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Historical deforestation due to expansion of crop demand: implications for biofuels

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Abstract

The report presents an independent estimate of the part of LUC emissions due to deforestation, starting from the 29% of historical deforestation area (and estimated emissions) caused by expansion of different crops. The deforestation area and emissions per tonne of extra crop are converted to emissions per MJ biofuel from that crop. The average global deforestation caused by increase in production of a crop or biofuel is estimated, making no geographical differentiation in where the extra demand occurs or where that would provoke deforestation.
The source of historical deforestation data is a report published by DG ENV [EC 2013] which estimates which areas of forest were lost to different crops and to other land uses (grazing, logged forest, urban and others.) between 1990 and 2008. It used historical deforestation data from FAO's Forest Resource Assessment 2010, interpreted with other FAO data.
The emissions are calculated only from deforestation and peat forest drainage, attributed to each MJ biofuel. This does not include emissions from the grassland area converted to cropland.
This method gives an independent verification of the general magnitude of LUC area and emissions which should be expected from bottom-up models of LUC for scenarios, and the results indicate that historical LUC emissions were higher than those estimated by most economic models.

Disclaimer:

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EXECUTIVE SUMMARY

Land use Change (LUC) due to biofuels is usually estimated starting off with increased biofuel crop demand and working out associated global land use changes and greenhouse gas emissions. Here, we present a completely independent estimate starting from historical deforestation area caused directly by historical expansion of different crops. First, we divide this by the historical increase in production of each crop, to find deforestation per tonne of crop. To find deforestation per megajoule (MJ) of biofuel, we divide by the MJ of biofuel which could be made from it. Finally, we convert deforestation area to deforestation emissions.

Therefore, the method does not estimate the impacts of EU biofuel policy in the future, but gives an independent estimate of the general magnitude of deforestation emissions which would have been associated with making one MJ of biofuel from various crops in the past.

We can only estimate the average global deforestation emissions for biofuels made from oilseeds, cereals or sugar cane, without geographical differentiation of where the production occurs. This means we cannot consider emissions from loss of carbon stored in mineral soils, which vary strongly depending on local soil type and climate.

SOURCES

The source of historical deforestation data for this study is a report prepared in the framework of a study contract for the European Commission Directorate General for the Environment (DG ENV) [EC 2013], which estimates which areas of forest were lost to different crops and to other land uses (grazing, logged forest, urban and others) between 1990 and 2008[1]. It is the first and only report that disaggregates global deforestation data to particular crops, as far as we are aware. It used historical deforestation data from the Food and Agriculture Organisation (FAO) Forest Resource Assessment 2010, interpreted with other FAO data.

METHOD

[EC 2013] reports the area of deforestation between 1990 and 2008, already allocated to different causes, of which 29% was expansion of crops. The driving force for the expansion of a crop is considered to be the net increase in production of that crop plus the increment in production needed to compensate the loss in countries where there was a decline in the area of the crop.

Dividing by this production increase, we obtain the area of deforestation in 1990-2008 per tonne of crop. We then divide this by the amount of biofuel which could be made from one tonne of crop, to obtain the deforestation area which would correspond to 1 MJ of biofuel. We allocate part of the deforestation-per-MJ to the by-products of biofuels on the basis of their economic value. Alternative results, using allocation by energy content, are shown in the appendix.

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[1] [EC 2013] only gave a breakdown of deforestation attributed to particular crop groups over the whole 1990-2008 period, so our results are also for the whole period. However, the rate of overall deforestation is slowing from ~14.2 Mha/yr in 1990-2000 to ~12.2 Mha/yr in 2000-2008, whilst the deforestation attributed to cropland expansion increased between the two periods (see Table 1).

The emissions due to this deforestation-per-MJ of biofuel were then found using standard data from FAO and the International Panel on Climate Change (IPCC)[2], and adding emissions from drainage of tropical peat forest for oil palm[3]. Finally, in line with other LUC calculations used by the Commission, these emissions are spread over 20 years in order to be able to compare them to direct annual emission savings per MJ of biofuel[4].

RESULTS

The table shows the land use change emissions from deforestation and peat forest drainage, aggregated for different crop groups, attributed to each MJ of biofuel.

It should be borne in mind that this study only estimates deforestation emissions, which are only part of LUC emissions: one should add the emissions caused by crop expansion onto grassland, which could increase the estimates, especially for ethanol, by up to about 77% (according to estimates based on the results of the International Food and Policy Research Institute (IFPRI) MIRAGE model delivered to the EC [Laborde, 2011]). Furthermore, we do not include emissions from loss of carbon from mineral soils, which in [JRC 2011] for example, account for an additional 8 to 30% of emissions.

The figures also have to be considered bearing in mind a number of limitations. Firstly, they inherit the uncertainties in estimations of deforestation area which arise principally from data limitations discussed in [EC 2013] along with methodological choices in attributing this to different causes. These are compounded with the uncertainties in carbon stock changes.

Emissions from deforestation ($gCO2/MJ$)	
Oilseeds biodiesel without peat emissions	63
Oilseeds biodiesel with peat emissions	123
Cereals ethanol	15
Sugar cane ethanol	39

Notably, we show that because [EC 2013] aggregates data at national level, it probably attributes too much deforestation to sugar cane and too little to soybeans.

Secondly, the results are derived from deforestation figures attributed to crop groups in the relevant areas. But as the expansion of one crop group at the expense of another can drive deforestation by the second crop group, the true figures for biodiesel and bioethanol are probably closer to each other.

Thirdly, for the calculation of deforestation per tonne of extra crop produced, assumptions have to be made about what drives increases in crop yield. The historical increase in crop yields can be broken down into two components: a time trend and a term that depends on price (reflecting fluctuations in demand). Here we assumed that all yield increase was due to the increase in demand.

[2] Only above and below-ground biomass C emissions have been considered in the calculations of deforestation emissions; changes in soil C stocks are not included. However, in the case of peat drainage, soil C emissions have been included in the calculations - see explanations in chapter 3 and footnote 3.

[3] Several studies indicate that loss of soil-carbon following drainage of peat-swamp forest account for about half the total LUC emissions from biofuels.

[4] The Commission has always spread LUC emissions over 20 years, for example in the rules for estimating direct LUC emissions in annex of the RED, and in its estimates of indirect land use change emissions. It is in line with the proposition that a batch of biofuel should achieve the claimed emissions savings within 20 years of consumption.

This gives the most optimistic (lowest) LUC results. Had we chosen the assumption that yields increase only with time, the results would be substantially higher, because the same emissions would be attributed to only a fraction of the demand increase.

Finally, we accounted for the deforestation caused by the shift of crop production from some countries where land was abandoned, to others where it expanded. However, *inside* some countries cropland may have been abandoned in some places whilst it expanded overall. Our method does not take this effect into account, but we estimate that, even if the resulting error is small on the global scale, this could lower the results.

CONCLUSION

This method gives an independent estimate of the general magnitude of deforestation emissions which would have occurred if various crops had been used to make biofuels in 1990–2008. These results are somewhat higher than those estimated by most economic models; this may be due to deforestation rates falling over time, and to some models not accounting for (or underestimating) emissions from drainage of tropical peat.

1. Introduction

Land Use Change (LUC) due to biofuels is a *marginal* phenomenon: it is the change in land use caused by a change in biofuel use or production. It can be expressed in terms of the area of land converted to crops or of the emissions resulting from that area change. To compare the LUC emissions with direct emissions from biofuel production, the emission change is divided by the amount of changed biofuel production, so that the units come out as ha/MJ biofuel or gCO_2/MJ biofuel.

LUC is usually estimated using economic models of world agriculture and trade or even the whole world economy. These models start off with a baseline model scenario representing the present agricultural/economic situation (or more usually a projection for some years ahead) and then "shock" the model with more demand for a particular biofuel, or with a whole biofuel policy. The model predicts the resulting changes in crop area and where they will happen. These results are converted to emissions using a second model, which projects the emissions caused by land use change in different locations and sometimes for different crops.

This is the correct scientific approach to an inherently complex problem, which has to rely on hundreds of assumptions and parameters contributing to the model results.

In a drive to clarify the approach, attempts have been made to make simplified calculations using spreadsheets. One approach is to choose a simplified chain of consequences from biofuel production (for example, which crops are substituted by by-products, and where they are produced). However, in reality many consequences occur simultaneously, and by selecting particular chains, very differing results can be obtained. Another approach is to estimate what the LUC effect would be if a certain quantity of biofuel would have been produced in the past, using some historical data and some transparent averaging. That is the approach used in another new JRC study "Estimates of Indirect land use change from biofuels based on historical data" [JRC 2014 – in publication].

All the approaches mentioned above start off with a biofuel demand and work out its associated LUC. Here, we present a completely independent estimate starting from the part of historical deforestation (and associated emissions) attributed to the expansion of different crops, and then working out how that relates to the production increase for each crop.

This report was made possible because for the first time (to our knowledge) estimates of the areas of deforestation caused directly or indirectly by the expansion of different crops, are calculated on a consistent basis. These are presented, in a European Commission report funded by DG ENV and undertaken by VITO, IIASA, HIVA and IUCN NL [EC 2013[5]]. This study reports deforestation allocated to different immediate causes, as detailed in Table 1. It combines national deforestation data from the Global Forest Resource Assessment, FRA 2010 [FAO, 2010a], cross-checked with results of the FAO remote sensing survey of forestry, with production data on agriculture and forestry from FAOSTAT [FAO, 2011]. The method for allocating deforestation to the different drivers required detailed analysis, tracking the direct and indirect contributions of agricultural

[5] The report can be found at: http://ec.europa.eu/environment/forests/pdf/1.%20Report%20analysis%20of%20impact.pdf

expansion on deforestation using a land-use transition model, and an extensive FAOSTAT database; the methodology was revised with the help of a review panel of independent experts. The land use data are only available for certain years, so [EC 2013] could report data for only two periods: 1990-2000 and 2000-2008.

Table 1. Global deforestation rates, allocated to different causes, according to [EC 2013]

Sector	1990-2000	2000-2008	1990-2008	
	Mha/y	**Mha/y**	**Mha***	**% of total deforestation**
Cultivated land and crops	**3.7**	**4.1**	69.4	**29%**
Pasture expansion and ranching	3.5	2.9	58.2	24%
Legal logging**	0.2	0.3	4.5	2%
Urban and infrastructure	0.5	0.5	8.9	4%
Natural hazards (esp.wildfires)	2.4	2.1	40.8	17%
Unexplained**	3.9	2.3	57.5	24%

* The values in this column are from EC, 2013. They could be slightly different from the sum of the values (per year) in column 2 and 3 because they are rounded to one decimal place.

**Industrial roundwood production (logging prior to agricultural expansion).

*** Illegal logging, fuel wood, reporting errors.

[EC 2013] also estimates the deforestation due to expansion of various individual crops and crop groups. However, these data are only reported for the combined period 1990-2008, so we are forced to work with deforestation data per crop covering this combined period, even though biofuels started to expand rapidly only in the second part of it.

We see that in the combined time period, crop expansion contributed for 29% to total deforestation. Although the overall rate of deforestation decreased from the first period (1990-2000) to the second (2000-2008), the average rate of deforestation *attributed to crop expansion* actually increased, from 3.68 to 4.07 Mha (Million hectares) per year. Therefore, one would expect that if we could use data only from the second period, this would increase our estimates of deforestation emissions from crops.

We convert the areas of deforestation in 1990-2008 into estimates of deforestation per crop. Then we divide those estimates by the increase in crop production (see details in text box 2), and calculate related emissions.

In text box 1, we discuss how to take the crop yield increase into account and we explain the assumptions made.

We make no geographical differentiation in where the extra production occurs: we simply look at the global average deforestation emissions per tonne of extra production for different crops.

Of course, the deforestation area and emissions per tonne of increased crop production do not depend on whether that increase is for food or for biofuel. But if the crop is used for biofuel, we only allocate part of the deforestation emissions (from that crop) to biofuel, and the rest to by-products, on the basis of their economic value. This method, which is one of the main approaches commonly used, takes into account the economic drivers for biofuel crop production.

An alternative would be to allocate emissions to biofuels and by-products on the basis of their energy content, which, for reasons of convenience, is used in the calculations of direct emissions in Annex V of the Renewable Energy Directive (RED)[6]. The results using this method of allocation are presented in appendix.

The results in this report are intended to provide an independent estimate of the magnitude of LUC emissions: our methodology may be approximate, but by starting from *reported* deforestation and *reported* production increase, it automatically includes many effects which must be estimated in models.

2. Method

This report starts with the estimates of the areas of deforestation caused directly by the expansion of different crops reported in [EC 2013]. Note that crop expansion only accounts for 29% of total deforestation in these data: the rest is attributed to other causes. **Starting from the reported areas of deforestation caused by different crops** between 1990 and 2008:

1. We assume that the total driving force for the expansion of a crop comprises two components: (a) the net increase in production, which equals the increase in demand (see text box 1), and (b) the increment in global production needed to compensate the loss in crop production caused by the crop area shrinkage which occurred in some countries (see text box 2). We divide the area of deforestation attributed to a crop first by the net increase in production of that crop (a) which occurred between 1990 and 2008 (FAOSTAT data), and then multiply the result by a correction factor (a/(a+b)) to account for the second component (b)[7]. This gives an estimate of ha of deforestation per tonne of what we call **gross** crop production increase (a+b). Of course, this is the same whether that is for food or biofuel. We also estimate how much of the deforestation area caused by oil palm expansion was tropical peat forest.

[6] Directive 2009/28/EC "on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC".

[7] We do it this way, because the correction factor is for the whole crop group, see text box 2.

2. To analyze the case where an extra tonne of crop production comes from the production of biofuel, we allocate the deforestation area between biofuel and by-products on the basis of their economic value[8]. In appendix, we also show the results of allocation by lower-heating value (LHV) of all used products of the crop[9]. This step gives the hectares of deforestation per MJ increase in biofuel production.
3. We multiply the deforestation areas per MJ biofuel by IPCC estimates of greenhouse gas emissions-per-ha (GHG/ha). In fact, [EC 2013] gives the areas of deforestation in a few major regions, so we use regional IPCC GHG/ha data to match. This step gives the grams of CO_2-equivalent emissions per MJ of increased biofuel production. For the part of the oil palm expansion on tropical peat we include the emissions resulting from peat drainage[3].
4. Finally, in line with other LUC estimates used by the Commission, and with the method of calculation of direct land use change emissions prescribed in the RED, we spread these land use change emissions over 20 years in order to be able to compare them to the direct annual emissions savings per MJ biofuel[4].

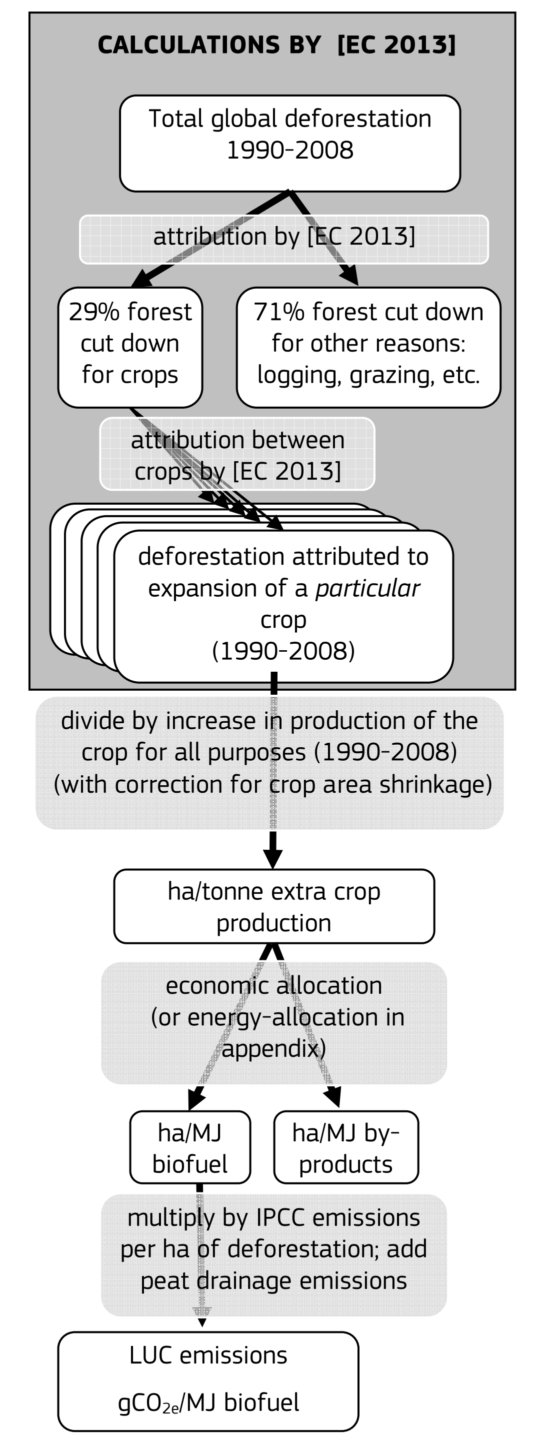

Figure 1. Method description

[8] For example, the deforestation per tonne of oilseed is allocated according to the value of the vegetable oil compared to the value of the oilseed meal by-product. This allocation is inherited by the biodiesel made from the vegetable oil.
[9] We did not include the substitution approach to allocate deforestation emissions to by-products because this would require a stack of assumptions and vastly complicate this simple analysis.

TEXT BOX 1: FINDING THE DIVISOR FOR DEFORESTATION

[EC 2013] reports the area of global deforestation which is caused by crop expansion, and we can convert that into emissions. But to work out deforestation emissions per tonne of crop (and hence per MJ of biofuel) we need to divide this by a measure of the amount of crop which acted as the driver for crop expansion. This section is about what this divisor should be.

The percentage net increase in crop production results from the increase in crop yield[10] and net crop area. For small % changes in a given time period[11]:

(% net increase in crop production) = (% increase in yield) + (% net increase in crop area)[12]

Furthermore, at **global** level, the net increase in crop production can be equated to the increase in demand[11,13]:

(% net increase in crop area) = (% increase in demand) - (% increase in yield)

Apart from annual fluctuations due to weather, crop yields increase inexorably with time, because farmers and agriculturalists "learn by doing". However, the yield is likely to increase more over a given time period if the price of the crop increases. Only the price-dependent part of the yield increase responds to demand increases. Thus one can decompose the yield increase over a given time period into two components:
- The first component is a fixed yield increase (which increases only with the length of the time period[14]).

- The second component depends on demand.

Since it is difficult to estimate the two components only from historical data, without the support of economic models, we have applied the simplified assumption that the crop yield increase is proportional to demand increase. Accordingly, in this first step, we divide the deforestation by the entire increase in demand, which, at global level, equals the increase in production.

If we had taken into consideration also the "fixed-rate" yield increase, the same historical deforestation would have been attributed to fewer tonnes of crop, so the emissions per tonne would be higher.

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[10] In this context, yield increase includes the effects of a greater share of double-or multiple-cropping.

[11] Mathematically, there is a third, second-order, term describing the increase in yield on the new crop area. However, this is negligible for the small % changes considered here.

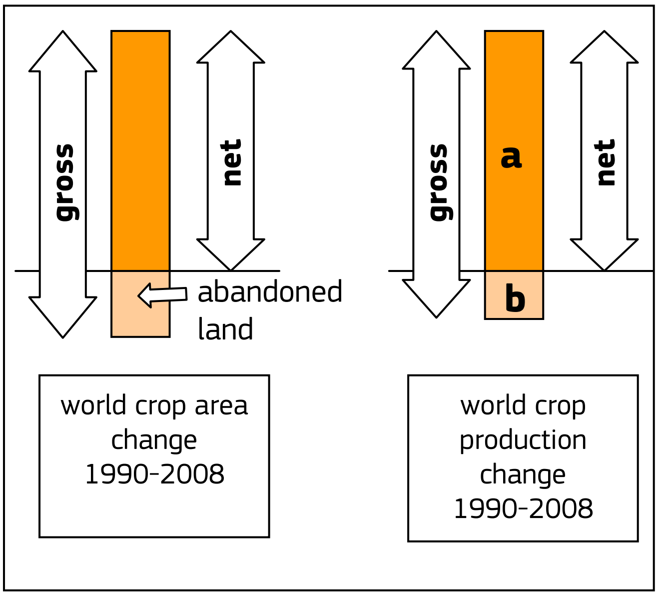
[12] [Bruinsma 2011] estimated that less than about one fifth of the increase in global crop production came from the net increase in crop area in recent decades (the rest from yield increase and cropping intensity).

[13] Ignoring changes in stocks, which are small and short-term. Obviously, the increase in production equals the increase in demand only at global level: at local/small scale level the two components can be different because of trade.

[14] Modelers often call this the "exogenous" rate of yield increase, as it is fixed, and not calculated endogenously by the models.

TEXT BOX 2: CORRECTING FOR LOSS OF PRODUCTION IN COUNTRIES WHERE CROP AREA SHRANK

We assume that the main driver for the expansion of crop area that causes deforestation is the net increase in the production of that crop. However, the area shrinkage which occurred in some countries and the area expansion in others also gives rise to some "baseline deforestation" which would have happened independently of any change in total demand[15]. For example, the most notable shift in the time period covered by the study was the fall in crop area in ex-Soviet Union and Warsaw Pact countries and the rise in crop area in South America.



These global shifts between countries can be taken into account by introducing a correction factor: instead of dividing the deforestation emissions simply by the increase in demand (which, at global level, equals the *net* increase in production[13]) as described in text box 1, we should divide it instead by what we call the ***gross*** increase in demand, defined by:

(gross increase in production) = a + b

where **a = the net-increase-in-production**

and **b= the increment in production required to compensate the loss caused by the shrinkage of crop area which occurred in various countries**[16].

It is not a good idea to do this on an individual crop basis, because that would miss similar crops displacing each other. For example, the major global shift mentioned above (e.g. less wheat area in ex-Soviet Union; more maize area in South America), would be completely missed if wheat and maize were considered separately. Therefore it is preferable at least to consider crop groups[17].

In practice, we start off with the deforestation by a crop divided only by **(a)**, the net increase in production (as explained in text box 1), and then apply a correction factor

[15] We recall that "baseline deforestation" caused by other drivers, such as logging, conversion to grazing, infrastructure and urban expansion, was already subtracted by [EC 2013] before our calculations start.

[16] This is more correct than adding the areas of abandoned land to the net crop area expansion, because the yields are different in ex-USSR and South America.

[17] To a lesser extent, different crop groups can also displace each other: one could argue that lost wheat production due to area shrinkage in ex-USSR was partly compensated by increased maize/soybean ratio in the US, and this in turn increased soy area in South America (compared to the increase without USSR area shrinkage). Thus one could argue that crop groups should be amalgamated. This is dealt with in the discussion of results.

a/(a+b), which reduces the deforestation per tonne. The correction factor is the same for all crops within one crop group.

To calculate **(b),** the loss in production due to crop land shrinkage, we identified all countries which suffered a contraction in the area of a particular crop (e.g. soybeans), and multiplied this by the average yield of that crop in that country between 1990 and 2008. Then we summed the losses of production for each crop. For cereals, we just added the tonnes of lost production, but for oilseeds we first converted the production to vegetable oil equivalents, using the fractions of oil that were assumed by [EC 2013].

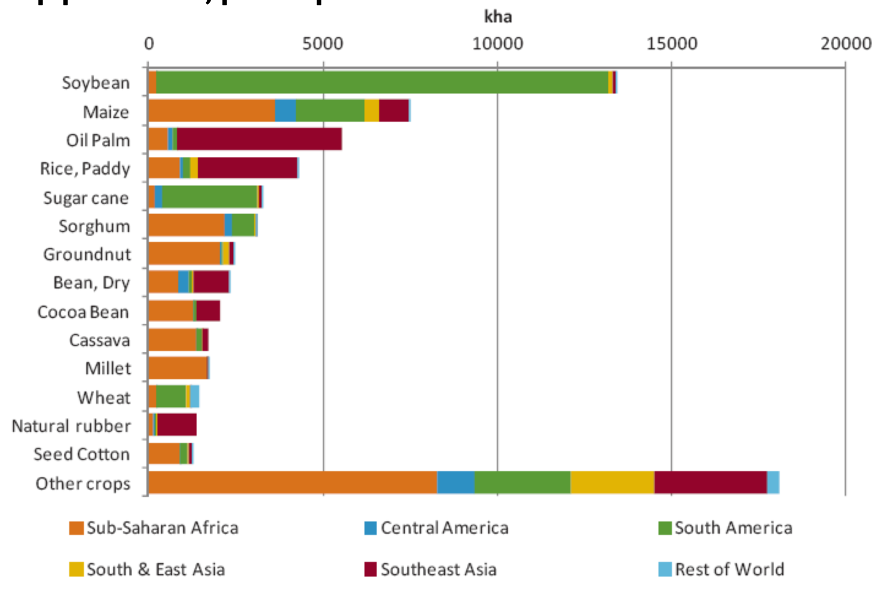
This is of course an approximation, because we assume that the yield on the lost crop area is the same as the average yield for that crop in that country. As the lost fields are likely to have lower than average yield, this overestimates the lost production and hence slightly underestimates deforestation emissions per tonne of crop. On the other hand, FAO country data do not show shifts of crop area inside a particular country, which would dilute the deforestation emissions further. It is difficult to estimate which of these factors would be more important.

3. Data

3.1 Deforestation

The recent report published by the European Commission [EC 2013] estimates that the global deforested area from 1990 to 2008 attributed to crop production amounts to 69.4 Mha. Based on assumptions about causality links, the report finds that the increase in production of five agricultural commodities alone may have caused half of the deforestation associated with cropland expansion, as can be seen in the figure below.

Figure 2. Contribution of specific crops to deforestation associated with expansion of crop production, per crop 1990-2008



Source: [EC 2013]

Soybeans, maize, oil palm, rice and sugar cane contributed to global deforestation for 19%, 11%, 8%, 6% and 5% respectively according to the same report (Table 2).

Table 2. Global deforested area attributed to crop expansion (1990-2008)

Deforested area attributed to:	**Mha**	**%**
Maize	*7.64*	11
Wheat	*1.50*	2
Rice	*4.17*	6
Sugar cane	*3.47*	5
Soybean	*13.19*	19
Oil palm	*5.55*	8
Total Crop expansion	69.41	100

Source: [EC 2013]

Moreover, the report states that one third of total gross deforestation between 1990 and 2008 occurred in just two countries, Indonesia and Brazil.

In Brazil, agricultural expansion is found to be the primary driver of deforestation and cropland expansion may be held responsible for about a third of total deforestation between 1990 and 2008. Soybean contributed for 57% of deforestation due the cropland expansion in Brazil.

In Indonesia, 8 Mha of deforestation was attributed to the expansion of cultivated land between 1990 and 2008 and more than 40% of deforestation was caused by oil palm production (Table 3).

Table 3. Attribution of deforestation to different crops and regions (1990-2008)

Oilseeds		**Δ ha of deforestation (Mha)**
Oil palm	**Indonesia**	3.18
	RoW*	2.37
Soybean	**Brazil**	8.65
	RoW*	4.54
Rest of oilseeds**	**World**	6.46

* Rest of the World

**Rest of oilseeds are all other oilseeds excluded palm oil and soybean.

Source: own calculations based on [EC 2013] data.

Estimating the area of palm oil expansion on tropical peat forest.

Recent reports by international organizations (e.g. Wetlands International, FAO, MBOP) and scientific literature [e.g. Page 2011 and Miettinen 2012] show that a significant part of deforestation in Indonesia and Malaysia occurred on tropical peat forest. These were drained mostly for establishing industrial plantations of oil palm or acacia. We calculated the increase in area of oil palm on peatland in between 1990 and 2008 was at least 1.71 Mha:

1. [Miettinen 2012] reports the historical expansion of industrial plantations on peat in Peninsular Malaysia, Sumatra and Borneo. By interpolating this graph we estimated that industrial plantation expanded by about 2.48 Mha between 1990 and 2008.
2. We deduced from the data in [Miettinen 2012] that oil palm represented 69% of total industrial plantations on peat in Peninsular Malaysia, Sumatra and Borneo[18].

[18] The fraction of oil palm in all industrial plantations was only available for 2010, but this represents the cumulative deforestation up to that time. This fraction increased with time, as oil palm has become the more profitable crop. So this leads to a small underestimate of the fraction of oil palm in the marginal deforestation in the final decade up to 2010, and hence an underestimate of oil palm deforestation area.

3. Therefore, palm oil plantations on peat lands expanded by about 0.69*2.48 = 1.71 Mha between 1990 and 2008. We take this as a total figure even though the data only cover Peninsular Malaysia, Sumatra and Borneo.
4. We subtracted the peatland area from the total deforestation due to oil palm reported in [EC 2013]. In Table 4 we chose to subtract this from the Indonesian deforestation figure, even though some of it occurred in the "rest of the world".

Table 4. Deforestation on peat and other forest (1990-2008)

		Δ ha of deforestation (Mha)
Oil palm	**Indonesia**	1.48
	Peatland	1.71
	RoW	2.37

Source: own calculations based on [Miettenen 2012] data.

Allocating by economic value

Biofuel production processes produce simultaneously the fuel of interest and other by-products. To attribute land use change emissions from deforestation to biofuels, total emissions have to be ascribed to the biofuels and to by-products.

As also explained in the Impact Assessment which accompanied the Renewable Energy Directive (RED) and Fuel Quality Directive (FQD)[19], the method used for regulatory purposes is the "allocation" approach: emissions can be allocated between biofuels and by-products in proportion to their energy content (LHV of the dry matter), mass or economic value (specifically, allocation by "energy content" is applied in the RED and FQD)[20].

For the purposes of this report, we allocate the estimated deforestation area (and related emissions) between biofuel and by-products on the basis of their economic value. This method has the advantage of better capturing the capacity for an animal-feed by-product to replace crops.

Results based on allocation by energy content ("RED-method") are also reported for comparison in appendix.

Table 5 shows the value shares of different products of oilseeds.

For consistency, we took the value shares for vegetable oils from Annex C1 of [EC 2013] report, except for oil palm products, which we had to calculate ourselves using the same methodology shown in Annex C1 of [EC 2013].

[19] SEC(2008)85 and related annexes.

[20] Another method is the "substitution" approach, which is better suited to policy analysis. However, applying this method would require many assumptions and vastly complicate this simple analysis.

Last column of Table 5 shows the results in terms of millions of hectares of deforested area which may be allocated to vegetable oil.

Table 5. Attribution of deforestation to vegetable oil (1990-2008)

Oilseeds		Δ ha of deforestation due to crop production (Mha)	Value share vegetable oil	Δ ha of deforestation due to oil production (Mha)
Oil palm	Indonesia	1.48	98%	1.44
	Peatland*	1.71	98%	1.67
	RoW	2.37	98%	2.32
Soybean	Brazil	8.65	36%	3.11
	RoW	4.54	36%	1.64
Rest oilseeds	World	6.46	78%**	5.05

*Peninsular Malaysia, Sumatra and Borneo.

**Weighted average of the value share of the rest of oilseeds available in [EC 2013] (soybean and palm oil excluded).

3.2 Carbon Emissions

Our source for carbon stocks data for forest biomass and dead wood at global and regional level is FAO (FAO, 2010a; FAO, 2010b; FAO, 2010c) (Table 6).

Table 6. Forest carbon stock

	AGB* (tC/ha)	BGB** (tC/ha)	DW*** (tC/ha)	Litter (tC/ha)
Indonesia	103.6	34.2		
Brazil	101.5	19.0	7.5	4.4
RoW	71.6		17.8	

*Aboveground biomass; **Belowground biomass; ***Dead wood

For oil palm plantations (OPP), we use carbon stocks data from [Syahrinudin 2005], who conducted a study on oil palm plantations in Indonesia. We show plantation carbon stocks averaged over the typical 25-year life of a plantation. These data are more detailed (providing information for different carbon pools) than IPCC default data. Carbon stocks data for cropland (including soybean and rest oilseeds) come from [IPCC 2006] (Table 7).

Table 7. Carbon stock for oil palm plantation (OPP) and cropland

	AGB (tC/ha)	BGB (tC/ha)	Litter (tC/ha)
Oil Palm Plantation	50.2	18.8	5.5
Cropland	5.0		

In the case of forest conversion to oil palm plantation, the soil carbon content does not change significantly. By contrast, when converting forests to cropland, 20-40% of original soil carbon stocks can be lost [IPCC 2006]. According to IPCC methodology, the loss of carbon stocks is calculated taking into account the specific climate region where the change occurs, the type of soil, as well as management and input factors. Unfortunately, the data we have on global deforestation are not disaggregated by climate region, so we did not attempt to include soil carbon emissions caused by deforestation on mineral soils; we only considered changes in above and below-ground biomass. Indicatively, according to the relative contribution of soil carbon emissions in [JRC 2011], this causes an 8-30% underestimate in emissions.

For each considered region, CO_2 emissions per hectare caused by land use change are calculated as the difference between forest carbon stocks and the carbon stock of the current land use (oil palm and croplands) (tC/ha) multiplied by 44/12 (to convert C into CO_2).

The calculation of emission factors for peat decomposition due to drainage is subject to large uncertainties: CO_2 emissions from peatland drainage are the result of complex interactions between environmental factors, land management and microbial activity, causing considerable spatial and temporal variations. This, together with the different methodologies applied to measure the emissions, results in a large variation in the estimated emission factors [Marwanto 2014].

For this study, we have used values derived from [Page 2011], which are based on an extensive literature review of the carbon losses and GHG emissions from oil palm plantations in South East Asia. The emission factor estimated in [Page 2011] is 27.3 tC $ha^{-1}yr^{-1}$, averaged over the 25-year life of an oil palm plantation.

CO_2 emissions due to land use change from the conversion of forests to different crops (oil palm, soybean, and rest of oilseeds) are shown in Table 8.

Table 8. Overall CO_2 emissions per hectare due to land use change

Crop	Region	CO_2 emissions (tCO_2/ha)
Oil palm	**Indonesia***	252
	RoW	55
	Peatland	2,500
Soybean	**Brazil**	467
	RoW	309
Rest oilseeds/crops	**World**	309

*Data for dead wood and litter were not included as they are not provided for forests in Indonesia by [FAO 2010] and [IPPC 2006] provides default factors only for litter and not for dead wood.

3.3 Net increase in crop production

Data on the net increase in production of different oilseeds and other crops (maize, wheat and sugar cane, all in millions of tonnes) between 1990 and 2008 are taken from FAOstat and are shown in the following tables (Table 9 and Table 10).

The net changes in production of oilseeds are multiplied by the extraction yields of the vegetable oil in [EC 2013] to show the net increase of vegetable oil equivalents (even if not quite all the oilseeds are crushed).

Table 9. Net increase in world oil crops production

	1990 (Mtonnes)	2008 (Mtonnes)	Δ Mtonnes 2008-1990	oil extracted as fraction of crop	Δ vegetable oil equivalent (Mtonnes)
Oil palm fruit (palm oil and Palm Kernel Oil)	60.9	214.2	153.2	0.22	34.3
Soybeans	108.5	231.2	122.8	0.18	22.1
Other oilseeds*	165.2	261.5	96.3	0.35	28.4
Δ TOTAL (tonnes)					**84.9**

* Rapeseed, sunflower seed, coconuts, cottonseed, groundnuts with shell, Jojoba seeds, karite nuts (sheanuts), linseed, mustard seed, olives, safflower seed, sesame seed, tallowtree seeds, tung nuts.

Source: data on production from FAOstat and extraction rates data from [EC 2013]

Table 10 shows the increase in production of palm oil in Indonesia between 1990 and 2008 and the increase in soybean production in Brazil for the same time period. These numbers are required because [EC 2013] specifies deforestation in the regions separately.

Table 10. Increase in palm oil production in Indonesia and soybean production in Brazil

	1990 (Mtonnes)	2008 (Mtonnes)	Δ Mtonnes 2008-1990	oil extracted as fraction of crop	Δ vegetable oil equivalent (Mtonnes)
Oil palm fruit (palm oil and PKO) Indonesia	11.2	85.0	73.8	0.22	16.5
Soybeans Brazil	19.9	59.8	39.9	0.18	7.2

Source: data on production from FAOstat and extraction rates data from [EC 2013]

The increases in production of maize, wheat and sugar cane, based on FAOSTATdata, are reported in Table 11.

Table 11. Net increase in production of non-oil crops (Mtonnes)

	1990	2008	Δ (2008-1990)
Maize	483.4	826.8	343.4
Wheat	592.3	683.2	90.9
Sugar cane	1,053.0	1,734.5	681.5

Source: FAOstat

3.4 Production lost by shrinkage of crop area in some countries

We calculated the change in harvested area of each crop in each country between 1990 and 2008, using the FAOSTAT crop database. We also calculated the average yield during this period. Then we selected all the countries which showed shrinkage in area of a particular crop, and multiplied the area reduction by the average yield in that country. This gives an estimate of the lost production due to area shrinkage. Then we totaled the lost production for all countries: see first data column in Table 12.

The second column in Table 12 repeats the overall net increase in production from Table 11. The last column shows the correction factor needed to compensate for the difference between gross and net increase in production due to crop area shrinkage in other countries: see text box 2.

Table 12. Calculating the correction factor for shrinkage of crop area in some countries

	Loss in production due to crop area shrinkage in some countries (1990-2008)	Increase in global production (2008-1990)	correction factor = [net increase (a)] / [loss+ net increase (b+a)]
	Mtonnes	Mtonnes	ratio
Maize	35	343	
Wheat	192	91	
Maize + wheat	227	434	**0.66**
Sugar cane	74	681	**0.90**

Table 13 shows the equivalent calculation for oilseeds. Here we first convert the loss in crop production from shrinkage into loss of vegetable oil production, as it is mostly in the vegetable oil market that displacements between oil crops are felt.

Table 13 Calculating the shrinkage correction factor for oil crops

	Loss in crop production from area shrinkage in some countries (1990-2008)	Fraction of crop which is oil	Loss in veg oil production	Net increase in global veg oil production (2008-1990)	correction factor = [net increase (a)] / [loss+ net increase (b+a)]
	Mtonnes		Mtonnes	Mtonnes	ratio
Soybean	5.7	18%	1.0	22	
Palm oil fruit	0.5	22%	0.1	34	
Other oilseeds	25.4	35%	8.9	28	
Total Veg Oil			10.0	85	**0.89**

4. Results

Deforestation and peat drainage emissions from biodiesel

The following table (Table 14) shows the estimated land use change emissions from deforestation and peat forest drainage, already attributed to vegetable oil production (using the economic allocation fractions listed in Table 5).

In column E, the sum of the CO_2 emissions (C) is divided by the net increase in world annual production of vegetable oils (D). This gives a first estimate of the deforestation and peat drainage emissions per tonne of net increase in annual vegetable oil production (=demand increase). Then we apply the crop group correction factor for the effect of crop shrinkage in some countries (F), as explained in text box 2. There we explain that the correction factor should be calculated for the crop group as a whole, and applied equally to each crop in the group.

For vegetable oils, we see that accounting for the loss of production due to the shrinkage of oil crop area, leads to an 11% reduction in emissions attributed to a tonne of vegetable oil.

One tonne of vegetable oil makes approximately 1 tonne of biodiesel, and the Lower Heating Value (LHV) of both is roughly 37.2 MJ/kg. Using these data, we can find the deforestation and peatland emissions attributable to one MJ of biodiesel or vegetable oil. In line with Commission practice, these land use change emissions are spread over 20 years in order to compare them with direct emissions from making biofuels.

Table 14. Emissions from deforestation and peat drainage

		Δ ha of deforestation due to oil production (Mha)	**CO_2 emissions per ha (tCO_2/ha)**	**CO_2 emissions ($MtCO_2$)**	**Δ veg oil demand (Mt)**	**tCO_2 / Δt veg oil = C/D**	**correction factor for area shrinkage**	**tCO_2 / Δt veg oil = ExF**	**gCO2/MJ veg-oil /20 years**
		(A)	**(B)**	**(C)**	**(D)**	**(E)**	**(F)**	**(G)**	**(H)**
Oil palm	**Indonesia**	1.44	252	364	8	48	0.89	42	57
	Peatland	1.67	2,752	4,607	9	519	0.89	464	624
	RoW	2.32	55	127	18	7	0.89	6	9
	Total	5.43		5,097	34	148	0.89	133	**179**
Soybean	**Brazil**	3.11	467	1,454	7	202	0.89	181	243
	RoW	1.64	309	506	15	34	0.89	30	41
	Total	4.75		1,960	22	89	0.89	79	**107**
Other oilseeds	**World**	5.05	309	1,564	28	55	0.89	49	**66**
OVERALL VEGETABLE OIL OR BIODIESEL				8,621	85	102	0.89	91	**123**

As the table shows, the global deforestation and peat drainage due to the increase in gross palm oil production from 1990 to 2008 lead to global emissions of 179 gCO_2/MJ of oil or biodiesel over 20 years, while the soybean expansion results in 107 gCO_2/MJ of oil or biodiesel. If we consider the total oilseeds production including palm oil, soybean and rest of oilseeds, the global emissions are 123 gCO_2/MJ of vegetable oil or biodiesel.

Results are also shown in Table 15 for oilseeds aggregated as a crop group, estimated as weighted averages over increased world vegetable production, with and without taking into account peatland emissions (but including the correction for crop area shrinkage).

Table 15. Results for oilseed as a group with and without peatland emissions

	g CO2/MJ veg oil/20 years
Oilseeds without peat emissions	63
Oilseeds with peat emissions	123

Deforestation emissions from ethanol

A similar calculation is carried out for the main ethanol feedstocks (wheat, maize and sugar cane). Deforestation attributed to these crops by [EC 2013] was divided first by the net increase in annual production for the crop over the same time period, and then correction was made for the additional production needed to compensate production lost by the shrinkage in area of cereals or sugar that occurred in some countries during this time period[21]. This resulted in a one-third reduction in emissions attributed to cereals-ethanol and a 10% reduction for sugar cane ethanol.

[21] We did it like this because the correction factor is a property of the crop group, but is applied to each crop.

Table 16. Deforestation attributed to cereals and sugar cane (1990-2008)

crop	Δ ha of deforestion (Mha)	Δ tonnes world production (net) for crop (Mtonnes)	ha of deforestation per tonne of net increase in crop production	Correction factor	ha of deforestation per tonne of GROSS increase in crop production
Maize	7.64	343	0.022	0.66	0.015
Wheat	1.50	91	0.016	0.66	0.011
Sugar cane	3.47	681	0.005	0.90	0.005

To convert the results per tonne of crops to results per MJ of ethanol we need to consider first the different LHV energy contents of the crops as shown in Table 17. The yield of ethanol was taken from [JEC 2011].

Table 17. Energy content of ethanol from 1 kg of moist crop

Crop	dry matter fraction	MJ/kg dry crop	MJ in dry matter fraction	MJ ethanol/kg of moist crop
Maize	0.86	17.3	14.88	8.76
Wheat	0.865	17	14.71	8.04
Sugar cane	0.275	19.6	5.39	1.84

Source: JEC-WTW v3.

Table 18 shows the final results in terms of gCO_2/MJ of ethanol over 20 years. The first column is the hectares-of deforestation per tonne of gross increase in annual crop production, brought over from Table 16. The second column is the IPCC value for carbon loss brought over from Table 8. The MJ of ethanol per kg crop is brought over from Table 17.

The allocation to by-products has been calculated by comparing the value of the by-products with the value of the crop. Thus the fraction of deforestation emissions allocated to ethanol is given by:

$$1 - \frac{value\ of\ byproduct\ from\ 1\ tonne\ crop}{value\ of\ 1\ tonne\ of\ crop}$$

Results of an alternative allocation by energy content are detailed in appendix.

Table 18. CO_2 due to directly to expansion of different crops (1990-2008)

Crop	ha of deforestation per tonne of GROSS increase in crop production	CO_2 emissions per ha (tCO_2/ha)	kgCO_2 from deforestation /kg crop	MJ ethanol /kg crop	If made into biofuel, value share of crop	g CO_2/MJ ethanol spread over 20 years
Maize	0.015	309	4.52	8.76	62%	**16**
Wheat	0.011	309	3.35	8.04	56%	**12**
Sugar cane	0.0046	309	1.42	1.84	100%[22]	**39**

Results per crop group are shown in the following table.

Table 19. Results per crop group

	g CO2/MJ ethanol /20 years
Cereals	**15**
Sugar cane	**39**

5. Discussion

Deforestation emissions are only part of LUC emissions

Our calculations only include emissions from land use change of forest to cropland, thus not including emissions from the grassland area converted to cropland (not given in [EC 2013]). Indicatively, in the IFPRI 2011-2012 LUC results, grassland conversion contributed to additional land use change emissions of 57% for biodiesel, 63% for cereals ethanol and 77% for sugar ethanol, and an even higher proportion of land use change area.

Deforestation emissions for ethanol are lower than for biodiesel

The emissions results for ethanol are lower than the vegetable oils' emissions. This is in line with most agro-economic models, which show a lower impact in terms of GHG emissions of cereals and sugar crops compared to vegetable oils.

The true historical deforestation emissions from biodiesel and ethanol are probably closer

Since cereals and oilseeds together account for most of the world's crops, the average land use change emissions for all crops will be close to the weighted average for these

[22] We should allocate part of this figure to electricity exported by sugar cane to ethanol plants. However, in the considered historical period this was very small.

crop groups. Expansion of one crop group can push expansion of others onto forest, and conversely part of the deforestation estimated to be attributed to one crop group may be caused by other crops displacing it 'from behind'. Therefore the deforestation emissions should be somewhere between the numbers for the crop group and the average for all crops. If one could take this effect into account in some way, the deforestation emissions for biodiesel and ethanol would approach each other.

By an analogous argument, the land use change results for a particular crop should lie between the results calculated for that crop alone, and the results attributed to the crop group. However, due to the ease of substitution between crops inside one group, we consider that the deforestation emissions for a particular crop should be closer to that of the crop group.

We have attributed historical yield increase entirely to demand growth.

By considering real data on deforestation, our method automatically takes into account the mitigating effect of intensification (by yield increase or by an increasing share of double-or multiple-cropping) on the area of crop expansion for a given demand increase. In fact we have attributed historical yield expansion entirely to demand growth, whereas in fact part of the yield increase occurs as a function of time ("learning by doing"). So we have attributed too much yield growth to the increase in demand, and hence underestimated the area increase and deforestation emissions.

We could have adopted the opposite extreme assumption, that yield increases *only* with time. The deforestation emissions results would have been higher because the same emissions would be attributed to only the part of the demand increase which is not accounted for by the increase in yield. Thus, for example, if yields increased by 10% and demand increased by 20%, the same emissions would be attributed to only half the increased demand under the alternative assumption[12].

The correction for crop area shrinkage does not include local crop shifts within a country, or the lower yields on abandoned land.

We corrected for the extra production needed to compensate the loss due to the shrinkage in area of a crop group that occurred in some countries. This accounts for the global shifts in crop area, for example loss of crop area in ex-Soviet Union and expansion in South America during this time period. In fact, it over-accounts for the effect, because we assumed that the yields on the land which was abandoned were the same as the national-average yields in those countries, whereas in practice they were probably smaller.

However, there must be also some shifts in crop area within individual countries, for which we had insufficient data to make a correction. The biggest effects would be expected in the largest countries. Probably the largest effect occurs in Brazil, where it is well known that cropland abandonment (because of soil degradation) accompanies deforestation.

The reported increase in crop area in Brazil is driven not only by the reported net increase in crop production, but also by the additional production needed to compensate for the loss of production due to land abandonment. However, as crop area increases in Brazil as a whole, the abandoned land does not show up in the net changes in crop area reported by FAO per-country. But Brazilian census data [IBGE 2006], indicates that between 1996 and 2005 the area of abandoned cropland was roughly a third of the area of crop expansion. The yield on the degraded land is likely to be lower than on the deforested land though, so correcting for this internal land abandonment would reduce the Brazilian contribution to our deforestation emissions by less than one third., The effect is likely to be smaller within smaller and more homogeneous countries, and most countries do not suffer as much land degradation as Brazil. Therefore we think the over-estimate of deforestation caused by failure to consider land abandonment *within each country* will be less than one third.

This analysis inherits uncertainties from the studies which provide its input data

Our results inherit the uncertainties in estimations of deforestation area which arise principally from data limitations discussed in [EC 2013] along with methodological choices in attributing this to different drivers. These are compounded with the uncertainties in carbon stock changes inherent in the input data from FAO's Forest Resource Assessment [FRA 2010] and [IPCC 2006].

[EC 2013] does not distinguish where inside a country a crop is causing deforestation, In the case of Brazil, deforestation by sugar cane expansion is likely to be mostly on woodland areas of the Cerrado, whereas deforestation by soybeans is more likely to be on rainforest. By mixing the types of forest, the deforestation emissions by sugar cane are likely to be overestimated, and those by soybeans underestimated.

Deforestation rates change with time

This analysis estimates which emissions from deforestation can be attributed to expansion of crop production in the time frame 1990-2008. The results would be different for other time frames. As shown in Table 1, deforestation rates *attributed to crop expansion* increased somewhat from the first to the second half of this period, even though the overall deforestation rate declined. But we cannot say how the results would change in a future scenario. Thus if an economic model foresees a slowing of deforestation it will tend to show lower emissions.

5. Conclusions

- The method used in the present study is simple; it gives an independent estimate of the general magnitude of LUC area and emissions which should be expected from models of LUC for scenarios which involve world trade in crops.
- This analysis estimates how much deforestation emission from biomass changes (including emissions from peatland drainage) was induced by each tonne of increased crop production between 1990 and 2008. This is then related to the emissions per MJ of biofuel, in the case that the extra production was for biofuels.
- The results of deforestation emissions, aggregated by crop group, are **15 gCO_2/MJ for cereals ethanol, 39 gCO_2/MJ for sugar cane ethanol and 123 gCO_2/MJ for biodiesel made from vegetable oils.**
- These results are derived from figures of deforestation attributed to crop groups in the areas of deforestation. But as the expansion of one crop group at the expense of another can drive deforestation by the second crop group, the actual figures are probably closer together.
- Our analysis inherits the limitations and uncertainties, in deforestation area and carbon stock changes, from the studies which provide its input data. For example, this probably leads to some over-attribution of deforestation to sugar cane and under-attribution to soybeans.

Comparing with LUC emissions from economic models

- Deforestation emissions are only part of Land Use Change (LUC) emissions: one should add emissions caused by crop expansion onto grassland. So the results imply that historical LUC emissions were higher than those predicted by most economic models. This is especially true for biodiesels, but that is mostly due to some models ignoring emissions from drainage of tropical peat. Including expansion on grassland could make our total LUC emissions up to 77% greater than our reported deforestation emissions.
- We have adopted the most optimistic assumption on the contribution of yield increase. That assumption attributes all historical yield increase to the increase in demand. Had we chosen the assumption that yields increase at a fixed rate with time, the results would be higher. Actual figures might be expected to be somewhere within these two assumptions.
- We corrected for the additional driver of deforestation (not due to demand increase) represented by the shrinkage in area of a crop group that occurred in some countries. This accounts for the global shifts in crop area, for example loss of crop area in ex-Soviet Union and expansion in South America during this time period.
- However, we could not correct for loss of cropland which occurs inside one country. Globally, such a correction could moderately reduce our emission estimates (up to one third in the case of Brazil).

Appendix: Results using allocation by energy content

		g CO2/MJ veg oil / 20 years ALLOCATION BY ECONOMIC VALUE	g CO2/MJ veg oil / 20 years ALLOCATION BY ENERGY VALUE
Oil palm	**Indonesia**	57	55
	Peatland	624	601
	RoW	9	9
	TOTAL	179	172
Soybean	**Brazil**	243	197
	RoW	41	33
	TOTAL	107	87
Rest oilseeds	**World**	66	52

	g CO_2/MJ ethanol / 20 years ALLOCATION BY ECONOMIC VALUE	g CO_2/MJ ethanol / 20 years ALLOCATION BY ENERGY VALUE
Maize	16	16
Wheat	12	12
Sugar cane	39	39

Although allocation by economic value better captures the capacity for an animal-feed by-product to replace crops, the Commission uses allocation by energy in the calculations of direct emissions in annex V of the Renewable Energy Directive[23]. So the energy allocation results are more suitable if they are to be compared with the direct lifecycle emissions tables in annex V.

Calculation of allocation by energy content

We start off with the same emissions per tonne of increased crop production as in the economic allocation calculation described in the results section. Then, when a crop is used for making biofuel, we allocate the deforestation emissions equally to the MJ of heat energy (LHV) in the biofuel and the other useful products. The allocation ratios are identical to those used in annex V calculations, and use LHV and by-product fractions. We see that allocation by energy moderately reduces some emissions results for biodiesel, but makes no noticeable difference for ethanol results.

[23] The volatility of prices makes the use of economic allocation for regulatory purposes unfeasible.

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