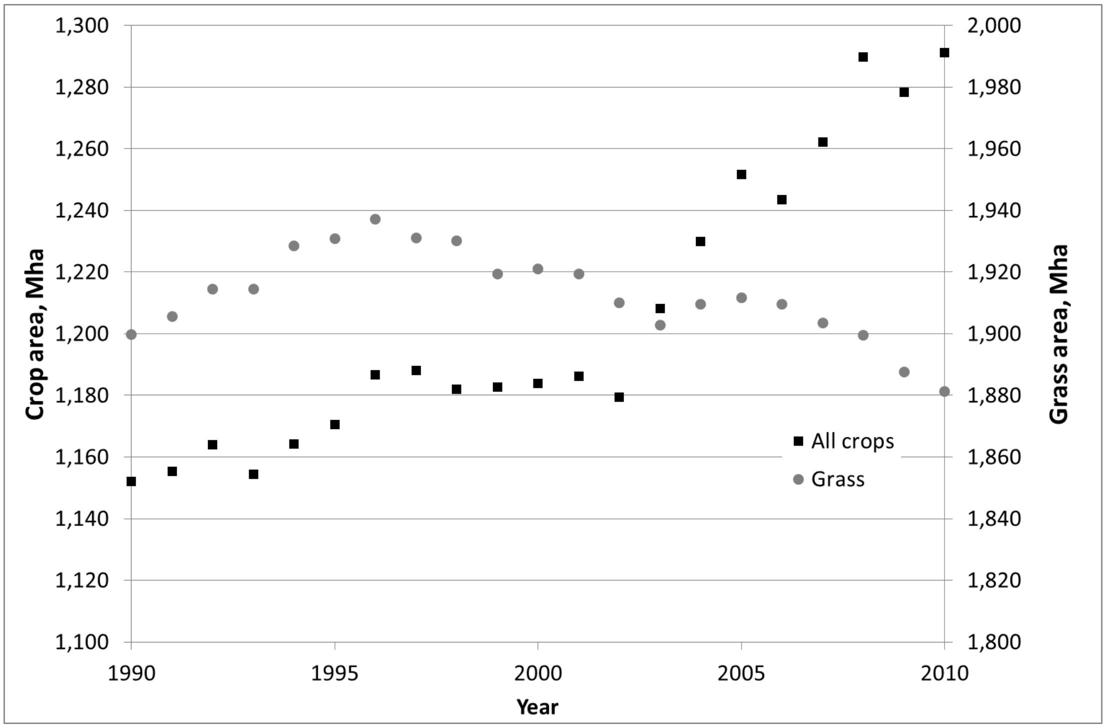

Figure 1. Changes in annually recorded global crop and grassland areas from 1990 to 2010 using data from FAOSTAT and screening out economically isolated grasslands.

3.2. Rescaled land use change emissions 1990 to 2010

When crop area expansion is broken down, it is clear that soy dominates, with maize following at about 55% of the soy rate (Table 3). Rice and rapeseed expanded at about 25% of the rate of soy from 1990 to 2010. In contrast, the area of wheat, the main grain consumed in the UK, has decreased at about 15% of the rate of increase of soy. The effect of normalization is to increase the LUC impact of soy by 36% compare with the single top-down value of Audsley et al, (2009) and to decrease barley by 21% (Table 3). This is a factor of 1.7 between crops in the top 25 of global production and clearly reflects a major difference in demand. Onion is the crop that lies closest to the mean.

These scalars thus increase the LUCE factor per ha of soy from the single value of 1.4 to 1.9 t CO_2e/ha and to decrease the values for wheat and barley to 1.3 and 1.1 t CO_2e/ha respectively. One value is given for all other crops together for convenience, but a separate value should be determined for any other individual crop of interest.

Table 3. Rates of expansion of crops from 1990 to 2010, normalized scalar for each crop and revised LUCE emissions. Crops are ordered by global production in 2010

Commodity	Rate of expansion, kha/year	Normalized scalar of LUC impact	Revised value for LUCE by crop from the single value of Audsley et al, (2009), t CO_2e/ha
Soybeans	2,502	1.36	1.94
Maize	1,431	1.20	1.71
Rice	616	1.07	1.53
Rapeseed	593	1.07	1.53
Oil palm fruit	488	1.06	1.50
Vegetables, fresh	443	1.05	1.50
Sugar, cane	315	1.03	1.47
Cassava	168	1.01	1.43
Onions	110	1.00	1.43
Tomatoes	98	1.00	1.42
Bananas	89	1.00	1.42
Watermelons	79	1.00	1.42
Coconuts	71	1.00	1.42
Cucumbers	47	0.99	1.41
Oranges	39	0.99	1.41
Potatoes	38	0.99	1.41
Cabbages	30	0.99	1.41
Grapes	-26	0.98	1.39
Sorghum	-47	0.98	1.39
Sweet potatoes	-52	0.98	1.39
Apples	-54	0.98	1.39
Cotton	-65	0.97	1.38
Sugar, Beet	-227	0.95	1.35
Wheat	-373	0.93	1.32
Barley	-1,228	0.79	1.13
Other crops	1,887	1.25	1.78
All crops	6,972	1	1.42

3.3. Effect of choice of baseline LUCEs and different estimated agricultural areas dedicated

The choice of what values to use for global land use change emissions and connected agricultural area has major effect on the results (Table 4). The potential baseline values range from 0.67 to 2.95 t CO_2e/ha: a range of 4.4 to 1. However, the more recent review by Vellinga and Van Middelaar (2011) seems likely to give the best estimate for global land use change emissions. The identification of connected agricultural areas depends on a degree of arbitrariness in identifying disconnected grasslands. This study applied the same broad approach as Audsley et al. (2009), but with more recent data and by applying more than one test. It is thus more discriminating.

Table 4. Baseline land use change emissions resulting from combining six sources of land use change emissions with three sources of the areas of connected agricultural activity. Results are in t CO_2e/ha.

		Harvested area data source		
		Audsley el al. (2009)	Vellinga & Van Middelaar (2011)	This study
Global LUC emissions data source	Audsley et al. (2009)	1.42	1.01	1.72
	Vellinga & Van Middelaar (2011)	1.62	1.15	1.95
	DeFries et al. (2002)	0.95	0.67	1.15
	Houghton (2003)	2.33	1.65	2.81
	Olivier et al. (2005)	2.44	1.73	2.95
	Vellinga & Van Middelaar (2011), including soil degradation.	1.67	1.18	2.01

3.4. Effects of time horizon on emissions

The time horizon used for calculating rates of change of crop areas includes market influences coupled with the technical change of generally increasing yields, which increase at a lower rate. There were evident differences over the time scales of 3 to 20 years, e.g. with the factor for soy being 50% larger over 15 than three years (Table 5). Overall, the effects of changing the time scale were relatively small, given the coefficients of variation over the six time periods analyzed. This is particularly the case for onions: the crop that was closest to the mean. The choice of time is arguably arbitrary, but it is rational to use a relatively long period to avoid short term influences.

Table 5. Range of LUCE values for emblematic crops using different time horizons to obtain the rates of change of crop area. Results are in t CO_2e/ha and use the baseline LUCE of Audsley el al. (2009). Onion is the crop closest to the mean.

	Time period of area change analysis up to 2010, years							
Commodities (integers show order in 20 year analysis)	20	15	10	7	5	3	Mean	Coefficient of variation, %
1. Soybeans	2.2	2.5	2.0	2.1	2.3	1.6	2.1	14%
2. Other crops	2.1	2.3	2.1	2.3	2.4	1.6	2.1	15%
3. Maize	2.0	2.2	2.0	2.3	2.6	1.5	2.1	17%
4. Rice	1.8	1.9	1.8	2.0	2.1	1.5	1.9	12%
6. Oil palm fruit	1.7	1.9	1.7	1.8	2.0	1.5	1.8	9%
10. Onion	1.6	1.8	1.6	1.7	1.9	1.5	1.7	7%
25. Wheat	1.5	1.7	1.7	2.0	2.1	1.5	1.7	13%
26. Barley	1.3	1.5	1.5	1.5	1.5	1.4	1.5	6%

4. Discussion

The top down approach offers a method of including both direct and indirect land use change GHGE in analyses, especially for animal diets or addressing national dietary consumption. This study indicates how the approach can be developed to address the relative expansion rates of crops at a global level and hence overcome a perceived limitation of the original method, i.e. all crops are equally “responsible” for land use change. It is evident that the global demand for soy outstrips all others and this approach accounts for that. Crop area expansion is effectively a measure of demand, although tempered by the generally increasing annual crop yields. Thus, where technical effectiveness is greater in increasing yields, the impact in area expansion is reduced. It is still relatively simple method to apply, with much lower disaggregated data needs than if trying to apply the bottom up approach that is implied by adherence to PAS2050 or any similar procedure for a particular crop.

There is opportunity for debate about values of some of the terms used, e.g. time scale, connected area of agricultural land and the global GHGE from land use change. The time scale needs to be sufficiently long to avoid short term fluctuations, but not so long as to miss global market trends and a scale of seven to ten years seems to be appropriate. The connected area of agricultural land is one that could be explored further by scrutinizing the trade in arable commodities to that including any subsistence farming is avoided. One problem that arose in dealing with grassland area changes is that of countries changing borders through major political transformations, e.g. the breakup of the Soviet Union. This presented some obstacles in determining whether grassland should be included or not over the time series.

Vellinga et al. (2013) reviewed the data sources on global land use change emissions and their assessment of the most suitable term seems a reasonable choice. Its continued application also makes analyses compatible with the Dutch *FeedPrint* approach.

5. Conclusion

A development of the top down method for accounting for all direct and indirect land use change emissions is presented, which reflects the relative rates of global crop expansion. This, in turn, reflects global demand and so puts a heavier burden on those commodities that are most dominant in driving land use change, e.g. soy. It is thus more equitable than the original top down method. It represents a method with relatively low computational and data demands.

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