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Land Use Change Related GHG Emissions Embodied in Commodity Production and Trade

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Summary

This report aimed, in a very short, time-limited study, to scope out whether reliable figures are available on the percentage of global GHG emissions that would be reduced per year if the UK, Europe or the world shifted towards consumption of palm oil, beef and soy that did not lead to conversion of natural habitats during production. In this summary, we present recommendations for estimates that could be quoted. These do not directly or fully answer the question, but they do come from reliable sources and illustrate the scale of the problem. It must be noted that all estimates of GHG emissions from land use change carry relatively high uncertainty, as land use is the most uncertain term in the global carbon budget.

- If the world shifted to conversion-free production of all agricultural commodities, **9-14%** of global GHG emissions would be reduced per year. This is based on estimates from internationally recognised organisations such as IPCC[1], FAO[2] and UNFCCC[3]. Whilst the practicality of preventing all conversion despite rising demand must be considered, the estimate illustrates the scale of the problem. Over the last 150 years, the amount of GHG emitted from land use change annually has remained relatively constant but has reduced as a proportion of the total due to increased use of fossil fuel energy.
- Estimates by Pendrill, *et al.* 2019a suggest that if the world shifted to conversion free beef, **25%** of global forest loss per year would be prevented (2.2Mha per year)[4]. For palm oil, this figure would be **4.5%** (0.4 Mha per year)[5]. For soy, a further **4.5%** of global forest loss would be prevented. Estimates of the GHG emissions caused by land conversion relating to these crops specifically were not found in the literature within the timeframe of the review and their calculation would carry very high uncertainty (see below). Deforestation, a good alternative figure to use as there is a clear link with GHG emissions, carries less uncertainty.
- Estimates of the contribution of Europe and more specifically the UK to global land conversion emissions carry uncertainties associated with modelling the flow of commodities on a global trade network. Pendrill *et al.* 2019 suggest that on average that EU has a deforestation emissions footprint of 0.3 t CO_2 yr^{-1} per capita. Based on a population of 513.2 million in EU[6] in 2018 the deforestation emissions for EU total **154Mt CO_2 yr^{-1}**. Other relevant sources include Vito *et al.* (2013), which estimates that Europe consumed **0.732Mha**[7] of embodied deforestation in 2004 (10% of global embodied deforestation). Few reliable estimates for UK consumption exist, but Pendrill *et al.* 2019a suggest the UK imported **31kha yr^{-1}** of embodied deforestation between 2010-2013[8]. Estimates of land conversion embodied in European and UK consumption carry less uncertainty than GHG emissions estimates.

Additional but low confidence estimates of the exact scenarios the report aimed to answer are provided in Annex 1. These have been calculated using figures from a variety of literature. Whilst the raw figures are reliable, the final estimates presented in this Annex are based on large assumptions and are each calculated in a different way so are not truly comparable. They are likely within the right order of magnitude but are not accurate and thus not recommended for use.

[1] Intergovernmental Panel on Climate Change: https://www.ipcc.ch/
[2] Food and Agriculture Organisation: http://www.fao.org/home/en/
[3] United Nations Framework Convention on Climate Change (UNFCCC): https://unfccc.int/
[4] 2.2Mha is slightly bigger than Wales; over ten years, this would result in loss of an area almost the size of the UK.
[5] 0.4Mha is the size of Kent; over ten years, this would result in loss of an area the size of Switzerland.
[6] https://data.worldbank.org/indicator/SP.POP.TOTL?locations=EU
[7] 0.732Mha is a similar size to Kent and Sussex combined; over ten years, this would result in loss of an area bigger than Ireland.
[8] 31kha is the size of Inner London; over ten years, this would result in loss of an area almost the size of Cornwall.

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1 Main report

1.1 Aims

This report aims to investigate the feasibility of measuring GHG emissions (in particular those from land use related changes in carbon stocking and sequestration) attributed to agricultural commodity consumption across a variety of scales (UK consumption, European consumption, global consumption) and a variety of production systems (e.g. 'conversion-free' vs 'conversion-causing' palm oil/beef/soy).

In particular, it aims to scope out whether reliable figures are available on the percentage of global emissions that would be reduced per year if the UK, Europe or the world shifted towards conversion-free palm oil, beef and soy.

1.2 Scope

This report is based on only twelve days of research prior to write-up. It therefore aims to be a useful primer presenting a selection of the most attainable information, rather than a comprehensive synthesis of the area.

1.3 Key Definitions

For the purposes of this report, the following definitions will be applied:

- **Agricultural emissions:** any GHG emissions from agricultural practices apart from land use emissions - for example emissions from fuel combustion for agricultural machinery, fertiliser production and enteric fermentation in livestock.

- **Conversion-causing:** commodity production that does result in conversion of natural habitat into agricultural land.

- **Conversion-free:** commodity production that does not involve the conversion of natural habitat into agricultural land.

- **Embodied deforestation:** the deforestation, or destruction of natural forest, associated with the production of a commodity.

- **GHG emissions:** the carbon equivalent of all greenhouse gases emitted in terms of their global warming potential, as a mass fraction weighted average and based on IPCC guidance. Some studies have definitions that vary slightly from this; where this is the case every effort has been made to highlight them as exceptions.

Further definitions are presented in the glossary (Annex 7).

2 Report structure

In order to determine the percentage of global emissions that would be reduced per year if the UK, Europe or the world shifted towards conversion-free production of key agricultural commodities, the following information is required:

- The area of converted land attributable to commodity production that is taking place each year and the proportion of total commodity production that is conversion-free vs conversion-causing. (Section 2.1)

- The total GHG emissions caused by commodity production, from both land use conversion and agricultural production emissions. (Section 2.2)

- Total GHG emissions overall, broken down into emissions related to commodity production and other emissions as related to fossil fuels. (Section 2.3)

- The proportion of global commodity supply reaching the UK or Europe that is from a conversion-free source. (Section 2.4)

The report addresses the data and methods available for each of these points in order, with a particular focus on palm oil, beef and soy where possible. Key estimates are presented in the Summary and additional estimates are presented in the Annexes.

2.1 How much land conversion attributable to commodity production is taking place each year? How much commodity production is conversion-free vs conversion-causing?

Estimations of the area of land converted for agricultural commodity production are required to calculate land use change emissions attributed to the agricultural sector. Information on land conversion on a country level can be combined with international commodity trade data to map the flow of embodied land use change and associated GHG emissions across the globe. This section outlines the methods used to generate land conversion figures, highlights key estimates in the literature and discusses the caveats associated with these calculations. This section focuses on global commodity production while section 2.4 discusses the impact of UK and European consumption.

Historic Land Conversion

Humans have been transforming the Earth for centuries and have had major impacts on the global environment over time. Humans have always depended on their environment to provide resources, but more recent exponential increases in the global population have made the conversion of natural landscapes to agriculture more prevalent (Ramankutty & Foley 1999). In the 1990s it was estimated that over the last 300 years approximately 12 million km^2 (1200Mha) of forests have been destroyed, while 5.6 million km^2 (560Mha) of grassland have been converted to pastures and cropland areas have expanded by 12 million km^2 (1200Mha) (Ramankutty & Foley 1999). Decreases in global forest over the last 300 years equate to between 15-25% of the total extent documented in 1700 (Goldewijk & Ramankutty 2010). Estimates based on the HYDE[9] database suggest global cropland increased from 265Mha in 1700 to 1471Mha in 1990 while pasture increased from 524Mha to 3451Mha (Goldewijk 2001). These estimates will be significantly higher today. Temporal differences in development are also highlighted, with developed countries undergoing significant agricultural expansion during the 19th century and developing countries experiencing growth during the 20th century (Goldewijk 2001). In some countries the mass conversion of natural ecosystems has ceased or reversed (Goldewijk & Ramankutty 2010). However, developed countries often import commodities associated with significant land conversion in developing countries. The accelerating population growth, rising incomes and changing consumption patterns puts pressure on global food production systems, which means the rate of land conversion remains high.

[9] https://themasites.pbl.nl/tridion/en/themasites/hyde/

Commercial vs. Subsistence Agriculture

Some papers highlight the contribution of subsistence agriculture to global land use change emissions. Hosonuma *et al*. (2012) suggest 40% of total deforestation is the result of commercial agriculture, but this rises to 80% if subsistence agriculture is included. The importance of commercial vs. subsistence agriculture varies between continents. Commercial agriculture is the main driver of deforestation in Latin America, accounting for 68%, while in Africa and Asia only 35% of deforestation is attributable to commercial production (Hosonuma *et al*. 2012). The contribution of subsistence agriculture is relatively equally distributed across continents and accounts for between 27-40% of deforestation (Hosonuma *et al*. 2012). It is worth noting that “subsistence agriculture” is an umbrella term that includes sustainable fallow management, small-scale agroforestry and shifting cultivation schemes (Ravikumar *et al*. 2017). These migratory systems consist of a cycle of growth, fallow and regrowth rather than causing permanent land conversion, which means these activities are relatively sustainable (Ravikumar *et al*. 2017). The inclusion of subsistence agricultural systems as drivers of deforestation can be a contentious issue, as estimates do not consider the impact of displacement of local farming activities by commercial operations (Ravikumar *et al*. 2017). For example, companies that acquire land used by local producers can often claim adherence to zero-land conversion commitments or meet certification scheme criteria, but this can trigger the movement of displaced producers into new areas (Harris *et al.* 2019). Further consideration of displacement and other complex drivers of land use change in local cultivation systems is required before incorporating the impact of subsistence agriculture into land conversion estimates.

Methods and Data Sources

Reports regarding patterns of land conversion associated with agriculture vary in focus with many centred on global consumption (section 2.1-2.3), but a few investigate the contribution of European and UK consumption (section 2.4). There is a heavy focus on Latin America and southeast Asia as case studies, as these are significant areas of commodity production, particularly beef and soybean in Brazil and palm oil in Indonesia and Malaysia. Beef, soy and palm oil are confirmed as the main drivers of large-scale land use change, accounting for 76% of agriculture-driven deforestation between 1990-2008 (Brack *et al.* 2016), with wood products and other cereals named as secondary causes of land conversion. Most studies focus on the impacts of commercial agriculture, but many papers highlight the significance of smallholder agriculture (International Sustainability Unit 2015).

Existing research converges on a general approach, whereby the area of land use change resulting from each commodity is estimated using remote sensing data and country-level reporting. Assigning the land conversion to commodities uses cropland data, often from FAO publications for each country[10]. Deforestation estimates are reported for a range of time periods to assess trends in deforestation rates.

The IPCC provide guidelines around land use classification of six broad categories of land: forest, cropland, grassland, wetlands, settlements and other land (Intergovernmental Panel on Climate Change 2003). Three data sources are described:

- Basic land use data includes datasets prepared for forestry and agricultural purposes;
- survey of land use data utilises assessments of losses and gains of each land class;
- geographically explicit land use data includes field observations from specific sites.

This land use classification system is widely used throughout the literature to describe patterns of change.

[10] http://www.fao.org/faostat/en/#home

The majority of studies used FAO data[1] to estimate land conversion rates (with a particular focus on deforestation) and attribute land use change to commodity production. The FAO data include land conversion from forest, cropland and grassland and provides figures for CO_2, CH_4 and N_2O emissions. The Global Forest Resources Assessment reports are highlighted as particularly valuable resource in forest land conversion estimates[11]. These reports are produced every five years and provide a consistent record of changes within global forests[12]. Global agricultural land conversion estimates are provided by FAO State of Food and Agriculture reports[13] while country-level commodity reporting provides data to attribute land conversion to each commodity.

The potential of remote sensing methods to illustrate land use change on a global scale is highlighted in several studies (Pendrill *et al*. 2019a; Persson *et al*. 2014). Field survey data on deforestation rates in individual countries can be collected from scientific literature and combined with the latest remote sensing analyses (Henders *et al*. 2015). Recent development of tools such as Global Forest Watch[14] and the Trase[15] platform establish links between deforestation and specific drivers (Haupt *et al*. 2018).

Major discrepancies between datasets are reported. Possible causes of these discrepancies are the over-reporting of deforestation from FAO Forest Resources Assessment data and the under-reporting associated with agricultural area information on a country level (Vito *et al.* 2013). These uncertainties are illustrated by recent remote sensing survey efforts and should be considered in all further analyses (Vito *et al.* 2013). For example, of the 239Mha global gross deforestation (between 1990-2008), 58Mha (24%) of reported deforestation cannot be linked to the recorded conversion of forests for commodity production purposes or other known deforestation activities (Vito *et al.* 2013). This unexplained deforestation may be the result of illegal deforestation and unreported activities, increases the uncertainty surrounding datasets.

This review found no sources reporting the proportion of "conversion-free" commodity production. This is maybe due the lack of specific interest in these figures, as policy-making and scientific research tends to focus on the adverse impacts of land conversion, rather than reporting the low impact commodity production. While a number of reports gave figures for the number of companies and organisations that have pledged to only use "zero-deforestation" products and highlight the current policies in place, such as the New York Declaration on Forests, reports providing an assessment of progress towards achieving the goal of "zero net deforestation by 2020" are limited.

Estimates of the proportion of agricultural products covered by zero-deforestation pledges were provided by Neeff and Linharest-Juvenal (2017). One count suggests 96% of global palm oil trade is covered by zero-deforestation pledges, while another suggests only 59% is covered. 20% and 26% of soy and beef supply chains respectively are covered by commitments respectively (Neeff & Linharest-Juvenal 2017). Only 33% of deforestation embodied crops and 8% of embodied livestock products are traded internationally (Vito *et al.* 2013). Estimates for the proportion of commodities consumed domestically that are covered by zero-deforestation certification schemes are not yet available. It is worth noting that the assessment criteria for these commitments are based on certification systems, which do not necessarily equate to "conversion-free" production and that pledges do not guarantee subsequent action.

[11] http://www.fao.org/forest-resources-assessment/en/
[12] http://www.fao.org/3/I8699EN/i8699en.pdf
[13] http://www.fao.org/publications/sofa/en/
[14] https://www.globalforestwatch.org/
[15] https://trase.earth/

Case studies of Malaysian palm oil provide estimates of the maximum area of existing cropland used for palm oil expansion. Between 1990-2005 oil palm cultivation in Malaysia expanded by 1.87Mha. The maximum cropland area converted was 0.83Mha and the maximum area of forest converted was 1.1Mha, which means that between 41-45% of expansion was on existing cropland, including rubber plantations (Koh & Wilcove 2008). This demonstrates an example of the calculations possible to assess how much commodity production is conversion-free on a country level. In the case of palm oil production in Malaysia and Indonesia, expansion often displaces rubber plantations that are sometimes considered to be "forest" (Koh & Wilcove 2008). Land conversion estimates would need to specify the types of land use defined as "forest", primary and secondary, and "existing cropland" to improve the accuracy of these estimates.

Theoretical studies examine the potential impacts of mitigation strategies and national diet changes on GHG emissions associated with each commodity (Poore & Nemecek 2018; Williams *et al.* 2010). However, these future scenarios do not consider the impact of using only commodities that have not caused land conversion. Future research into the effect of consuming only conversion-free products is needed to gain information.

Additional Considerations

- Estimates suggest that only one third of all deforestation embodied crops are internationally traded, with the remainder consumed domestically. Internationally traded crops account for 22.4Mha deforestation out of the total 239Mha gross deforestation worldwide between 1990-2008 (Vito *et al.* 2013). Estimates of the proportion of conversion-free commodity production are only provided for internationally traded goods.

- Many studies supported the inclusion of deforested land used to cultivate feed crops for livestock rearing as a component of embodied emissions for livestock products (Vito *et al*. 2013; Persson *et al.* 2014; Sandstrom *et al.* 2018).

- The growing importance of soybean and palm oil as biofuels is discussed in some studies, which detail the land conversion GHG emissions embodied in the amount of biofuel crops required to meet global biofuel targets (Ravindranath *et al.* 2009; Wicke *et al.* 2008).

- Discrepancies exist between deforestation estimates from remote sensing and FAO sources. There may be some bias in deforestation statistics, as the FAO statistics are largely based on self-reported data (Koh & Wilcove 2008). For example, while by one estimate 82% of sampled soybean cultivation properties had not deforested since 2008, 70% of surveyed properties did not comply with the Forest Code legal reserve requirements (Azevedo *et al*. 2015). Illegal deforestation could mask embodied emissions if models use self-reported statistics rather than remote sensing estimates.

- Productivity varies between commodities. Cultivating the same area of land will yield different amounts of each commodity, which poses difficulties when estimating the contribution of each commodity to land conversion. Productivity would also vary according to climate, management practices, underlying habitat properties, which makes it difficult to define productivity factors for each commodity.

- Reported statistics vary between studies. This is potentially due to the accuracy of data sources used and the inclusion of different components of land conversion, such as indirect land use.

- The criteria used to classify deforestation differs between studies. For example, rubber plantations are sometimes classed as secondary forest. In southeast Asia, palm oil expansion often occurs on rubber plantations, but this land can be reported as conversion of both forest or existing cropland (Koh & Wilcove 2008).

2.1.1 Global Agricultural Land Conversion

Estimates of global gross deforestation rates range from 7.6-8.5Mha yr^{-1} with 70-85% of this attributable to agriculture between 2010-2015 (EU 2018; Hosonuma *et al.* 2012). This aligns with another estimate, which attributes 5.5Mha yr^{-1} to agriculture between 2005-2013 (Pendrill *et al.* 2019a). The European Commission suggest agriculture is responsible for 53% or 128Mha of gross deforestation worldwide between 1990-2008 (Vito *et al*. 2013), while similar figures are quoted for the impact of palm oil, soy, beef and wood products, which are responsible for 113Mha deforestation between 2000-2012 (Haupt *et al.* 2018). It is suggested that 31% of global gross deforestation is associated with the international trade of these commodities (Haupt *et al.* 2018). Annex 2 summarises selected statistics detailing land conversion attributable to global agriculture.

2.2 How much GHG emissions does commodity production cause…

2.2.1 …through land use change?

Methods and available data

In order to estimate GHG emissions from land use change, it is necessary to estimate the carbon stocking of land before and after the change. This includes both that within above-ground biomass (live and dead) and that within soil. Carbon stocking varies both with land use type (for example forest typically stores more carbon than cropland) and within land use type (for example primary forest stores more carbon than secondary forest). Estimates typically also consider the ability of each land use type to act as a carbon sink and remove carbon from the atmosphere. For example, in addition to storing more carbon than cropland, forest can typically also sequester more carbon per year than an equivalent area of cropland.

Methods to estimate national or landscape scale emissions include (Houghton *et al.* 2012):

- **Bookkeeping models:** These use national land-use statistics and inventory-based carbon density estimates.

- **Satellite based estimates:** These use a variety of modelling approaches to track land use change, in some cases including degradation.

- **Process-based models:** These estimate changes in the biomass in vegetation, including environmental drivers such as weather as dynamic inputs.

The most widely implemented and accepted methods are those recommended in the IPCC guidance. This is based on a bookkeeping approach but allows for inclusion of additional data where available. There are three tiers of approach that countries can adopt to report on their carbon balance (Intergovernmental Panel on Climate Change 2003):

- **Tier I** is the most basic approach, relying on spatially coarse data (such as national or global land use, deforestation and production statistics) and the IPCC ‘default’ emission factors for calculating associated carbon stocks (IPCC Emissions Factor

Database (EFDB) 2019[16]). The 'default' emissions are IPCC estimates of the carbon removed per hectare of many different types of forest and the fraction of carbon left in the case of various specified land use changes (e.g. montane tropical forest to cropland).

- **Tier II** builds on Tier I by using country-specific data and emission factors, with finer scale spatial resolution. This allows for greater specificity of the most important land use types locally, and for the creation of emission factors specific to particular regions within a country.

- **Tier III** is the most rigorous approach, providing estimates of the greatest certainty. As well as using very high-resolution subnational data and emissions factors (landscape-scale and sometimes species-specific), it incorporates process-based models that are adapted to the country's specific circumstances and that are repeated over time to track change. This approach must consider and model the relationship between above ground biomass and soil, as well as the effect of forest age on the carbon stored. Climate data is typically also included. Models and data used must undergo a strict auditing and validation process.

Countries are expected to report their GHG inventories (including both land use emissions and other emissions) to the UNFCCC following these guidelines[17] More industrialised countries, listed as Annex I parties, are expected to report using Tier II or III, while developing countries are permitted to use Tier I. The methods used by Annex I and non-Annex II parties do not produce directly comparable results.

Most academic papers use approaches that would fit into Tiers II or III of the IPCC methodology. However, this does not mean there is little variation in the approaches that they take – the framework allows for wide methodological variation within these Tiers, as they call for local emissions factors to be applied. This has led to large variety in figures reported (see Table 2, Annex 3).

Limitations

GHG emissions from land use change is considered the "most uncertain term in the global carbon budget" (Houghton *et al*. 2012). For example, the uncertainty of the UK's 2016 domestic land-use carbon emissions is estimated to be in the range of 40-50% of the reported figure (Brown *et al* 2018). Some datasets that once reported on land-use emissions (Gütschow *et al.* 2016) have chosen to no longer include this, due to the strong differences across datasets and methods used to estimate it (Gütschow *et al.* 2019). Therefore, interpretation of any figures presented should be done with caution and used with low confidence (Friedlingstein *et al.* 2019).

Much of this uncertainty arises from:

- **Spatial variability in carbon density even within the same habitat type** (Houghton *et al.* 2012). This could be due to differences in microclimate, species composition and past disturbances.

- **Difficulties in measuring habitat degradation rather than simply changes in extent.** Habitat degradation is a significant contributor to land use change emissions. For example, one study estimated that 25% of land use change GHG emissions from

[16] https://www.ipcc-nggip.iges.or.jp/EFDB/main.php
[17] GHG Data from UNFCCC https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/ghg-data-from-unfccc. Accessed 2020-03-14.

tropical forests come from degradation rather than deforestation and that in 28 of 74 countries studied the GHG emissions from degradation exceeded those from deforestation (Pearson *et al*. 2017). However, degradation is more difficult to detect and monitor than changes in habitat extent. For example, degradation is much more difficult to pick up in satellite imagery than deforestation, relying on high resolution imagery and only picking up change that affects canopy cover (Pearson *et al.* 2017; Mitchell *et al.* 2017). The UNFCCC recognise degradation as a significant driver of emissions through their REDD+ programme (Reducing Emissions from Deforestation and Forest Degradation)[18].

- **An incomplete understanding of the carbon and other GHG stored within soil.** Many studies do not report on this at all within figures they present, due to the lack of consistency in data (Guillaume *et al.* 2018). Those that do have disagreed not only in extent but also direction of results (Guillaume *et al.* 2018). It is generally accepted that conversion from natural habitat to cropland negatively impacts carbon storage within the top metre of soil, but the effects of erosion and redeposition on this are unclear (Houghton *et al.* 2012). Nitrous oxide is another significant emission from soil around which there is little agreement on the specifics (Castanheira & Freire 2013).

- **Exclusion of important habitat types.** Many studies only account for forest or tropical forest, and exclude effects from peatlands, wetlands, mangroves, human settlements and infrastructure (Houghton *et al.* 2012). Peatlands in particular are a very significant carbon sink (Pendrill *et al*. 2019b), with their conversion and degradation likely accounting for around a fifth of all land-use related GHG emissions (Tubiello *et al*. 2014).

- **Exclusion of or larger variation in models of carbon differences caused by land use management and production system** (Houghton *et al.* 2012). Not all models include management factors, such as wood harvest, grazing and selective logging. Those that do differ greatly in how these are calculated. Obtaining reliable data for inclusion of such factors at a large scale is also challenging.

- **Differentiating between natural and anthropogenic land use change processes** that affect the land's role as both a source and a sink (Shukla *et al.* 2019)

- **High annual fluctuations in data,** meaning that combining datasets presents challenges in terms of scaling (Gütschow *et al.* 2019).

Inconsistencies also arise from the differing forest definitions and different amortisation periods used between different studies.

Results

A collation of several sources estimating emissions factors for some key habitat types and commodities is presented in Table 2, Annex 3. More detailed emissions factors can be found within the IPCC[19] and FAO[20] databases.

[18] United Nations Framework Convention on Climate Change Reducing Emissions from Deforestation and Degradation (UNFCCC REDD+) Programme: https://redd.unfccc.int/
[19] Intergovernmental Panel on Climate Change Emissions Factors Database: https://www.ipcc-nggip.iges.or.jp/EFDB/main.php
[20] Food and Agriculture Organisation Corporate Statistical Database 'Emissions – Land use' data: http://www.fao.org/faostat/en/#data

2.2.2 …through agricultural emissions?

Land use is not the only way in which agricultural commodity production leads to GHG emissions. Emissions attributable to commodity production may also come from mineral fertiliser (produced from fossil fuels), electricity and fuel used on farms for machinery and transport. In livestock production, GHG is also released through enteric fermentation during digestion, manure and emissions associated with the production of feed (Lynch 2019). Estimations of agricultural emissions carry higher certainty than emissions associated with land use change and are therefore included in significantly more sources, with lower variation between estimates.

As the main focus of this report is on emissions from land use change, only studies that show agricultural emissions but also include land use change emissions are presented (Table 3, Annex 3), rather than studies presenting agricultural emissions alone. However, it is important to note when considering the overall question of moving to more climate-friendly production systems, that switching to conversion-free commodity production is not the only way in which a reduction in commodity related GHG emissions can be achieved. It would also be important to consider ways to reduce emissions related to production practices taking place within conversion-free farms and plantations.

The FAO database mentioned in the previous section also provides emissions factors for agricultural emissions[15].

2.2.3 …overall?

Table 3 in Annex 3 presents figures that consider the relative emissions from land use change (Section 2.2.1) and agricultural production practices (Section 2.2.2). Estimates for the proportion of emissions associated with agriculture that result from land use change range between 20 and 49%.

2.3 How much GHG is emitted in total? How much of this relates to commodity production vs other emissions?

To work out the percentage of global greenhouse gas emissions that would change each year with a shift to conversion free production of agricultural commodities, it is necessary to compare this to the overall GHG emitted, including from the burning of fossil fuels, waste and industrial processes. Once again, the main international guidance on doing this comes from the IPCC, and many variations and other methodologies have been applied across a variety of studies.

Estimates of the percentage of total anthropogenic GHG emissions caused by land use change range between 9 and 14%, and are presented more fully in Table 4, Annex 4. Whilst the actual emissions from land use change have remained relatively stable throughout this time, other emissions sources (such as emissions from fossil fuel-based energy use) have increased significantly (Gütschow *et al.* 2019). Therefore, land use change emissions have reduced as a proportion of the total but remain a significant contribution to overall emissions. The relatively steady land use emissions reflect decreasing deforestation rates balancing against decreasing sequestration ability due to previous land use change.

2.4 What proportion of global commodity supply reaching the UK or Europe is from a conversion-free source? What proportion of the UK's or Europe's GHG emissions results from the land use change associated with commodities that we consume?

No data are available that reliably track all commodities from their point of production to their point of consumption, so estimating the proportion of this that causes land use change emissions is challenging and based on numerous assumptions. Most trade databases (e.g. HMRC[21], UN Comtrade[22], FAO[23]) only record bilateral trade (the direct trade between two countries). This tells you the last country from which your products were imported but does not identify whether these products have been re-exported through intermediate trading countries or have come directly from the country of origin. It also does not account for the process by which commodities have become embedded in another product (for example, palm oil within chocolate). Most companies importing commodities have long and complex supply chains and mix products from different sources, so are unaware themselves of the true geographic origin of their products.

However, it is possible to estimate the sourcing patterns of a country's (or region's) consumption using multi-regional input-output (MRIO) modelling. This is an economic tool used to model global trade flows, based on tables representing the monetary inputs and outputs across different countries and their commercial sectors. It is not without limitations (for example, a country's exports are assumed to be averaged across the total of its production. Also, data poor countries are simply grouped together into 'Rest of World' regions) but is widely accepted as a useful tool for estimation. Examples include Exiobase, EORA and GTAP (Tukker *et al.* 2014; Lenzen *et al.* 2013, 2012; Aguiar *et al*. 2019).

Most MRIOs also have environmental extensions, which provide additional data on environmentally relevant metrics, which often include the land use and carbon emissions associated with production of each commodity. These are calculated using combinations of other global data sources. Unfortunately, none of the global MRIOs investigated within this study include GHG emissions associated with land use change within their carbon emissions extension; they report only on the direct emissions from agriculture. Where acknowledged at all, the reasons for this are stated to be the uncertainties described in previous sections, compared to the relatively accepted methods for calculating agricultural emissions (Gütschow *et al*. 2019). For example, the UK Carbon Footprint is a project that uses MRIO to estimate the embedded carbon of UK consumption, but currently does not include emissions from embedded land use change (Wiedmann *et al.* 2008).

One project which has linked MRIO to land use change related GHG emissions is PRINCE (Policy Relevant Indicators for Consumption and Environment); a three-year project aiming to develop methodology to measure the environmental impacts embedded in Swedish consumption. Land use change emissions formed one of the case study projects, concluding that Swedish consumption was responsible for an estimated 3.9MtCO_2 yr^{-1} of emissions through land use change embodied in consumption[24]. A variety of data sources were used as inputs to a land-balance model to estimate the likely deforestation and peatland drainage associated with the consumption. Emissions factors were used to transform this estimate into a carbon equivalent. Whilst the estimates calculated in this project referred to Swedish consumption and therefore did not provides estimates for the UK's or Europe's consumption,

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[21] Her Majesty's Revenue and Customs (HMRC): https://www.uktradeinfo.com/Statistics/BuildYourOwnTables/Pages/Home.aspx
[22] United Nations Comtrade: https://comtrade.un.org/
[23] Food and Agriculture Organisation (FAO): http://www.fao.org/faostat/en/#data
[24] PRINCE Case Studies – Prince. https://www.prince-project.se/case-studies-2/. Accessed 2020-03-10

it acts as a proof of concept, demonstrating that it should be possible to carry out a similar analysis for the countries in question if adequately resourced, using a similar approach.

An alternative to MRIO analysis for modelling trade flows is Material Flow Analysis (MFA). Some studies investigating land-use change emissions from a consumption-based perspective have also used this approach (Kastner *et al.*2014; Sandström *et al.* 2018). MFA is based on running physical commodity data through re-export algorithms in order to estimate its most likely flow through the supply chain. This approach is able to give information on commodities rather than more generic sectors but is not designed to model the flow of commodities once they are embedded in another product. It is also possible to combine MRIO and MFA into a hybrid approach, which improves geographic and commodity resolution.

There is currently relatively little available data detailing the land-use change related GHG emissions for overall UK and European consumption, but some studies that do attempt to address this are explored in the following sections. Considering the low certainty associated with land use change emissions in general, and the added uncertainty associated with supply chain modelling, these estimates should be treated with caution.

The difficulties in tracking commodities through supply chains are more fully described in Harris *et al.* (2019), alongside further methodological options of varying complexity that could be used to estimate the breakdown of a country's consumption.

2.4.1 UK Embodied Land Conversion Footprint

The UK's Carbon Footprint (1997-2016) and Exiobase data provides estimates of CO_2 emissions embedded in imported goods and services but does not account for land-use change emissions associated with these goods and services. However, WWF publications such as "How Low Can We Go?" and "The UK Soy Story" as well as some academic papers report embodied land use change or land-use change emissions. Estimates for the UK land conversion footprint vary significantly. The WWF (World Wide Fund for Nature) and RSPB (Royal Society for the Protection of Birds) 'Risky Business' report (2017) suggests the annual UK demand for major commodities required a total of 13.6Mha yr^{-1} between 2011-2015 (Haupt *et al.* 2018). According to Pendrill *et al.* (2019a) an estimated 31kha yr^{-1} of deforestation was imported by the UK between 2010-2013. Previously land use change emissions associated with UK food consumption have been estimated as 100-101Mt CO_2eq yr^{-1} (Audsley *et al.* 2009; Williams *et al.* 2010). The UK accounts for 2.1% of global land conversion emissions (Audsley *et al.* 2009). Available estimates are presented in Annex 5.

2.4.2 Europe Embodied Land Conversion Footprint

Globally Europe is the largest net importer of agricultural commodities driving deforestation according to the International Sustainability Unit Tropical Forests Review (2015). Major imports of soybean come from Brazil, Argentina and Paraguay, meat products from Brazil and palm oil from Indonesia and Malaysia. The EU27 imported 36% of all internationally traded deforestation embodied crop and livestock products annually between 1990-2008, which is the equivalent of 9Mha deforested land each year (Vito *et al.* 2013). Europe's deforestation emissions are 0.3t CO_2 yr^{-1} per capita, which is 15% of the total food carbon footprint (Vito *et al.* 2013). Another source suggests land use change emissions account for 30% of Europe's food consumption emissions based on 2010 data (Sandström *et al.* 2018). Annex 6 brings together estimates of the land conversion footprint embodied in Europe's commodity consumption.

3 Conclusions: Is it currently possible to report reliable estimates on the percentage of global emissions that would be reduced per year if the UK/Europe/the world shifted to conversion-free palm oil, beef and soy?

Whilst it is currently possible to estimate the percentage of global GHG emissions caused by conversion of natural habitat for agricultural commodity production, it is only possible to do so with a high degree of uncertainty. Breaking this down to UK or European consumption adds further uncertainty.

A comprehensive set of relevant estimates found within the time frame of this review are presented in Annexes 2-6 to this report. The most relevant of these to the specific questions the report aimed to answer are presented in the Executive Summary and in Annex 1. Those in Annex 1 are based on simple calculations using several estimates to provide a figure that more directly answers the reports key questions than figures found in the literature alone and so should not be considered to have a high level of confidence.

If wishing to find out more about the potential for adaptations in land use change to be used in climate change mitigation, especially in relation to the cost effectiveness and economically viability of doing so, the IPCC report 'AR5 Climate Change 2014: Mitigation of Climate Change' would make useful further reading.

Underlying the problem of land conversion, however, it must be recognised that global population is increasing, incomes are rising, and consumption patterns are changing, with the result that demand for almost all products is increasing (Bringezu *et al.* 2017). The practicality of suggesting the world would be able to shift to entirely conversion-free production in the near future must therefore be considered. Some models of future scenarios include the intensification of agricultural production depending on projected population growth (Angelsen 2010). An increase in agricultural productivity is also assumed in some models, with a proposed mean increase of 1.13% per year, based on extrapolation of current trends. A more optimistic estimate of 1.53% increase in yields per year would counteract the need for agricultural area expansion (Angelsen 2010). The role of developing more environmentally friendly and cost-efficient production systems will be critical to achieving this.

References:

Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R. & van der Mensbrugghe, D. 2019. 'The GTAP Data Base: Version 10'. *Journal of Global Economic Analysis* 4 (1): 1–27. https://doi.org/10.21642/JGEA.040101AF.

Angelsen, A. 2010. 'Policies for Reduced Deforestation and Their Impact on Agricultural Production'. *Proceedings of the National Academy of Sciences* 107 (46): 19639–44. https://doi.org/10.1073/pnas.0912014107.

Asner, G. 2009. 'Measuring Carbon Emissions from Tropical Deforestation: An Overview'.

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C. & Williams, A. (2009). How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050. WWF-UK.

Azevedo, A.A., Stabile, M.C.C. & Reis, T.P.N. 2015. 'Commodity Production in Brazil: Combining Zero Deforestation and Zero Illegality'. *Elem Sci Anth* 3 (0): 000076. https://doi.org/10.12952/journal.elementa.000076.

Brack, D., Wellesley, L. & Glover, A. 2016. 'Agricultural Commodity Supply Chains: Trade, Consumption and Deforestation', January. https://www.chathamhouse.org/publication/agricultural-commodity-supply-chains-trade-consumption-and-deforestation

Bringezu, S., Ramaswami, A., Schandl, H., O'Brien, M., Pelton, R., Aquatella, J., Ayuk, E., *et al.* 2017. 'Assessing Global Resource Use: A Systems Approach to Resource Efficiency and Pollution Reduction.' IRP.

Castanheira, É.G. & Freire, F. 2013. 'Greenhouse Gas Assessment of Soybean Production: Implications of Land Use Change and Different Cultivation Systems'. *Journal of Cleaner Production* 54 (September): 49–60. https://doi.org/10.1016/j.jclepro.2013.05.026.

COWI, Directorate-General for Environment (European Commission), Ecofys, Milieu. 2018. Feasibility study on options to step up EU action against deforestation.

Fargione, J.E., Hill, J., Tilman, D., Polasky, S. & Hawthorne, P.L. 2008. 'Land Clearing and the Biofuel Carbon Debt.' Science. https://doi.org/10.1126/science.1152747.

Friedlingstein, P., Jones, M.W., O'Sullivan, M., Andrew, R.M., Hauck, J., Peters, G.P., Peters, W., *et al.* 2019. 'Global Carbon Budget 2019'. *Earth System Science Data* 11 (4): 1783–1838. https://doi.org/10.5194/essd-11-1783-2019.

'GHG Data from UNFCCC | UNFCCC'. n.d. Accessed 14 March 2020. https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/ghg-data-from-unfccc.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N. & Foley, J.A. 2010. 'Tropical Forests Were the Primary Sources of New Agricultural Land in the 1980s and 1990s'. *Proceedings of the National Academy of Sciences* 107 (38): 16732–37. https://doi.org/10.1073/pnas.0910275107.

Goldewijk, K.K. 2001. ‘Estimating Global Land Use Change over the Past 300 Years: The HYDE Database’. *Global Biogeochemical Cycles* 15 (2): 417–33. https://doi.org/10.1029/1999GB001232.

Guillaume, T., Kotowska, M.M., Hertel, D., Knohl, A., Krashevska, V., Murtilaksono, K., Scheu, S. & Kuzyakov, Y. 2018. ‘Carbon Costs and Benefits of Indonesian Rainforest Conversion to Plantations’. *Nature Communications* 9 (1): 1–11. https://doi.org/10.1038/s41467-018-04755-y.

Gütschow, J.M., Jeffery, L., Gieseke, R., Gebel, R., Stevens, D., Krapp, M. & Rocha, M. 2016. ‘The PRIMAP-Hist National Historical Emissions Time Series’. *Earth System Science Data* 8 (2): 571–603. https://doi.org/10.5194/essd-8-571-2016.

Gütschow, J., Jeffery, L., Gieseke, R. & Günther, A. (2019): The PRIMAP-hist national historical emissions time series (1850-2017). v2.1. GFZ Data Services. https://doi.org/10.5880/pik.2019.018

Harris, M., Hawker, J., Croft, S., Smith, M., Way, L., Williams, J., Wilkinson, S., *et al*. 2019. ‘Is the Proportion of Imports Certified as Being from Sustainable Sources an Effective Indicator of UK Environmental Impact Overseas?’ Joint Nature Conservation Committee and Stockholm Environment Institute.

Haupt, F., Streck, C., Bakhtary, H., Behm, K., Kroeger, I. & Schulte, I. 2018. Zero-deforestation Commodity Supply Chains by 2020: Are We on Track? For the Prince of Wales' International Sustainability Unit. https://climatefocus.com/sites/default/files/20180123%20Supply%20Chain%20Efforts%20-%20Are%20We%20On%20Track.pdf.

Henders, S.U., Persson, M. & Kastner, T. 2015. ‘Trading Forests: Land-Use Change and Carbon Emissions Embodied in Production and Exports of Forest-Risk Commodities’. *Environmental Research Letters* 10 (12): 125012. https://doi.org/10.1088/1748-9326/10/12/125012.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A. & Romijn, E. 2012. ‘An Assessment of Deforestation and Forest Degradation Drivers in Developing Countries’. *Environmental Research Letters* 7 (4): 044009. https://doi.org/10.1088/1748-9326/7/4/044009.

Houghton, R.A., House, J.I., Pongratz, J., van der Werf, G.R., DeFries, R.S., Hansen, M.C., Le Quéré, C. & Ramankutty, N. 2012. ‘Carbon Emissions from Land Use and Land-Cover Change’. *Biogeosciences* 9 (12): 5125–42. https://doi.org/10.5194/bg-9-5125-2012.

Intergovernmental Panel on Climate Change. 2003. ‘Good Practice Guidance for Land Use, Land-Use Change and Forestry’. IPCC National Greenhouse Gas Inventories Programme.

International Sustainability Unit, The Prince of Wales' Charitable Foundation. 2015. Tropical Forests: A Review, https://www.issuelab.org/resource/tropical-forests-a-review.html

IPCC. 2014. ‘AR5 Climate Change 2014: Mitigation of Climate Change — IPCC’. 2014. https://www.ipcc.ch/report/ar5/wg3/.

‘IPCC Emissions Factor Database (EFDB)’. n.d. Accessed 14 March 2020. https://www.ipcc-nggip.iges.or.jp/EFDB/find_ef.php?reset=.

Karstensen, J., Peters, G. & Andrew, R.M. 2013. Attribution of CO_2 emissions from Brazilian deforestation to consumers between 1990 and 2010. Environmental Research Letters. 8. https://doi.org/10.1088/1748-9326/8/2/024005

Kastner, T., Erb, K-.H. & Haberl, H. 2014. 'Rapid Growth in Agricultural Trade: Effects on Global Area Efficiency and the Role of Management'. *Environmental Research Letters* 9 (3): 034015. https://doi.org/10.1088/1748-9326/9/3/034015.

Kissinger, G., Herold, M. & de Sy, V. 2012. 'Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers'. Center for International Forestry Research. Accessed 13 March 2020. https://www.cifor.org/library/5167/.

Klein Goldewijk, K. & Ramankutty, N. 2010. 'Land Use Changes during the Past 300 Years'. *Land Use, Land Cover and Soil Sciences* 1 (January).

Koh, L.P. & Wilcove, D.S. 2008. 'Is Oil Palm Agriculture Really Destroying Tropical Biodiversity?' *Conservation Letters* 1 (2): 60–64. https://doi.org/10.1111/j.1755-263X.2008.00011.x.

Langner, A., Achard, F, & Grassi, G. 2014. 'Can Recent Pan-Tropical Biomass Maps Be Used to Derive Alternative Tier 1 Values for Reporting REDD$\mathplus$ Activities under UNFCCC?' *Environmental Research Letters* 9 (12): 124008. https://doi.org/10.1088/1748-9326/9/12/124008.

Lenzen, M., Kanemoto, K., Moran, D. & Geschke, A. 2012. 'Mapping the Structure of the World Economy'. *Environmental Science & Technology* 46 (15): 8374–81. https://doi.org/10.1021/es300171x.

Lenzen, M., Moran, D., Kanemoto, K. & Geschke, A. 2013. 'Building Eora: A Global Multi-Region Input–Output Database at High Country and Sector Resolution'. *Economic Systems Research* 25 (1): 20–49. https://doi.org/10.1080/09535314.2013.769938.

Lynch, J. 2019. 'Availability of Disaggregated Greenhouse Gas Emissions from Beef Cattle Production: A Systematic Review'. *Environmental Impact Assessment Review* 76 (May): 69–78. https://doi.org/10.1016/j.eiar.2019.02.003.

Mitchell, A.L., Rosenqvist, A. & Mora, B. 2017. 'Current Remote Sensing Approaches to Monitoring Forest Degradation in Support of Countries Measurement, Reporting and Verification (MRV) Systems for REDD+'. *Carbon Balance and Management* 12 (1): 9. https://doi.org/10.1186/s13021-017-0078-9.

Pearson, T.R.H., Brown, S., Murray, L. & Sidman, G. 2017. 'Greenhouse Gas Emissions from Tropical Forest Degradation: An Underestimated Source'. *Carbon Balance and Management* 12 (1): 3. https://doi.org/10.1186/s13021-017-0072-2.

Pendrill, F., Martin Persson, U., Godar, J. & Kastner, T. 2019. 'Deforestation Displaced: Trade in Forest-Risk Commodities and the Prospects for a Global Forest Transition'. *Environmental Research Letters* 14 (5): 055003. https://doi.org/10.1088/1748-9326/ab0d41.

Pendrill, F., Martin Persson, U., Godar, J., Kastner, T., Moran, D., Schmidt, S. & Wood, R. 2019. 'Agricultural and Forestry Trade Drives Large Share of Tropical Deforestation Emissions'. *Global Environmental Change* 56 (May): 1–10. https://doi.org/10.1016/j.gloenvcha.2019.03.002.

Martin Persson, U., Henders, S. & Cederberg, C. 2014. 'A Method for Calculating a Land-Use Change Carbon Footprint (LUC-CFP) for Agricultural Commodities – Applications to Brazilian Beef and Soy, Indonesian Palm Oil'. *Global Change Biology* 20 (11): 3482–91. https://doi.org/10.1111/gcb.12635.

Petrenko, C., Paltseva, J. & Searle, S. 2016. 'Ecological Impacts of Palm Oil Expansion in Indonesia. White Paper for International Council on Clean Transportation.

Poore, J. & Nemecek, T. 2018. 'Reducing Food's Environmental Impacts through Producers and Consumers'. *Science* 360 (6392): 987–92. https://doi.org/10.1126/science.aaq0216.

'PRINCE Case Studies – Prince'. n.d. Accessed 10 March 2020. https://www.prince-project.se/case-studies-2/.

Ramankutty, N. & Foley, J.A. 1999. 'Estimating Historical Changes in Global Land Cover: Croplands from 1700 to 1992'. *Global Biogeochemical Cycles* 13 (4): 997–1027. https://doi.org/10.1029/1999GB900046.

Ravikumar, A., Sears, R.R., Cronkleton, P., Menton, M. & Pérez-Ojeda del Arco, M. 2017. 'Is Small-Scale Agriculture Really the Main Driver of Deforestation in the Peruvian Amazon? Moving beyond the Prevailing Narrative'. *Conservation Letters* 10 (2): 170–77. https://doi.org/10.1111/conl.12264.

Ravindranath, N.H., Manuvie, R., Fargione, J., Canadell, J.G. Berndes, G., Woods, J., Watson, H. & Sathaye, J. 2009. 'Greenhouse Gas Implications of Land Use and Land Conversion to Biofuel Crops'. In *Biofuels: Environmental Consequences and Interactions with Changing Land Use*, 111–25.

Reijnders, L. & Huijbregts, M.A.J. 2008. 'Palm Oil and the Emission of Carbon-Based Greenhouse Gases'. *Journal of Cleaner Production* 16 (4): 477–82. https://doi.org/10.1016/j.jclepro.2006.07.054.

Saatchi, S.S., Houghton, R.A., Dos Santos Alvalá, R.C., Soares, J.V. & Yu, Y. 2007. 'Distribution of Aboveground Live Biomass in the Amazon Basin'. *Global Change Biology* 13 (4): 816–37. https://doi.org/10.1111/j.1365-2486.2007.01323.x.

Saikku, L., Soimakallio, S. & Pingoud, K. 2012. 'Attributing Land-Use Change Carbon Emissions to Exported Biomass'. *Environmental Impact Assessment Review*, Trends in biogenic-carbon accounting, 37 (November): 47–54. https://doi.org/10.1016/j.eiar.2012.03.006.

Sandström, V., Valin, H., Krisztin, T., Havlík, P., Herrero, M. & Kastner, T. 2018. 'The Role of Trade in the Greenhouse Gas Footprints of EU Diets'. *Global Food Security* 19 (December): 48–55. https://doi.org/10.1016/j.gfs.2018.08.007.

Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.O., Roberts, D.C., Zhai, P., *et al.* 2019. 'Special Report on Climate Change and Land — IPCC Site'. 2019. https://www.ipcc.ch/srccl/.

Tubiello, F., Salvatore, M., Golec, R., Ferrara, A., Rossi, S., Biancalani, R., Federici, S., Jacobs, H. & Flammini, A. 2014. *Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks: 1990-2011 Analysis*. https://doi.org/10.13140/2.1.4143.4245.

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K. & Wood, R. 2014. *The Global Resource Footprint of Nations. Carbon, Water, Land and Materials Embodied in Trade and Final Consumption, Calculated with EXIOBASE 2.1*. TNO.

VITO, IIASA, HIVA, IUCN NL (2013) The impact of EU consumption on deforestation: Comprehensive analysis of the impact of EU consumption on deforestation. Technical report 2013 – 063. European Commission, DG ENV. Available at: http://ec.europa.eu/environment/forests/pdf/1.%20Report%20analysis%20of%20impact.pdf

Wicke, B., Dornburg, V., Junginger, H.M. & Faaij, A.P.C. 2008. 'Different palm oil production systems for energy purposes and their greenhouse gas implications'. Article. Biomass and Bioenergy. 2008. http://localhost/handle/1874/32968.

Wiedmann, T., Wood, R., Lenzen, M., Minx, J., Guan, D. & Barrett, J. 2008. 'Development of an Embedded Carbon Emissions Indicator: Producing a Time Series of Input-Output Tables and Embedded Carbon Dioxide Emissions for the UK by Using a MRIO Data Optimisation System', July. https://www.sei.org/publications/development-embedded-carbon-emissions-indicator-producing-time-series-input-output-tables-embedded-carbon-dioxide-emissions-uk-using-mrio-data-optimisation-system/.

Williams, A.G., Audsley, E., Chatterton, J.C., Murphy-Bokern, D. & Brander, M. 2010. Greenhouse gas emissions from UK food and drink consumption by systems LCA: current and possible futures. LCA-Food 2010: VII International conference on Life Cycle Assessment in the agri-food sector, 22 to 24 September 2010, Bari (Italy). https://core.ac.uk/reader/140825

WWF.2017. 'Deforestation and Social Risks in the UK's Commodity Supply Chain' Risky Business: Understanding the UK's Overseas Footprint for Deforestation-Risk Commodities. https://www.wwf.org.uk/sites/default/files/2017-10/Risky%20Business%20-%20October%202017.pdf

WWF. 2019. 'The UK Soy Story: How Retailers' Commitments to Tackling Soy-Driven Deforestation Compare' https://www.wwf.org.uk/sites/default/files/2019-10/WWF-UK_Retailers_Soy_Policies_October2019.pdf

Annex 1: Low Confidence Estimates

Estimates of the exact scenarios the report aimed to answer (low confidence, only estimates for scenario 1a would be recommended for use):

These have been calculated using figures from a variety of literature. Whilst the raw figures from the literature are reliable, the final estimates presented in this Annex are based on large assumptions and are each calculated in a different way so are not truly comparable. They are likely within the right order of magnitude but are not accurate and thus not recommended for use.

What percentage of global GHG emissions would be reduced per year if…

1. *…the world shifted to…*

a. …conversion-free produce across all agricultural commodities?
Estimate: **9-14%** Confidence level: **Medium**
Sources: The range is based on estimates taken directly from the literature (Tubiello *et al.* 2014; Houghton *et al*. 2012; Shukla *et al*. 2019; Friedlingstein *et al*. 2019; IPCC 2014).
Caveats: Coming from internationally recognised organisations such as IPCC, FAO and UNFCCC, these estimates carry higher confidence than any others within this report. However, all estimates of GHG emissions from land use change carry high uncertainty, for example due to the high variation in carbon stocks within the same habitat type and an incomplete understanding of carbon in soil (see Section 2.2.1).

b. …conversion-free palm oil?
Estimate: **0.36-0.65%** Confidence level: **Very low**
Sources: No direct estimates were found in the literature within the timeframe of this scoping review, but an estimate was calculated based on other figures available. Palm oil cultivation is responsible for 0.4Mha yr^{-1} deforestation (Pendrill *et al*. 2019a)[5]. Estimates of the average land use emissions from conversion of tropical forest to oil palm plantations range from 174-187 tons C/ha (Guillaume *et al*. 2018; Reijnders & Huijbregts 2008). If assuming all oil palm related land conversion is associated with loss of tropical forest, it could be estimated that this is responsible for 69.6M-74.8M tons of C per year. Based on a total global emissions estimate of 11.5Gt C yr^{-1} [25] , if the world shifted to conversion-free palm oil, 0.6-0.65% of global GHG emissions would be reduced per year. According to an alternative estimate, palm oil is estimated to drive 4.5% of global forest loss. Deforestation accounts for 7.98% of total GHG emissions[26]. Based on these figures, it could be estimated that if the world shifted to conversion-free palm oil, 0.36% of global GHG emissions would be reduced per year.
Caveats: Not all palm oil related conversion is associated with tropical forest loss – this is a critical assumption. The estimate brings together data sources that were not designed to be combined and may therefore be inconsistent with each other. The second estimate assumes that land use change emissions only arise from deforestation, so does not take into account other important factors related to GHG emissions, such as peatland and soil carbon.

[25] Friedlingstein *et al*. 2019.
[26] Calculated from Tubiello *et al*. 2014.

c. …*conversion-free beef*[27]*?*

Estimate: **Over 2%** *Confidence level*: **Very low**

Sources: No direct estimates were found in the literature within the timeframe of this scoping review, but an estimate was calculated based on other figures available. An estimated 25% of global forest loss (2.2Mha/yr)[4] is associated with cattle production (Pendrill *et al.* 2019a). Assuming deforestation accounts for 7.98% of total GHG emissions[28] it could be estimated that if the world shifted to conversion-free beef, global GHG emissions would be reduced by 2% per year.

Caveats: The estimate brings together data sources that were not designed to be combined and may therefore be inconsistent with each other. It assumes that land use change emissions only arise from deforestation, so does not take into account other important factors such as peatland and soil carbon.

d. …*conversion-free soy?*

Estimate: **0.36%** *Confidence level*: **Very low**

Sources: No direct estimates were found in the literature within the timeframe of this scoping review, but an estimate was calculated based on other figures available. Soybean cultivation drives 0.4Mha yr^{-1} deforestation worldwide[5], which calculates to 4.5% of global forest loss (Pendrill *et al.* 2019a). Deforestation accounts for 7.98% of total GHG emissions[12] Based on this, it could be estimated that if the world shifted to conversion-free soy, 0.36% of global GHG emissions would be avoided per year.

Caveats: Same caveats as beef (see above). Also soy has been shown to have highly variable land use change emissions across the many types of land use commonly converted for soy production (Castanheira & Freire 2013; Persson *et al.* 2014).

2. …*Europe shifted to…*

a) …*conversion-free produce across all agricultural commodities?*

Estimate: **1.34%** *Confidence level:* **Very Low**

Sources: No direct estimates were found in the literature within the timeframe of this scoping review, but related estimates exist. An estimate suggests the average EU deforestation emissions footprint is 0.3 t CO_2 yr^{-1} per capita (Pendrill *et al.* 2019b). Based on a population of 513.2 million in EU in 2018[29] the deforestation emissions for Europe total 154Mt CO_2 yr^{-1}. Based on the estimate of 11.5GtC per year[9], the deforestation embodied in Europe's food consumption accounts for 1.34% of total anthropogenic emissions.

Caveats: This estimate is calculated from a combination of sources that do not cover the same time period and only cover deforestation, rather than all land conversion. It is worth noting that approximately 36% of Europe's food originates from countries outside of Europe, so most impacts are within the region itself (Sandström *et al.* 2018).

b) …*conversion-free palm oil?*

Estimate: **0.15%** *Confidence level*: **Very Low**

Sources: 11% of Europe's total net imported deforestation embodied crops were attributable to palm oil between 1990-2008 (Vito *et al.* 2013). Based on the estimate of total EU food consumption above, this suggests that 16.94Mt CO_2 yr^{-1} are attributable to European palm oil consumption. Based on the estimate of 11.5GtC per year[9], the deforestation embodied in Europe's palm oil consumption accounts for 0.15% of total anthropogenic emissions.

[27] Note that there is likely some overlap and double counting between the figures presented for beef and the figures presented for soy, as soy is a common feed stock for cattle. Beef estimates will therefore include the land use relating to the soy that is fed to cattle within their estimates.
[28] Calculated from figures presented in Tubiello *et al*. 2014
[29] https://data.worldbank.org/indicator/SP.POP.TOTL?locations=EU

Caveats: This estimate only includes deforestation and is based on the combination of data from several sources covering different time periods and using different methods.

c) *…conversion-free beef?*
Estimate: **<0.01%** *Confidence level*: **Very Low**
Sources: Less than 1% of land use change emissions of Europe are attributed to pasture expansion for beef production (Sandström *et al*. 2018). This figure is so small because the vast majority of beef consumed in Europe originates from European countries and the method used in obtaining this estimate only includes agricultural activities that have expanded total area under production (Sandström *et al*. 2018).
Caveats: The methods of this paper could underestimate beef emissions, as only agricultural areas that expanded their total area were included in this analysis.

d) *…conversion-free soy?*
Estimate: **0.75%** *Confidence level*: Very Low
Sources: 56% of Europe's total net imported deforestation embodied crops were soybeans between 1990-2008 (Vito *et al*. 2013). Given the total food consumption of Europe accounts for 1.34% of total GHG emissions, if we assume consumption patterns to be constant over time then 56% of total GHG emissions would equate to 0.75% of total GHG emissions.
Caveats: This calculation includes sources covering different time periods and using different methods, so are not consistent with each other.

3. *The UK shifted to…*

a) *…conversion-free produce across all agricultural commodities?*
Estimate: **0.028-0.27%** *Confidence level:* **Very Low**
Sources: Between 2010-2013 the UK imported 31kha yr^{-1} of embodied deforestation (Pendrill *et al.* 2019a). Total deforestation amounts to 8.87Mha yr^{-1} (Pendrill *et al*. 2019a), so the UK imports 0.35% of this per year. If deforestation accounts for 7.98% of total GHG emissions[12], land conversion embodied in UK food consumption is responsible for 0.028% of total global GHG emissions. Another estimate suggests UK food consumption accounts for an estimated 2.1% of global land use change emissions (Audsley *et al.* 2009). Global land use change emissions are 1.5GtC yr^{-1} [12], which means UK food consumption is accountable for 31.5Mt C yr^{-1}. Based on the Friedlingstein *et al*. (2019) estimate of 11.5Gt C yr^{-1} total GHG emissions, the land conversion embodied by UK food consumption equals 0.27% of total GHG emissions.
Caveats: The lower estimate is calculated using more recent data (published in 2019) while the higher estimate uses data published in 2009, so these are not comparable. The two estimates are calculated using different methods and different assumptions and are not consistent with each other. Only deforestation is considered.

b) *…conversion-free palm oil, beef or soy?*
Estimates for the contribution of UK consumption of specific commodities were not found in this review. WWF Risky Business (2017)[30] report the total land footprint of the UK's imports of commodities. For example, the UK consumes 1.1Mt palm oil on average each year, which requires 1.16Mha of land. These estimates are for the total amount of land required to meet the UK's annual demand for each commodity, rather than the land converted. No other sources reporting the land conversion associated with the UK's commodity consumption were found.

[30] https://www.wwf.org.uk/riskybusiness

Annex 2: How much land conversion attributable to commodity production is taking place each year? How much commodity production is conversion-free vs conversion-causing?

This Annex presents estimates found in the literature associated with Section 2.1. Table 1 presents estimates of land conversion rates associated with all commodities. Following this, estimates associated with the case study commodities soy, beef and palm oil are presented.

Table 1: Global agricultural land conversion statistics, an explanation of their source and any considerations.

Estimate	Explanation	Source
The agricultural sector was responsible for 128Mha gross deforestation worldwide between 1990-2008. This represents 53% of the total gross deforestation for the period.	This estimate was produced from the FAO Global Forest Resources Assessment 2010.	Vito *et al.* 2013
7.6Mha forest were lost every year between 2010-2015, with the most intense deforestation occurring in the tropics, particularly the Amazon and Congo basins and southeast Asia. Agricultural expansion is responsible for 70-85% of total deforestation, with commercial and subsistence agriculture accounting for 40% and 33% respectively.	Total deforestation estimates are based on FAO data. Data collated from a number of papers: (Gibbs *et al.*2010; Kissinger *et al.* n.d.; Hosonuma *et al.* 2012; FAO, 2016) were used to attribute deforestation to agricultural expansion.	COWI *et al.* 2018
Global deforestation 8.5Mha yr^{-1} between 2000-2012. 40% of total deforestation is the result of commercial agriculture, however this proportion rises to 80% if subsistence farming is included.	This estimate is based on the FAO Global Forest Resources Assessment of 2010, which divides the forest change rates into four periods between 1990-2010. Only estimates loss of forests (not other natural habitats). Hosonuma *et al.* (2012) highlight the importance of subsistence agriculture (including permanent and shifting cultivation systems) in driving deforestation, but also states that subsistence agriculture is relatively equally distributed across continents. Between 27-40% of tropical deforestation is attributable to subsistence agriculture (Hosonuma *et al.* 2012). This estimate seems high, but it is suggested that sustainable fallow management and small-scale agroforestry are also included as subsistence agriculture (Ravikumar *et al.* 2017). There is some controversy surrounding this issue, as estimates do not consider the complex drivers of community-level deforestation, including displacement (Ravikumar *et al.* 2017). “Migratory agriculture” refers to shifting cultivation, which rather than causing permanent land conversion involves a cycle of growth, fallow and regrowth. These systems are relatively sustainable and low-impact compared to commercial agriculture (Ravikumar *et al.* 2017). Careful consideration is needed before incorporating the impact of subsistence agriculture into deforestation estimates.	International Sustainability Unit 2015 Hosonuma *et al.* 2012 Ravikumar *et al.* 2017
Gross tropical deforestation totalled 195Mha with palm oil, soy, beef and wood products responsible for 113Mha between 2000-2012. 31% of total deforestation is associated with the export of these major commodities.	These estimates were collated from several studies including Keenan *et al.* (2015) and Henders *et al.* (2015).	Haupt *et al.* 2018

5.5Mha yr^{-1} forest loss is attributed to agriculture globally (2005-2013)	Estimated global forest loss only (not loss of other natural habitats). Forest extent derived from remote sensing data and cropland data from FAOSTAT 2000-2014.	Pendrill *et al.* 2019a
Due to the growing population, agricultural land area in developing countries will increase by 23% by 2050 assuming current population growth rates and an extrapolation of current yield trends (mean 1.13% annual increase)	Estimates of agricultural production worldwide are taken from the FAO State of Food and Agriculture report (2005) and future estimates are based on the Global Food Equation: $\text{Pop} * (\text{Food}/\text{Pop}) = (\text{Food}/\text{Ag land}) * \text{Ag land}$ It is predicted that agricultural land area in developing countries will increase by 2-49% by 2050. This depends on the assumptions of population growth and resulting intensification of food production. 23% is assumed to be the medium scenario in this mode. The model assumes a mean increase in yield of 1.13% per year, based on the extrapolation of current yield trends.	Angelsen 2010

Commodity Case Studies

Soy

Soybean cultivation drives 0.4Mha yr^{-1} deforestation worldwide (Pendrill *et al.* 2019a). Soy is estimated to be responsible for 5.4% of global embodied deforestation, equating to 13Mha between 1990-2008 (European Union 2018). Global soy production has doubled since 2000, with Brazil and Argentina accounting for 50% of global production in 2013 (Brack *et al.* 2016). Soy is responsible for the loss of 29Mha between 1990-2010 in Brazil's Cerrado region alone (Tropical Forests Alliance 2020). WWF research suggests that in the Brazilian Cerrado, up to 25Mha of degraded land is suitable for soy production without the need for further conversion, meaning the soy production of the Cerrado could potentially double, or even triple, by 2050 without causing land conversion. Attaining global emissions targets through the use of biodiesel increases the demand for soy. The land required to meet biodiesel demand and global emissions targets is 361Mha for soy (Ravindranath *et al.* 2008)

Palm Oil

Palm oil cultivation is responsible for 0.4Mha yr^{-1} deforestation (Pendrill *et al*. 2019). Palm oil accounts for 2.3% of embodied deforestation, up to 5.5Mha between 1990-2008 (European Union 2018). Indonesia and Malaysia account for 80-86% of palm oil production, with the EU, India and China as the main consumers (Brack *et al.* 2016; Fargione *et al.* 2008). Palm oil are in Indonesia increased from 4.1Mha in 2006 to 8.9Mha in 2015, with projections suggesting this will reach 17Mha by 2025 (Petrenko *et al.* 2016). Other estimates suggest that between 1990-2005, 55-59% of palm oil expansion in Malaysia and 56+% in Indonesia occurred at the expense of forests (Koh & Wilcove 2008). Accelerating demand for palm oil triggers a 1.5% annual rate of deforestation in Indonesia and Malaysia, with 27% of these new plantations occurring on peatland (Fargione *et al.* 2008). Note that many papers describing the rate of deforestation caused by palm oil cultivation are outdated, but there were few offering more recent estimates found during this review.

Beef

Over 40% of forest loss is associated with cattle production (2.2Mha yr^{-1}) (Pendrill *et al.* 2019a). Beef was the main driver of deforestation across case study countries (Argentina, Bolivia, Brazil, Paraguay, Indonesia, Malaysia and Papua New Guinea) accounting 2.1Mha yr^{-1} (1.6Mha yr^{-1} in Brazil alone) which equates to 60% of the embodied deforestation in these countries (Henders *et al.* 2015).

Some studies suggest the consumption of beef has only grown slowly, with major producers named as the US, Brazil, EU and China (Brack *et al.* 2016).

Levels of production remain high, but only 8% of livestock products are internationally traded (Vito *et al.* 2013). The majority of Brazilian beef is consumed domestically and exported beef accounts for 15% of embodied beef emissions in Brazil (Karstensen *et al.* 2013). When both pastures and the land used for feed production are included in the land conversion estimates, beef is responsible for 62.5Mha of the global embodied deforestation (European Union 2018).

Annex 3: How much GHG emissions does commodity production cause through land use change and through other mechanisms?

This Annex presents estimates found in the literature associated with Section 2.2. Table 2 presents estimates of a selection of emissions factors associated with land use change. Table 3 presents estimates of the total GHG emissions from agricultural commodity production (including specific statistics on the case study commodities). This is down to show the percentage of commodity-related emissions that come from land use change compared to other agricultural emissions such as fossil fuels.

Table 2: A selection of land use change related emissions factors.

Estimate	Commodity	Comment	Source
Estimates of the above ground carbon stored in various vegetation types within the Amazon basin range between 100 and 300Mg per ha	All		Saatchi *et al.* 2007
"Brazil's Amazon Fund uses 100 tons/C/hectare to calculate emissions reductions"	All	Brazil's Amazon Fund is a finance initiative aimed at preventing deforestation through responsible investments.	Asner, c.2009.
"Between 2010-2014 the expansion of agriculture and plantations across the tropics led to net emissions of 2.6Gt CO_2 yr^{-1}"	All		Pendrill *et al.* 2019b
Estimates of emissions from conversion of several land use types to soy varied from 0.1–17.8kg CO2eq per kg soybean.	Soy		Castanheira & Freire 2013
"Rainforests in Sumatra converted to jungle rubber, rubber, and oil palm monocultures lost 116 Mg C ha−1, 159 Mg C ha−1, and 174 Mg C ha−1, respectively. Up to 21% of these carbon losses originated from belowground pools, where soil organic matter still decreases a decade after conversion" […] "up to 61% of the carbon stored in the undisturbed	Palm oil, rubber		Guillaume *et al.* 2018

ecosystem was lost in managed systems."			
Land use change from tropical forest to palm oil plantation leads to a loss of 187 tons C/ha	Palm oil	This study only investigated carbon, not other GHGs.	Reijnders & Huijbregts 2008
Deforestation embodied emissions are 327±73Mt CO_2 in Argentina, Bolivia, Brazil, Paraguay, Indonesia, Malaysia and Papua New Guinea between 2000-2011	Palm oil		Henders *et al.* 2015
Land conversion to palm oil plantations often results in the destruction of peatlands. An emission factor of 61t CO_2 ha^{-1} yr^{-1} has been proposed to adjust GHG emissions as a result of this land conversion	Palm oil		Sandström *et al.* 2018

Table 3: A selection of estimates of GHG emissions by commodity (land use change emissions and other agricultural emissions).

Estimate	Commodity	Comment	Source
"Over the period 1990-2010, total AFOLU net emissions increased 8%, from an average of 7,497Mt CO2 eq in the 1990s to an average of 8,103Mt CO2, eq in the 2000s."	All	AFOLU stands for Agriculture, Forestry and Land Use – thereby capturing all emissions associated with commodity production.	Tubiello *et al.* 2014
"For the period 2001-2010, the largest [AFOLU] emission source was agriculture (50%), followed by net forest conversion (38%), peat degradation (i.e., cultivation of organic soils and peat fires) (11%) and biomass fires (1%)."	All	As above	Tubiello *et al.* 2014
Embodied deforestation imports account for 17-31% of national agricultural emissions (0.25-0.42Gt CO_2 yr^{-1} of 1.45Gt CO_2 yr^{-1} total).	All		Pendrill *et al.* 2019b
Land use change embodied emissions account for approximately one fifth of current GHG emissions.	All		Saikku *et al.* 2012
Estimates of soybean meal LUC emissions range from 0.40 to 7.69tCO2/t product while non LUC emissions range from 0.48 to 0.72tCO2/t product; soybean LUC emissions range from 0.37 to 12.37 while non LUC emissions range from 0.32-0.64tCO2/t product; beef LUC emissions range from 24 to 726 tCO2/t product while non LUC emissions range from 28 to 32.4tCO2/t product; palm oil LUC emissions range from 1.16 to 8.00tCO2/t product while non LUC emissions are estimated at 2.2tCO2/t product.	Soy, palm oil and beef	This study reviewed and collated results from many previous studies. See the full paper for a description of the varying assumptions in the studies reviewed, which accounts for some of the variation in the figures presented.	Persson *et al.* 2014
"Emission of CO2 […] currently corresponds in South Asia with an emission of about 2.8–19.7kg CO2 equivalent per kg of palm oil."	Palm oil	These figures refer to both agricultural emissions and land use change emissions. Multiple calculations were undertaken based on varying assumptions, leading the large range in figures presented.	Reijnders & Huijbregts 2008
When producing beef, the mean land use change emissions are 12kg CO2eq 100g $protein^{-1}$; the mean feed	Beef		Poore & Nemecek 2018

production and transport related emissions are 1.4kg CO2eq 100g protein^{-1}; the mean livestock related emissions are 28kg CO2eq 100g protein^{-1}			
Beef production is responsible for 0.9Gt CO_2 yr^{-1} between 2010-2014 in the tropics	Beef		Pendrill *et al.* 2019
"LUC represents more than 70% in 28 scenarios (all tropical region scenarios, with 9 out of 15 in warm temperate moist regions and 9 out of 15 in warm temperate dry regions). LUC amounts to less than 45% in the scenarios in which severely degraded grassland has been converted in warm temperate regions."	Soy	The proportion of soy emissions that are associated with land use change depend very strongly on the type of land that was converted for soy production.	Castanheira & Freire 2013

Annex 4: How much GHG is emitted in total? How much of this relates to commodity production vs other emissions?

This Annex presents estimates found in the literature associated with Section 2.3. Table 4 presents estimates of the total anthropogenic GHG emissions over different time periods and the proportion of this made up by emission associated with land use change.

Table 4: A selection of estimates of total anthropogenic GHG emissions over different time periods and the proportion of this made up by emission associated with land use change.

Estimate	Explanation	Source
"Agriculture, Forestry and Other Land Use activities accounted for […] globally during 2007-2016, 23% (12.0 ± 2.9GtCO2eq yr-1) of total net anthropogenic emissions of GHGs (medium confidence).		Shukla *et al.* 2019
"There is no clear trend in annual [land use change] emissions since 1990"		Shukla *et al.* 2019
"Average total anthropogenic emissions by sources were about 44,000Mt CO2 eq in 2001-2010. AFOLU emissions by sources contributed 21% (agriculture and combined FOLU sources each contributed 11%)."	AFOLU stands for Agriculture, Forestry and Land Use. FOLU stands for Forestry and Land Use.	Tubiello *et al.* 2014
"Annual GHG emissions (mainly CH4 and N2O) from agricultural production in 2000–2010 were estimated at 5.0–5.8GtCO2eq/yr, comprising about 10–12% of global anthropogenic emissions. Annual GHG flux from land use and land-use change activities accounted for approximately 4.3–5.5GtCO2eq/yr, or about 9–11% of total anthropogenic greenhouse gas emissions. The total contribution of the AFOLU sector to anthropogenic emissions is therefore around one quarter of the global anthropogenic total"		IPCC 2014
"Net CO2 emissions from deforestation and other land-use change were 5.5±2.7GtCO2 on average during 2009-2018, accounting for about 14% of all emissions from human activity"	The global carbon project is a collaboration between many academics and organisations around the world to synthesise a consistent global carbon budget.	Friedlingstein *et al.* 2019
"[In] the global carbon budget averaged over the last half-century, 82 % of the total emissions (EFF+ELUC) were caused by fossil CO2 emissions and 18 % by land use change." […] "All components except land use change emissions have significantly grown since 1959"	As above	Friedlingstein *et al.* 2019
"The contribution of LULCC to anthropogenic carbon emissions were about 33% of total emissions over the last 150yr (Houghton 1999), 20% of total emissions in	LULCC stands for Land Use and Land Cover Changes	Houghton *et al.* 2012

the 1980s and 1990s (Denman *et al.* 2007), and 12.5% of total emissions over 2000 to 2009 (Friedlingstein *et al.* 2010). The declining fraction is largely the result of the rise in fossil fuel emissions."		
"Emissions from tropical deforestation and forest degradation are estimated to account for 7–14% (17% when including peat degradation) of the total anthropogenic CO2 emissions (Baccini *et al* 2012; Harris *et al* 2012)."		Langner *et al.* 2014

Annex 5: UK Embodied Land Conversion Footprint

This Annex presents estimates found in the literature associated with Section 2.4.1. Table 5 presents estimates of the land conversion and associated GHG emissions embodied in the UK's commodity consumption.

Table 5: Selected estimates of the land conversion and associated GHG emissions embodied in the UK's commodity consumption.

Estimate	Explanation	Source
The UK demand for 7 major commodities (beef, leather, timber, soy, palm oil, paper, cocoa and rubber) requires 13.6Mha (2017 estimate)	This assessment was obtained using data from CDP and forest assessments including "Forest Trend's Supply Change Initiative" and Global Canopy Programme's "Forest 500".	Haupt *et al.* 2018
Between 2010-2013 the UK imported 31kha yr^{-1} of embodied deforestation	Data on forest, cropland, pasture, plantations and other land from FAOSTAT and academic papers were fed into a Land-Balance Model to obtain information on the amount of deforestation attributed to each land use class. Crop attribution models divided the deforestation to cropland area by crops using FAOSTAT data. The deforestation footprint was calculated to give the embodied deforestation in the production of each commodity by amortising the deforestation attributed to each commodity over the last 5 years.	Pendrill *et al.* 2019a
UK land use change emissions are estimated as 100Mt CO_2 equivalent, with 90% of these arising from livestock production (84% to red meat).	Data on UK imports and exports from FAOSTAT and Defra statistics is combined with the data on animal feed required for commodity production. UK household food survey data was used to estimate the proportion of each commodity used in manufacturing other products. Land conversion emissions were estimated using a top-down approach.	Williams *et al.* 2010
UK food consumption accounts for 101Mt CO_2 equivalent from land use change. An estimated 2.1% of global land use change emissions are allocated to the UK food supply chain, which equates to 40% of the total emissions embedded in UK food consumption arise from land conversion. 75% of these land conversion emissions are allocated to ruminant meat.	This figure is presented in the WWF report "How Low Can We Go?" in 2010 and was produced using data from Defra, US Department of Agriculture and the FAO. Commodity flow data was obtained from FAOSTAT data for 2005. Data were compiled to an inventory of emissions from primary production and land use change. Regional consumption data were used to create the UK inventory. The CO_2 estimate of 101Mt is attributable to total UK food consumption rather than UK consumption sourced from overseas.	Audsley *et al.* 2009.
In 2015 the UK imported around 3.3Mt yr^{-1} of soy, requiring 1.68Mha overseas. This is just under 1% of the average area of harvested soy worldwide.	These figures were based on direct import data, but there were significant amounts of indirect soy products arriving via the Netherlands. There are uncertainties in the calculation of soy embedded within products. FAOSTAT data up to 2014 were used.	WWF The UK Soy Story; WWF Deforestation and Social Risks in the UK's Commodity Supply Chains. 2017
UK palm oil imports accounted for 1.16Mha yr^{-1} for the same time period. An approximate estimate of the land	Estimates were calculated as above.	WWF Deforestation and Social Risks in the UK's

involved in beef production is 3.4Mha yr^{-1} on average between 2011-2015.		Commodity Supply Chains. 2017

Annex 6: Europe Embodied Land Conversion Footprint

This Annex presents estimates found in the literature associated with Section 2.4.2. Table 6 presents estimates of the land conversion and associated GHG emissions embodied in Europe's commodity consumption.

Table 6: Selected estimates of land conversion embodied in European commodity consumption.

Estimate	Explanation	Source
EU is ranked first in major importers of agricultural products and accounted for 39.1% of global total import value in 2016.	It is worth noting that EU is also the first major exporter of agricultural products (41.1% of the total export value in 2016).	FAO 2018
EU27 consumed 732kha or 10% of global embodied deforestation consumption in 2004	The annual total global embodied deforestation consumption was estimated as 7290kha. Global deforestation estimates are derived from Global Forest Resources Assessment in 2010, FAO land use statistics and Remote Sensing Survey conducted between 1990-2005 by FAO and European Commission JRC.	Vito *et al*. 2013
Between 1990-2008 the EU27 imported 36% of all deforestation embodied crop and livestock products traded internationally each year, which equates to 9Mha of deforested land.	33% of deforestation crops and 8% of embodied livestock traded worldwide.	Vito *et al*. 2013
56% of Europe's total net imported deforestation embodied crops are soybeans and 11% are oil palm between 1990-2008.	FAO data on land use and agricultural production were used to allocate deforestation to crops and LANDFLOW modelling was used to assign this embodied land use to Europe.	Vito *et al*. 2013
In 2009, beef imported from Brazil to the EU accounted for 102,000ha deforestation, 73,000ha from Brazilian soy and 33,000ha from Indonesian palm oil. Today's EU embodied deforestation ranges from 0.25-0.5Mha yr^{-1}.	This report collates data from FAO to assess the contribution of the EU. Estimates of EU embodied deforestation are taken from Henders *et al*. (2015) and Vito *et al*. (2013).	COWI *et al.* 2018
Average EU deforestation emissions footprint is 0.3t CO_2 yr^{-1} per capita. This equates to 15% of the total food carbon footprint.	This estimate is obtained using both a physical trade model and an MRIO approach. Emissions incorporate above ground biomass, below ground biomass, soil organic carbon and peatland drainage. Emissions figures are likely to be underestimations, as this study reports on the expansion of cropland/pasture only and does not include the clearing of new areas.	Pendrill *et al.* 2019b
Land use change emissions account for 30% of Europe's food consumption emissions between 2002-2011.	Country level FAO data were used to provide food consumption data and animal feed requirements were incorporated. Bilateral trade flows were assessed, and emissions were calculated using a top-down approach. Fertiliser emissions and indirect GHG emissions were also incorporated. Sandstrom *et al*. provide EU average emissions as well as for each country. Emissions are divided into land use change, international trade, enteric fermentation, manure management, rice cultivation and fertiliser contribution among others.	Sandström *et al.* 2018
On average 64% of Europe's food supply emissions are from the consumption of domestic products imported from other EU countries. Imports from Latin America account for 25% of EU food supply emissions.	This study reinforces the conclusion from EU Commission that 36% of Europe's food supply originates from overseas. Methods as above.	Sandström *et al.* 2018
76% of total land use change emissions are from oil seed products,	Commodity specific data were obtained using FAO data.	Sandström *et al.* 2018

predominantly soybean, whereas <1% of land use change emissions were due to beef production.		

Annex 7: Glossary

Above ground biomass: All organic material found above the soil in any given habitat, including both live and dead vegetation (stumps, stems, foliage, *etc*.).

Amortisation period: Amortisation is the process of gradually writing off an initial cost. In the context of GHG emissions, it is the process by which emissions are allocated to changing land over a period of time, rather than all at the initial point of conversion.

Below ground biomass: All organic material found below the soil in any given habitat, including both live and dead vegetation (roots, soil hummus, peat, *etc*.).

Carbon sink: Absorbs more carbon than it releases (for example forests).

Carbon source: Releases more carbon than it absorbs (for example burning fossil fuels).

Commodity: A raw material or primary agricultural product that can be purchased and traded.

Commercial agriculture: Large scale production of agricultural commodities, aimed at making profit for a company or business, rather than to simply feed local populations.

Confidence: Subjective assessment by the report's authors on the reliability of estimates given. The authors would recommend the use of high confidence estimates. The authors would recommend the use of medium confidence estimates if caveats and assumptions are made clear. The authors would not recommend the use of low confidence estimates.

Consumption: The ultimate use of a commodity or product. For example, if palm oil is produced in Indonesia, imported and processed into cosmetics products in the Netherlands and then exported for final sale in the UK, the UK would be the country of consumption.

Deforestation: the loss of forest habitat, often due to clearing of forests by humans.

Existing cropland: land previously converted to agricultural cropland. Some definitions include rubber plantations as existing cropland, but some define this land use as forest.

Europe: This refers to the EU countries at the point each reference was written (i.e. including the UK).

Forest: An area with a tree canopy cover above a certain percentage and covering a minimum area. For example, the FAO define forest as any land with over 10% tree canopy cover and an area of more than 0.5ha, but other sources have varying definitions. This can be a major source of discrepancy between estimates. Forests must have trees present and be absent from any other major land use.

Gross deforestation: Total forest area cleared (does not take newly planted forest into account).

Habitat degradation: The loss of biodiversity or ecosystem services (in the context of this report, the loss of biomass and therefore carbon) within a habitat, without changing the habitat type.

Indirect land use change: land converted as a result of displacement of activities by commercial agriculture or land converted to grow feed crops for livestock. This land use change is embodied within commodity production in many estimates as an indirect cause of land conversion.

Land use change / Land conversion: The transformation of land from one predominant use to another predominant use. Often used to refer to the conversion of natural habitat such as forest to cropland but could also refer to any other land use change (e.g. conversion from one type of crop to another, conversion from pasture to cropland or rewilding of cropland to secondary forest).

Net deforestation: Total forest area cleared, minus total forest area planted.

Production system: The management techniques used for the production of a commodity. For example, cattle can be reared intensively in cattle sheds or grass fed on pasture. These two different systems are likely to have very different impacts on the various aspects of sustainability.

Remote sensing methods: Remote sensing is a term used to describe any technique that gathers information about something without physical contact (for example taking a photo) but is often used to refer to satellite or drone imagery.

Smallholder agriculture: Production of commodities taking place on small farms or plantations, typically supporting a single family through a mixture of cash crops and subsistence farming.

Soil organic carbon: The organic matter found within soil, typically from plant remains (e.g. humus, charcoal).

Subsistence agriculture: Production of commodities where the primary aim is to feed the farmer’s family, leaving little extra for trade.

Zero-deforestation: commodity production causes no deforestation. Sometimes refined to “zero-net deforestation” which means commodities may embody some deforestation, but the same amount of forest is replaced. These terms are used as criteria in some certification scheme.