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Delegations will find attached document COM(2019) 142 final ANNEXES 1 to 2.

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ANNEXES 1 to 2

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to the

**REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE
COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE
COMMITTEE OF THE REGIONS**

on the status of production expansion of relevant food and feed crops worldwide

ANNEX 1

REVIEW OF THE LITERATURE ON EXPANSION OF CROPS ONTO HIGH CARBON LAND

Scope

This review undertaken by the Commission's Joint Research Centre gives an overview and summarizes the most relevant results of the scientific literature on the expansion of production areas of agricultural commodities into high carbon-stock land, as defined in RED II.

Soybean

There is only one peer-reviewed study that estimates deforestation caused by soybean on a global scale covering a time-frame that includes deforestation after 2008. [Henders et al. 2015] started with GIS-based measurements of year-by-year deforestation in all tropical regions, and allocated it to different drivers, including soy and palm oil expansion, according to a comprehensive review of the regional literature (the review is detailed in their Supplementary Information). However, their data only cover the period 2000-2011.

JRC estimate of percentage deforestation in Brazilian soy expansion			
	Amazon	Cerrado	rest of Brazil
% of Brazilian soy expansion 2008-17	11%	46%	44%
% of expansion on forest	5%	14%	3%
BRAZIL WEIGHTED AVERAGE of expansion on forest	8.2%		

Given the lack of studies providing recent data on a global scale, data were combined from Brazil, other South American countries and the rest of the world. For Brazil, data on soy expansion since 2008 was taken from the Brazilian IBGE-SIDRA database and combined with data on expansion into forest areas in the Cerrado [Gibbs et al. 2015], averaging for the period 2009-13 in the Amazon [Richards et al]¹ and the rest of Brazil [Agroicone 2018]. It resulted in a weighted average of expansion into forests of 10.4%: This was combined with the numbers from Argentina, Paraguay, Uruguay and Bolivia and the rest of the world, as follows:

JRC estimate of Latin America average percentage of soy expansion onto forest					
2008-2017	Brazil	Argentina	Paraguay	Uruguay	Bolivia
% of Latin American soy expansion	67%	19%	7%	5%	2%
% onto forest	8.2%	9%	57%	1%	60%
Latin America Average % onto forest	14%				
ESTIMATE OF WORLD AVERAGE % OF SOY EXPANSION ONTO FOREST					
Fraction of world soy expansion in Latin America	53%				
Assumed % expansion onto forest in rest of the world	2%				
World average fraction of soy expansion onto forest	8%				

For other Latin American countries, the only quantitative data found is [Graesser et al. 2015], who measured the expansion of all arable crops onto forest. For the rest of the world, where the greatest soy expansions since 2008 have been observed, i.e. India, Ukraine, Russia and Canada, little evidence for soy cultivation causing direct deforestation could be found. Therefore, a low share of 2% expansion onto forests was assumed for the rest of the world. As a result, the world average fraction of soy expansion was estimated at 8%.

¹ According to [Gibbs et al. 2015, fig.1] the average percentage of soy expansion on forest in the Amazon from 2009-2013 was ~2.2%. 2008 data are not included as the Brazilian Government's Plan for Preventing and Controlling Deforestation in the Amazon (PPCDAa) Brazil forest law, which was followed by a dramatic reduction in Amazon deforestation, was not yet enforced. The estimate of [Gibbs et al. 2015] used the official PRODES deforestation database, which was also used to monitor the compliance with the PPCDAa law. However, [Richards et al.2017] observed that since 2008, the PRODES database has diverged increasingly from other indicators of forest loss. This is the result of it being used to enforce the law: deforesters have learnt to deforest small patches or in areas that are not monitored by the PRODES system. Using data from the alternative GFC forest monitoring database, [Richards et al.2017] show (in their Supplementary information) that since 2008 PRODES underestimates deforestation by an average factor of 2.3 compared to the GFC database. Data from forest fires confirms the GFC year-on-year variations in deforestation area, and not those seen by PRODES.

Comparison with other recent reviews

Most of the data on deforestation by soy pre-dates the Brazilian soy moratorium of 2008, and are therefore not relevant to the present estimate.

A review commissioned by Transport and Environment [Malins 2018] contains a careful review of regional data on soy expansion and deforestation concluding that *at least* 7% of global soy expansion since 2008 was on forest. However, different years were used for the soy expansion fractions and data and results from [Agricone 2018] and [Richards et al 2017] were not used.

A review commissioned by Sofiproteol [LCAworks 2018] also includes a review of the regional literature on deforestation by soy in the world from 2006-2016. It concludes that 19% of global soy expansion has been onto forest. However, the source of their assumption concerning the expansion onto forest in “rest of Brazil” is unclear, and they have sometimes elided “natural land” with forest. Furthermore, when calculating averages, they weight the regional soy data by the total regional production of soy rather than the area of its expansion. Therefore, the number of 19% cannot be considered to be very robust.

Agroicone prepared a document for the Commission which cites unpublished 2018 work by Agrosatelite showing a huge reduction in the fraction of forest in soy expansion in the Cerrado (especially in the Matipoba part) in 2014-17, from 23% in 2007-14 to 8% in 2014-17.

Palm oil

Using sampling of palm oil plantations in satellite data, [Vijay et al. 2016] estimated the fraction of palm oil expansion onto forest from 1989 to 2013, and reported results by country. When setting those national averages in relation to the increases in national harvested area of palm oil in 2008 to 2016, the study derived that, globally, **45%** of palm oil expansion was onto land that was forest in 1989.

The supplementary data of [Henders et al. 2015] allocated for the 2008-11 period an average of 0.43 Mha/y of observed deforestation to palm oil expansion. This represents **45%** of the estimated increase in world planted area of palm oil in that period².

In a global study for the European Commission, [Cuypers et al. 2013] attributed measured deforestation to different drivers, such as logging, grazing, and various crops, at a national level. Their results imply that 59% of oil-palm expansion was linked to deforestation between 1990 and 2008.

² Harvested area data is available for all countries. However, it is smaller than planted area because immature palm trees do not bear fruit. However, the ratio of *increase* in planted area to harvested area also depends on the area-fraction of immature palms from replanting. Planted area increases were found in national statistics of Indonesia and Malaysia, and combined with adjusted harvested area increases for the rest of the world.

Comparison of regional studies for Indonesia and Malaysia

Estimated percentage of expansion onto forest						
	years	Malaysia		Indonesia		ROW
% of world palm expansion 2008-15	2008-15	15%		67%		17%
		Peninsula Malaysia	Malaysian Borneo	Indonesian Borneo	Rest of Indonesia	
% of national expansion 2008-15	2008-15	19%	81%	77%	23%	
Gaveau et al. 2016	2010-15		75%	42%		
Abood et al 2015	2000-10			>36%		
SARvision 2011	2005-10		52%			
Carlson et al. 2013	2000-10			70%		
Gunarso et al. 2013	2005-10	>6%				
Gunarso et al. 2013	2005-10	47%		37-75%		
Austin et al. 2017	2005-15			>20%		
Vijay et al. 2016	2013	40%		54%		13%
Vijay et al. 2016	2013			45%		

[Abood et al. 2015] found that 1.6 million hectares of deforestation in Indonesia between 2000 and 2010 took place inside concessions granted to industrial palm oil producers. That is 36% of the total expansion of planted palm oil area in that period, according to Indonesian Government figures.

For the same period, [Carlson et al. 2013] estimated a greater % of deforestation: 1.7 Mha of forest loss in palm oil concessions in Indonesian Borneo; about 70% of the harvested area expansion in that region [Malins 2018]. In a later paper, [Carlson et al. 2018] report 1.84 Mha forest loss in palm oil concessions in Indonesian Borneo and 0.55 Mha in Sumatra, for the period 2000-2015.

[SARvision 2011] found that from 2005 to 2010, 865 thousand hectares of forest were cleared inside the boundaries of known palm oil concessions in Sarawak, the Malaysian province in Borneo where most palm oil expansion takes place. This corresponds to about half of the increase in palm oil harvested area in that time³.

[Gaveau et al. 2016] mapped the overlap of deforestation with expansion of industrial (i.e. not smallholder) palm oil plantations in Borneo, over 5-year intervals from 1990 to 2015. They point out that the great majority of palm oil plantations in Borneo were forest in 1973; lower fractions of deforestation come about when one restricts the delay time between clearance and planting of palm oil. Their results show that for industrial palm oil plantations in Indonesian Borneo, ~42% of the expansion from 2010 to 2015 was onto land that was forest only five years earlier; for Malaysian Borneo the figure was ~75%. The assessment applied a more restricted definition of forest than RED2 considering only forest with >90% canopy cover, and excluding secondary forest (i.e. re-grown forest and shrub after historical clearance or fire).

³ Planted-area data for that region and time period could not be found.

In a later paper, [Gaveau et al. 2018] show for the period 2008-17, that in Indonesian Borneo, 36% of the expansion of industrial plantations (88% of which were palm oil) was onto old-growth forest cleared the same year, whilst in Malaysian Borneo the average was 69%. In Indonesian Borneo, the rate of deforestation by plantations in different years correlated very strongly with the price of crude palm oil in the previous season, whereas in Malaysian Borneo the correlation was weaker, suggesting longer-term centralized planning of deforestation. The results showed that the rate of palm oil expansion has declined since its peak in 2009-12 while the fraction of it that occurs on forest remained stable.

[Gunarso et al 2013] analysed land cover change linked to oil-palm expansion in Indonesia and Malaysia for the Roundtable on Sustainable Palm Oil (RSPO). The most recent changes they report refer to areas of palm oil that were planted between 2005 and 2010. They show the % of this area that was under various land use categories in 2005. Adding the categories that would *unequivocally* meet the definition of forest in the Directive, a minimum of 37% was obtained for the expansion onto forest for all Indonesia. However, other land use categories reported includes scrubland (which is principally degraded forest, according to the paper), and this would generally also meet the Directive's definition of forest. This is a large category in Indonesia, as forest near plantations is often degraded by wildfires years before the plantation expands onto that land. Counting these prior land-use types as forest (as they may have been in year 2000), raises the total % deforestation for Indonesia 2005-10 to about 75%, confirming approximately the findings of [Carlson 2013].

For Malaysia, [Gunarso et al 2013] report that from 2006-10, 34% of palm oil expansion was directly onto forest. However, they also reported considerable expansion onto "bare soil" in 2006, and supposed that some of that was bare because it was being converted from forest. From their supplementary information, it can be seen that over a third of the bare soil in 2006 was forest six years earlier, indicating that it is likely to have been areas of forest cleared ready for planting. Including these forest areas would push the fraction of deforestation-linked palm oil expansion up to 47% in Malaysia.

Instead of using satellite images to identify the previous land-cover where Indonesian palm oil plantations expanded, [Austin et al. 2017] referred to land-use maps issued by the Indonesian Ministry of Environment and Forestry. They found that only about 20% of the land used for the expansion of industrial palm oil in 2005-15 had been classified as "forest" on those maps five years before. Their definition of forest specifies >30% canopy cover (instead of >10% in the Directive), and does not include scrub, which would sometimes qualify as forest under the definition of the Directive. A further 40% of the palm oil expansion occurred on land-use categories that included scrub. For these reasons, it is considered that [Austin et al 2017]'s figure of 20% expansion onto forest in 2010-2015 is likely to be an underestimate for the purpose of this report.

JRC estimate of percentage of palm oil expansion onto forest for rest-of-the-world				
	year of expansion	Latin America	Africa	rest Asia
% of world palm oil expansion 2008-15	2008-15	9%	3%	5%
Furumo and Aide 2017	2001-15	20%		
Maaijard et al. 2018			6%	
Vijay et al. 2016	2013	21%	6%	4%
weighted average for ROW	2013	13%		

As shown in the table, lower shares of expansion into forest are reported for the rest of the world. Weighting the results for Latin America, Africa and the rest of Asia (excluding Indonesia and Malaysia) an average share of expansion of palm oil plantations into forest of 13% was derived.

Overall, taking into account the results from the regional studies on palm oil expansion into high-carbon stock land in Malaysia and Indonesia and evidence for such expansion in the rest of the world the world-average share of palm oil expansion onto forest of 45% proposed by [Vijay et al 2016] can be considered a good estimate.

Fraction of oil-palm expansion onto peat

	years	Malaysia		Indonesia		ROW
% of world palm expansion 2008-15	2008-15	15%		69%		16%
		rest of Malaysia	Sarawak	Indonesian Borneo	Rest of Indonesia	
% of national expansion 2008-15	2008-15	33%	67%	77%	23%	
Fraction of palm-oil expansion onto peat						
SARvision 2011	2005-10		32%			
Omar et al. 2010	2003-2009	30%				
Abood et al 2014	2010			21%*		
Austin 2017	2005-2015			>20%		
Gunarso et al. 2013	2005-10			26%		
Miettinen et al. 2012, 2016	2007-15	42%		24%		
Miettinen et al. 2012, 2016	2010-15	36%		25%		
Interpolated world average for 2008-15		23%				
* fraction of known oil-palm <i>concessions</i> on peat						

[Abood et al. 2014] found that 21% of known Indonesian palm oil concessions were located over peatlands, and 10% over deep peat (>3 metres), which is supposed to be protected from drainage under a 1990 Indonesian government decree. From 2000-2010, they reported 535 kha of peat-swamp forest were lost on Indonesian palm oil concessions, which is 33% of the palm oil expansion on concessions.

[Miettinen et al. 2012, 2016] analysed high-resolution satellite images to track the spread of mature palm oil plantations onto peatland at times between 1990 and 2015. They used the JRC's European Digital Archive of Soil Maps to identify peat areas and report that between

2007 and 2015 palm oil plantations expanded 1089 kha onto Indonesian peatland and 436 kha onto Malaysian peatland. Dividing by the increase in mature palm oil area in that time period⁴, gives a share of 24% palm oil expansion onto peat in Indonesia, and 42% in Malaysia. For the latest period they report, 2010-2015, the corresponding figures are 25% and 36%.

The Malaysian Palm Oil Board published a study of palm oil [Omar et al. 2010], based on GIS identification of palm oil cultivation, and a soil map from the Malaysian Ministry of Agriculture. They report that the percentage of palm cultivation on peat in Malaysia grew from 8.2% in 2003 to 13.3% in 2009, corresponding to 313 and 666 kha respectively. In the same period, their data show the total area of palm oil expanded from 3813 to 5011 kha, so the fraction of that expansion that was on peat was 30%.

[SARvision 2011] found that from 2005 to 2010, 535 thousand hectares of peat-forest were cleared inside the boundaries of known palm oil concessions in Sarawak, the Malaysian province where most palm oil expansion takes place. This corresponds to about 32% of the increase in palm oil harvested area in that time⁵. This misses peat-forest loss for palm oil outside concession boundaries, and any conversion of peatland that was not forested at the time of conversion.

[Gunarso et al. 2013] report an anomalously low fraction of palm oil expansion on peat in Malaysia (only 6% between 2000 and 2010, according to their supplementary information). This is far below any other estimate, even from the Malaysian sources, so it was discounted⁶.

For Indonesia, [Gunarso et al. 2013]’s supplementary data show 24% of palm oil expansion between 2005 and 2010 was onto peat-swamp, and this only rises to ~26% if the conversion from peat swamp via “bare soil” are included.

[Austin et al. 2017] report that the fraction of Indonesian palm oil expansion onto peat remained at ~20% for all the time-periods they studied (1995-2015), without any correction for “bare soil”. The reason why Austin’s results are lower than others is the use of the “BBSDLP⁷” peat map from the Indonesian Ministry of Agriculture (H. Valin, private communication, 5 December 2018). The BBSDLP map does not include areas with less than 0.5 m depth of peat⁸, and this is partly why it shows 13.5% less peat area than maps from Wetlands International, which themselves probably underestimate peat area by about 10-13%, according to ground surveys. [Hooijer and Vernimmen 2013].

⁴ Miettinen et al only counted mature palm areas, so in this case it is appropriate to divide by mature palm area rather than total planted area. Data from US Department of Agriculture Foreign Agricultural Service on “harvested area” was used, which in fact refer to “mature planted area”, and have been checked against other data such as oil-palm seedling sales. Data from FAO are less useful because, for example, they reflect temporary reductions in harvested area in 2014/15 due to flooding in Malaysia.

⁵ *Planted*-area data for that area and time period could not be found.

⁶ [Gunarso et al. 2013] hint at an explanation: they only identified planting on peat if the land was wet peat-swamp five years before; if it was already drained, it became another land-use type, such as “bare soil”. Converting swamp to palm oil requires not only tree clearance but also the construction of a dense network of drainage channels, and soil compaction, which prolongs the time before oil-palm trees can be identified on satellite pictures. Thus, whereas in Peninsula Malaysia (with little peatland) no oil-palm expanded onto bare soil in 2005-10, in Sarawak, 37% expansion was onto “bare soil”. Furthermore, there is a high rate of conversion from peat-swamp to “agroforestry and plantations”, and then from “agroforestry and plantations” to oil-palm in successive 5-year periods, so in addition perhaps early-stage oil-palm plantations were mistaken for agroforestry or plantations of other crops.

⁷ BBSDLP is the Indonesian Center for Research and Development of Agricultural Land Resources.

⁸ 0.5m of tropical peat contains about 250-300 tonnes of carbon per hectare, which will almost all be released in the first decade after drainage.

Quantitative data for the fraction of palm expansion onto peatland in the rest of the world is not available. From 2008-15, 9% of palm oil expansion was in Latin America, 5% in the rest of Asia and 3% in Africa. There are considerable areas of tropical peat in South America, especially in Peru, Bolivia, Venezuela and along the Amazon, but these are not significant production areas of palm oil. However, the world's largest tropical peat swamp is in the Congo basin. There, already at least one huge palm oil concession, of 470 kha (e.g. 10% of the entire area of palm oil in Malaysia), has been granted, and it lies 89% on peat [Dargie et al. 2018]. The fear is that as production growth in SE Asian countries slows, more investment will flow into developing palm oil on peatlands in Africa and Latin America.

Placing the most weight on the results of [Miettinen et al. 2012, 2016], which can be considered as the most advanced pieces of scientific literature, and assuming zero peatland drainage for palm in the rest of the world, gives an interpolated weighted average estimate of 23% expansion of palm oil onto peat for the whole world between 2008 and 2011.

Sugar cane

More than 80% of global sugar cane expansion took place in Brazil from 2008 to 2015.

[Cuypers et al. 2013] estimated that 36% of world sugar cane expansion between 1990 and 2008 was onto land that was previously forest. However, that is likely an over-estimate for the purposes of the analysis: deforestation was allocated between forestry, expansion of pasture, and expansion of different crops, at *national scale*. Little deforestation was attributed to pasture land, because it hardly showed any *net* expansion; by contrast, sugar cane expanded greatly and therefore received a high allocation of the national deforestation. However, the *regions* of Brazil where sugar cane expanded mostly do not overlap with areas of high deforestation, and this was not considered in the analysis of [Cuypers et al. 2013].

[Adami et al. 2012] reported that only 0.6% of sugar cane expansion in the Centre-South of Brazil went onto forest between 2000 and 2009. Although the region accounted for about 90% of world sugar cane expansion in that time period, there was some expansion in other regions of Brazil not covered by this study.

[Sparovek et al. 2008] agreed that in 1996-2006 sugar cane expansion in the Brazilian Centre-South was almost entirely onto pasture or other crops (as there is very little forest left in that region); however, another 27% of expansion occurred in “peripheral” areas around and inside the Amazon biome, in the Northeast and in the Atlantic Forest biome. In these peripheral regions, there was a correlation between forest loss per municipality and sugar cane expansion. However, no figures on the share of expansion onto forest are given in the paper.

As a result no adequate quantification of deforestation by sugar cane could be derived from the literature.

Maize

Cereals are not usually thought of as causing deforestation, because most production is in temperate zones where deforestation is generally modest. However, maize is also a tropical crop, often grown by smallholders, and also often rotated with soybeans on large farms. And a disproportionate part of maize expansion happens in tropical regions where deforestation is more common and carbon-intensive.

% of world maize harvested area expansion 2010-15	
China	29.8%
Brazil	11.6%
Angola	10.5%
Nigeria	9.8%
Argentina	8.9%
Russian Federation	7.0%
Mali	3.1%
Mexico	1.7%
Cameroon	1.6%
other (mostly developing) countries	16%
WEIGHTED AVERAGE YIELD 2010-15 (t/ha)	3.935

The expansion in China was concentrated onto marginal land in the North-East of the country [Hansen 2017], which one supposes to be mostly steppe grasslands rather than forest. The expansion in Brazil and Argentina could be assigned the same % deforestation as soy in Brazil. [Lark et al. 2015] found that, of US maize expansion between 2008 and 2012, 3% was at the expense of forest, 8% shrubland and 2% wetlands. Nevertheless, it is difficult to make a global estimate without looking into detail at what is happening in each country.

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ANNEX 2

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GIS ANALYSIS

1.

Method

In order to estimate deforestation and related emissions associated with the expansion of biofuel crops since 2008 into areas with a tree canopy cover density greater than 10 %, a geospatial modelling approach was used to combine a deforestation map from Global Forest Watch (GFW) with crop type maps from MapSPAM and EarthStat. Further details of the approach are summarized below, and data sources used in the analysis are listed in the Table below. The analysis was undertaken using a pixel size of approximately 100 hectares at the equator.

Data Sources

Crop Data

At present, globally consistent maps showing the expansion of all individual biofuel crops through time are not available, although research is ongoing to achieve this for palm oil and soybean through the interpretation of satellite imagery. For this analysis, we relied on two sources for single-year, single-crop maps: MapSPAM (IFPRI and IIASA 2016), which captures the global distribution of 42 crops in the year 2005⁹, and EarthStat (Ramankutty et al. 2008), which maps crop and pasture areas in the year 2000. Both sources of crop data result from approaches that combine a variety of spatially-explicit input data to make plausible estimates of global crop distribution. Data inputs include production statistics at the scale of administrative (subnational) units, various land cover maps produced from satellite imagery, and crop suitability maps created based on local landscape, climate and soil conditions.

Given the lack of up-to-date global maps for individual crops as well as the lack of consistent information about their expansion through time, a major assumption used in our analysis is that total deforestation and associated GHG emissions occurring within an area since 2008 can be allocated to a specific crop based on each crop's proportional area relative to the total agricultural land area, including pasture, present in the same pixel of the crop map.

Deforestation Data

Published maps of global annual tree cover loss derived from Landsat satellite observations, available on Global Forest Watch for years 2001 through 2017, formed the basis of our deforestation analysis. The tree cover loss data are available at a 30-meter resolution, or a pixel size of 0.09 hectares. The original tree cover loss data of Hansen et al. (2013) do not distinguish permanent conversion (i.e., deforestation) from temporary loss of tree cover due to forestry or wildfire. Therefore, for this analysis we included only the subset of tree cover loss pixels that fell within areas dominated by commodity-driven deforestation, as mapped at a 10-kilometer resolution by Curtis et al. (2018)¹⁰. Thus areas where other drivers, such as forestry or shifting agriculture, are dominant were excluded from analysis. Within the commodity-driven deforestation class, only pixels with a percent tree cover above 10 percent were

⁹ Updated MapSPAM data for the year 2010 were released on January 4, 2019, just after this analysis was completed.

¹⁰ Work is ongoing to update the Curtis et al. (2018) study to show dominant drivers for post 2015 tree cover loss years.

considered for analysis, with “percent tree cover” defined as the density of tree canopy coverage of the land surface in the year 2000. Given the specific criteria included in RED2 (see “b” and “c” in Background above), analysis results were disaggregated into deforestation for the years 2008 through 2015 for areas with greater than 30 percent tree cover and areas with 10-30 percent tree cover.

Curtis et al. (2018) point out that multiple forest loss drivers may be present within a landscape at any given time, and the dominant driver may vary in different years during the 15-year study period; their model assigned only one dominant driver that contributed to the majority of tree cover loss within that landscape during the study period. One assumption used in this analysis was that all tree cover loss within areas dominated by commodity-driven deforestation was for the expansion of new agricultural areas. This assumption would tend to over-estimate the effect of commodity-crops in those pixels. On the other hand, agriculture may also be expanding in areas dominated by shifting agriculture or forestry; other classes from the Curtis et al. (2018) map that were excluded from our analysis. This implies that the method could under-estimate the deforestation due to crops. However, the footprint areas of the nine crops included in this analysis fell primarily into the commodity-driven deforestation class, and therefore crop areas outside this class were assumed to have small area ratios (see Crop Allocation Model section below) and therefore the contribution of these areas to the final totals should be small.

Peatland Data

Peatland extent was defined using the same maps as Miettinen et al. 2016, who mapped changes in land cover from 1990 to 2015 in the peatlands of Peninsular Malaysia, Sumatra and Borneo. For Sumatra and Kalimantan, Miettinen et al. (2016) included peat from the Wetlands International 1:700,000 peatland atlases (Wahyunto et al. 2003, Wahyunto et al. 2004), where peat was defined as follows: “soil formed from the accumulation over a long period of time of organic matter such as the remains of plants”. Peat soil is generally waterlogged or flooded all year long unless drained.” As outlined in Wahyunto and Suryadiputra (2008), the peatland atlases in turn compiled data from a variety of sources which primarily used imagery (satellite, radar, and aerial photography data), as well as survey and soil mapping, to map peat distribution. For Malaysia, peat from the European Digital Archive of Soil Maps was used (Selvaradjou et al. 2005).

An analysis specific to deforestation from palm oil expansion in peat soils was undertaken due to the importance of peat in this biofuel crop’s overall land use and GHG footprint. Using industrial palm oil expansion data from Miettinen et al. 2016, the area of tree cover loss that occurred before the year of known palm oil expansion from 2008 through 2015 was estimated.

GHG Emissions Data

Emissions from deforestation since the year 2008 were estimated as the loss of carbon from the aboveground biomass pool. Emissions are expressed in units of megatons of carbon dioxide (Mt CO₂).

Emissions from aboveground biomass loss were calculated by overlaying the map of tree cover loss (from 2008 through 2015) with a map of aboveground live woody biomass in the year 2000. The biomass map, produced by Woods Hole Research Center and derived from satellite and ground observations, is available on Global Forest Watch. All biomass loss was assumed to be “committed” emissions to the atmosphere upon clearing, although there are lag times associated with some causes of tree loss. Emissions are “gross” estimates rather than “net” estimates, meaning that the land use after clearing, and its associated carbon value, was

not considered. The carbon fraction of aboveground biomass was assumed to be 0.5 (IPCC 2003) and carbon was converted to carbon dioxide using a conversion factor of 44/12, or 3.67. One advantage of using a pixel-based forest biomass map with continuous values, rather than assigning categorical carbon stock values to different land cover types (e.g., forest, shrubland, IPCC Tier 1 values, etc.) is that the data used for estimating biomass loss is completely independent of the choice of land cover map used to estimate land cover change.

Emissions associated with other carbon pools, such as belowground biomass (roots), dead wood, litter and soil carbon, including peat decomposition or fires, were excluded from the analysis.

Analysis Extent

The extent of the global analysis was defined by overlaying the commodity-driven deforestation map (Curtis et al. 2018) with the biofuel-relevant crops of interest (palm oil, coconut, wheat, rapeseed, maize, soybean, sugar beet, sunflower and sugar cane). Only pixels that were included in one of the nine crops of interest and that touched the commodity-driven deforestation class were considered in the analysis.

Crop Allocation Model

Total deforestation and emissions within a given 1-kilometer pixel were allocated to different biofuel crops of interest based on the proportion of each crop present in the pixel (“Crop X”, e.g. soy) relative to the total area of agricultural land in the pixel, defined here as the sum of cropland and pasture land. In this way, each biofuel crop’s relative contribution to the pixel’s total agricultural footprint served as the basis for allocating its associated deforestation and GHG emission footprint.

Because a single, globally consistent and up-to-date map of agricultural land disaggregated by crop type was not readily available, we applied a two-step process to approximate each biofuel crop of interest’s relative role in deforestation and emissions in a given location (Eq. 1). In the first step, we used crop data for the most recent year available (MapSPAM, Year 2005) to calculate the ratio of Crop X to total cropland within a pixel. In the second step, we used EarthStat data (Year 2000) to calculate the ratio of total cropland to total pasture+cropland within a pixel. (EarthStat data were used because MapSPAM does not include maps of pasture land, and the expansion of pasture land also plays a role in deforestation dynamics.) Combining these two steps made it possible to approximate the relative contribution of Crop X to the total agricultural footprint within a given pixel, albeit using different data sources from different time periods.

Equation 1:

$$\frac{\text{MapSpam Crop X (2005)}}{\text{MapSPAM total crop area (2005)}} \times \frac{\text{Earthstat total crop area (2000)}}{\text{Earthstat total crop + pasture area (2000)}} = \frac{\text{Crop X}}{\text{crop + pasture}}$$

Final Calculations

Once the crop allocation maps were created for each biofuel crop of interest, we multiplied the total deforestation and GHG emissions by the proportion of Crop X in each 1-kilometer pixel, and calculated global summary statistics disaggregated by deforestation and emissions occurring on land with greater than 30 percent tree canopy density and on land with 10-30 percent tree canopy density.

The GIS results show the deforestation observed during the 8 calendar years 2008 to 2015, which associated with different crops. To see what % of the crop expansion is associated with deforestation, the total area of deforestation during these years was divided by the corresponding increase in crop area. To take into account that a crop can still cause

deforestation even when the overall global crop area declines but expands in some countries, the shares were calculated based on the *gross* increase in global crop area, which is the sum of the increases in crop area in countries where it did not shrink.

Further, data on harvested areas was adjusted to obtain information on planted areas: for annual crops, the increase in crop area was assumed to be the same as the increase in harvested area. For (semi-)permanent crops, the fraction of the crop area, which is not harvested because the plants have not yet reached maturity, was taken into account. Sugar cane needs to be replanted about every five years, but there are only four harvests, as it is still immature after the first year. Oil-palm is replanted about every 25 years and bears fruit in the last 22 years.

For most crops, the database [FAOstat 2008] was used, which shows the area harvested by calendar year. Only for palm oil, data from [USDA 2008] was chosen, because it reports data on all mature palm oil areas, including in years where harvesting was impeded by flooding. The database also includes more countries for this crop.

Table: Summary of Data Sources in WRI GIS-analysis.

Dataset	Source
Forest and Peat Extent	
Tree Cover 2000	Hansen et al. 2013
Peatlands	Miettinen et al. 2016
Deforestation	
Tree Cover Loss	Hansen et al. 2013 (+ annual updates on GFW)
Commodity-driven deforestation	Curtis et al. 2018
Palm oil Expansion, 2000-2015 (for estimation of deforestation on peat)	
Indonesia, Malaysia	Miettinen et al. 2016
GHG Emissions	
Aboveground Biomass	Zarin et al. 2016
Crop and Pasture Extent Data	
MapSPAM (physical area)	IFPRI and IIASA 2016
EarthStat	Ramankutty et al. 2008

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