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Identifying marginal biomass supply and its carbon footprint under varying future framework conditions

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Appendices

Acknowledgement

During the course of the TOPWASTE project, we have studied biomass supply and its carbon footprint at length – in order to find data allowing to assess the consequences of using or avoiding biomass use in energy and materials production. This work has been a joint effort between several projects, i.e. the projects:

- Analysis of environmental and climate effects of producing and using biomass for electricity, heat and transportation in Denmark, financed by the Danish Energy Angency 2013-2014

- Analyses for commercialization of hydrogen technologies, financed by the Energy Technology Development and Demonstration programme, 2014 – 2016

- TOPWASTE, financed by the Strategic Research Council, 2011 - 2015

Part of this work was already partly published as part of the report 'Carbon footprint of bioenergy pathways for the future Danish energy system' (Wenzel et al., 2014).

An essential part of the work has been the identification of candidates for marginal woody biomass supplies at a global scale. For this purpose, the partial equilibrium econometric model GLOBIOM was applied with great support from the developers of the model at International Institute for Applied System Analysis, IIASA, dr. Michael Obersteiner and dr. Petr Havlik. Runs of the GLOBIOM model under selected boundary conditions were used to identify probable origins of biomass supplies at varying market conditions. We truly appreciate the great support on this part. Models for carbon footprint calculation were developed by Dr. David Neil Bird, JOANNEUM RESEARCH RESOURCES - Institute for Water, Energy and Sustainability, Graz, Austria, and we are truly greatfull for the collabaroation with Neil Bird on this.

1 Biomass types

The work was confined to include the most significant biomass categories for a Danish energy system, i.e.:

- Manure
- Straw residues from agriculture
- Woody biomass

Woody biomass, in turn, may be domestic or imported. The study does not distinguish between these, because the market for wood pellets and chips is assumed to be international, the marginal thus being one and the same.

The wood pellets or chips may derive from different sources of wood, and the study comprises different origins such as: thinning residues, plantation wood and wood harvested from existing forests. Plantation is assumed to be able to take place on different types of land, including marginal land, grassland, forest land and agricultural cropland.

1.1 General aspects of the biomass models

In the consequential modelling, the marginal supply is defined as the supply being the response to the changes in demand deriving from the decision studied. This marginal supply is inherently, therefore, a function of both scale, place and time of the studied change in demand/supply, i.e. it matters where an extra demand or supply is located, it matters when the extra demand/supply is placed on the market, and it matters how big it is. Further, it also matters what type of market the demand is placed on, i.e. if the biomass is purchased through an international biomass Exchange or maybe placed with a specific forest owner, maybe even on specific conditions of sustainable or certified forestry.

The approach to identifying the biomass marginal is a most critical aspect of LCA, because the Carbon Footprint results will be very sensitive to the assumptions on the biomass marginal.

The biomass modelling in general always comprises two aspects, i.e.:

- Direct life cycle implications: The environmental consequences resulting from the various activities (or life cycle stages) associated to the production of these biomasses (e.g. soil preparation, fertilization, harvest, etc.). These are the implications before any system expansion, and in case land use is implied, it is also referred to as ‘direct land use change’ (DLUC).

- System implications: The environmental consequences occurring as a result of using these biomasses (or the land needed to grow it) for bioenergy instead of using it for their previous uses. These system implications are giving rise to different “life cycle consequences”. These are the implications due to system expansion, and in case land use is implied, it is also referred to as ‘indirect land use change’ (ILUC).

System expansion occurs either when a constrained resource (e.g. straw, manure) is taken from another fate or use, or if a production of a product is displaced, as e.g. when agricultural land is used for energy crops at the expense of food/feed crops. The use of such constrained resources or displacement of other products triggers market responses leading to various consequences, among which is the replacement of the used resource or displaced product. The production and handling of this substitute is included in the modelling and referred to as system expansion or “system implications”.

The direct life cycle implications of using manure and straw will be modelled according to the models in Hamelin (2013) and as described in Appendix G. For the use of woody biomass, detailed models are given in Appendices A – E. An overview of the system implications considered for the selected biomass types are presented in Table 1. For a given biomass, there is, in some cases, more than one system implication that has been considered (as shown in Table 1).

Table 1 System implications considered for the biomass sources involved in the assessment

Biomass source	System implication
Agricultural residues	
Straw (wheat straw)	Avoiding incorporation (ploughing) of the straw to soil (details of the applied model are given in Appendix G)
Animal slurry	Avoiding reference slurry management (details of the applied model are given in Appendix G)
Woody biomass (residues and bioenergy plantation) †	
Woody residues (thinnings, other residues)	Avoiding on-site decay (details of the applied model are given in Appendix D)
Forest remaining forest (punctual harvest from existing un-managed forest) (natural regrowth after harvest)	DLUC, including changes in sequestration capacity** (details of the applied model are given in Appendix B)
Plantation on forest land	DLUC, including changes in sequestration capacity** (details of the applied model are given in Appendix A)
Plantation on marginal land‡	If no other uses of the marginal land: DLUC** If this land could have otherwise be used to grow food/feed/energy crop (through inputs and investments): DLUC and ILUC*,** (details of the applied model are given in Appendix C)
Plantation on grassland (high C or low C)δ	DLUC and ILUC**,β (details of the applied model are given in Appendix C)
Plantation on cropland	DLUC and ILUC**

† Three locations (biomes) were looked at for the origin of the plantation and residues: boreal, tropical and temperate.

δ High C and low C grassland have been considered

**See Appendix A-E for more details on how DLUC consequences were considered, and Appendix F for ILUC consequences.

‡ This corresponds to degraded or "un-used" land. It should however be noted that this scenario was not selected as a marginal biomass source.

* Land that is marginal today - but good enough for establishing a plantation - may well in the future be good enough for food/feed production as well, if future prices for food/feed and agricultural inputs makes it attractive enough.

β The extent of ILUC will here depend on various parameters such as if the grassland was un-managed or grazed, and if grazed, to the extent the productivity in cattle production could be increased (see Appendix G for more details).

1.2 Identifying manure and straw marginals

The consequences of using manure and straw – being constrained resources taken from alternatives uses/fates – are described in more detail in Appendix G.

1.3 Identifying candidates for woody biomass marginals

The marginal biomass supplies for the various time perspectives and framework conditions have been identified by a two tier approach:

1. Using a reasoning related to the economy and governance and to the scale of demand and supply - mainly related to the identification of candidates the marginal supply at a smaller global scale and shorter term

2. Using a partial equilibrium econometric model called GLOBIUM (Havlik et al., 2011) to reveal probable candidates for responding biomass supplies on a large scale global biomass demand and on the longer term

The short term decisions in the Danish energy system context are likely to relate to lower global biomass-for-energy demand scenarios, simply because the decisions to be supported are likely to occur soon and last for a shorter time period, and therefore at a time where global bioenergy demand is not very much higher than today.

Longer term decisions are more likely to relate to larger scale global biomass-for-energy demands.

1.3.1 The influence of economy and governance

A higher demand for biomass due to bioenergy policies worldwide will contribute to increasing biomass market prices in general although price development drivers for specific product categories (e.g. wood panels, paper, and construction wood) may be unlinked. In a more simplistic market view, however, increased demand may have a two-sided impact on forestry and agriculture.

On the one hand, it increases the incentive to change management regimes to produce more biomass of the type with the most attractive price and market, and forestry may for this reason develop towards higher yields and also higher C-stock: when energy-biomass gets a higher value. Better prices for biomass for energy may mean that the bioenergy market altogether becomes more important in terms of contribution to the profit margin for the forest owner. This means the incentive to co-optimize timber and bioenergy production increase which in turn can imply higher overall biomass yields and stocks in the forest. This was already observed in Swedish forestry (Berndes et al. 2012) and German forestry (Schweinle et al., 2013). However, at the same time in certain geographies and on certain national markets with low integration or other barriers, non-commercial forest owners may not fully orient themselves towards global market prices and longer term optimization. Private economy considerations, liquidity, inheritance or self-dependency from auto produced wood may also guide management decisions towards something different from global and long term optimum (USDA, 2008). The fact that the average forest holding size and ownership structures varies significantly across EU (European Commission, Directorate General for Agriculture and Rural Development, 2012), USA (USDA, 2008) and globally, may therefore explain why it has been reported that roundwood currently finds large scale direct use in energy production in certain EU countries (EC, DG ENTR, 2013, p. 299), probably mostly so in household boilers. For wood pellets specifically, Sikkema et al. (2013) finds that it is likely that within a decade (by 2020) or so more than half of all wood pellets produced in the world will be traded internationally, indicating that currently local or regional markets dominates.

The same holds true for agriculture, where increased prices on the bioenergy markets give incentive for multi-cropping and changed breeding developments towards higher biomass yields as opposed to only high kernel yields. On the other hand, higher bioenergy market prices also increase the incentive for new land cultivation and hereby deforestation and C-stock reduction.

Which of these developments has the stronger influence on overall global C-stock change is believed to depend on the development in land governance. If a strong international and global policy to avoid further deforestation is enforced, it will have a high influence on the cost of land and create high incentives for intensification of crop yields, forestry yields and animal production. This would most probably imply increasing C-stock in both forestry and agriculture hand-in-hand with increased biomass production. But if land governance is weak or insufficiently global, i.e. not enforced sufficiently by the key nations having land areas potentially in danger of further deforestation or C-stock reduction, there is a risk that C-stock reduction happens in such regions of the World.

In some cases, it is experienced that business economy for the farmer can lead to planting energy crops on farmland, depending on the specific conditions including subsidy schemes and other economic drivers. An example is the US ethanol industry, which is heavily subsidized, and also recent developments in biogas application have led to agricultural shift towards energy crops. In Germany, 7000 biogas plants exist (2013) depending to a large extent on energy crops like maize and grass. The area used to produce these energy crops is around 800.000 ha (equal to one third of Danish agricultural land), and the production of biogas from these crops equals around 1% of German energy consumption. Also in Denmark, subsidy schemes and regulation promotes the addition of energy crops to manure in order to render manure biogas more attractive. In the case of energy crops for solid biofuels, it has been acknowledged in Sweden that conditions can prevail leading to crops like willow being attractive in a business perspective (Azar and Berndes, 1999).

Conditions are, thus, seen that make energy crops, including woody crops, an interesting business case for farmers. This does, however, not necessarily mean that plantation on cropland candidates as one of the most probable sources of woody biomass supply, because it depends on policy including subsidy schemes and CO_2 price. But the point is that it is seen before, and can happen again, that the economic framework conditions for farmers end up creating an attractive framework for energy crops also for woody biomass.

1.3.2 The significance of the scale of demand

An important background assumption is the scale of global bioenergy demand. If the overall demand for bioenergy remains small, more is available for a Danish demand, and also the most Carbon Footprint friendly ways of providing biomass will remain available. On the other hand, if global bioenergy demand increases to a very large scale of demand for climate reasons or other, i.e. other nations follow the same development as pursued by Denmark, one might ask, if competition for biomass implies that marginal demands are pushed towards biomass supplies of other origin than were available at the smaller scale.

At present, the global scale of demand is still relatively small, and some countries in Europe are the predominant customers. On the shorter term, therefore, all biomass categories are potentially available. Pre-commercial thinning and harvesting residues from timber production is a category often mentioned as an option for a biomass type with low carbon footprint. The scale of such residues available is, however, limited. Chum et al. (2011) state total roundwood production to be at the scale of 15-20 EJ/year, and Bang et al. (2013) find the total forest product output to be around 25 EJ/year of which nearly 15 EJ/year is sold for energy while timber and other products constitute the rest. Total timber production being, thus, around or below 10 EJ/year, there is a limit to the scale of residues available, some of this potential being already used for paper production and energy. Our estimate is that thinnings and harvesting residues above a scale of bioenergy demand of 5 EJ/year is not a realistic biomass marginal – but until then it can potentially be a marginal or part of the marginal. Further, the biomass potential lying in the C-stock increase from co-optimization of a multi-output forestry, i.e. timber and energy products, giving rise to increasing C-stock and biomass harvest together, is also limited by the scale of the market for timber products. It is difficult to see this rise much beyond 10-15 EJ/year of timber (roundwood), and the related co-product of energy biomass from such forest optimization is believed to be limited to the same order of magnitude. At a smaller scale, therefore, such biomass categories may represent potential marginal, while at a larger scale, other more abundant categories of biomass like plantation are more realistic marginals.

The point of addressing the smaller scale is to identify potential marginal biomass supplies for the shorter term decision in the Danish energy policy. For decision with a the longer term influence, the study incorporates background conditions representing a World with a larger bioenergy demand in order to reflect a world adapting a climate agenda and aiming at meeting the demands of the 2 degree C scenario. According to Chum et al. (2011) a review of 164 long-term energy scenarios showed bioenergy deployment levels in year 2050 ranging from 118 to 190 EJ per year for less than 440 ppm CO_2eq concentration targets (25th and 75th percentiles). Looking at the characteristics of current hour-by-hour models used when designing the Danish renewable energy system, it seems that many such studies tend to underestimate the need for biomass to balance fluctuating power production. In any case, however, the scale of biomass demand in renewable energy systems on the longer term is high. Chum et al. (2011) estimates the total available biomass potential by 2050 to be in the range of 100 – 300 EJ/year, and the demand is, thus, seen to be depending on using more or less the full potential.

At the larger scale of demand, therefore, only the large scale categories of biomass can come into play as marginals.

1.3.3 Identifying candidates for biomass marginal supply in a larger scale global demand scenario

As part of the effort to identify potential marginal biomass supply, a partial equilibrium econometric model called GLOBIOM (Havlik et al., 2011) developed by the International Institute for Applied Systems Analysis (IIASA) was used. The model is used to simulate which categories of biomass would come into play (on the market) under varying conditions. The GLOBIOM model can briefly be characterized as follows:

The model comprises agricultural and forestry sectors incl. bioenergy and the World divided in 30 economic regions. A representative consumer is modelled through a set of so-called iso-elastic demand functions. Land cover types include cropland, grassland, short rotation tree plantation, managed forest, unmanaged forest, other natural vegetation. The model is calibrated based on the biophysical model EPIC, and calibrated to year 2000 FAOSTAT activity levels and solved in 10-year time steps.

Food demand increases linearly with population, and GDP per capita changes determine demand variation (depending on income elasticities). Scenario on future diets were built based on (FAO, 2006): Consumption does not exceed 3600 kcal/cap/d, except for USA (these numbers include waste). Net afforestation with traditional forest is not taken into account.

The existing GLOBIOM model has been run under three different baseline pathway conditions, the so-called SSPs (Shared Socio-economic Pathways) representing a specific development in background framework conditions. See Appendix H for further explanation of the GLOBIOM model and the SSP2 scenario.

The SSP2 was applied for this study, as the BAU development in this SSP is judged to be the most realistic basis. In this baseline development pathway, GLOBIOM models how much biomass can be expected to be sold on the market at different biomass price levels from low to high. In this study price levels of 1.5, 5 and 8 USD/GJ of biomass is used. Moreover, the model at these price levels was run under the condition from very low CO_2 prices (0 USD/ton) to relatively high prices (50 USD/ton) to represent both low and high incentives to avoid biogenic CO_2 emissions. Figure 1 shows the outcome of the model run under these conditions, presenting the consequence in terms of the changes in land use modelled to happen.

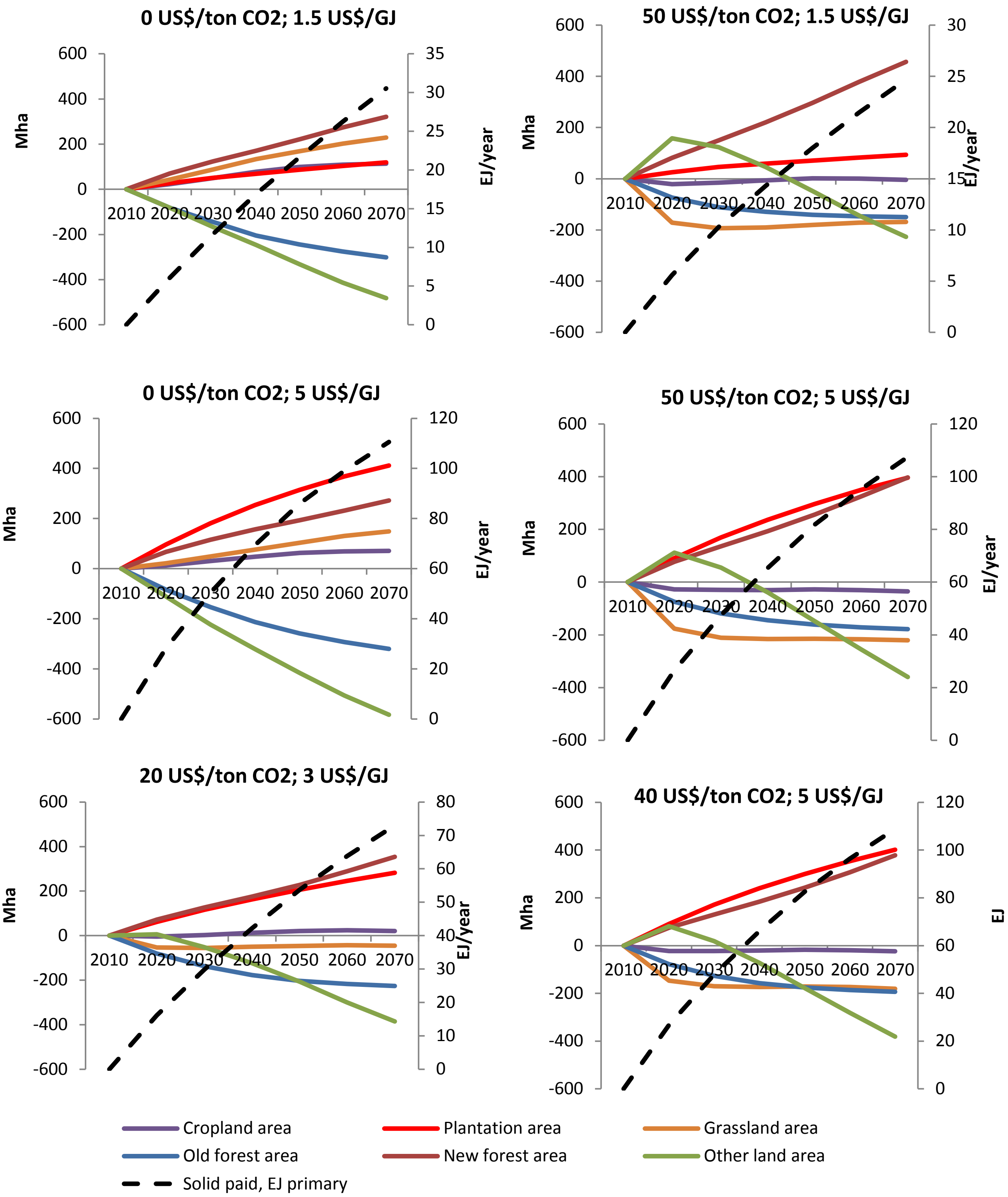

Figure 1 *Models of total LUC at global scale at various CO_2 and biomass prices using GLOBIOM. 'Solid paid' represents the energy equivalent of the solid biomass modelled to be harvested and sold under the given conditions*

A closer look at the responses to changing biomass prices and CO_2 prices, as identified by the model, reveal the following:

Plantation land: Plantation is seen to always increase compared to 2010 level. It responds very much to the biomass price, at high biomass prices, plantation is the predominant land increase. This is inherently logic as plantation is happening in order to harvest and sell biomass. At low biomass price, plantation does not increase much, and the relatively low biomass harvest in these scenarios may come also from harvest from old forests and to a lesser extent new forest. Plantation area does not respond much to CO_2 price, but its location does. At a high CO_2 price, plantation predominantly happens at land with low carbon stock as long as such land is available (like grassland), while at a low CO_2 price, the plantation is seen to happen at old forest land and other land (including savannah).

New forest land: New forest land is seen to increase from 2010 onwards in all scenarios. This almost lies inherent in the definition, as new forest land in GLOBIOM is defined as forest less than 10 years old. The increase in new forest land is not responding to biomass price at all, which is understandable as the incentive for establishing new forest land is not the sale of biomass for energy. Increasing CO_2 price, however, give rise to increasing new forest land, as establishing new forest land can be a way to cost-effectively reduce net GHG emissions for a country. In conclusion, new forest land cannot be a significant part of the marginal, as it does not respond to demand of biomass (i.e. increasing biomass prices).

‘Other land’/Savannah: Savannah and other similar land types with relatively high carbon stock are believed to be the dominating response under ‘other land’. At low CO_2 price, ‘other land’ is lost quite rapidly from 2010 and onwards. At higher CO_2 price, ‘other land’ initially increases, but after 2020 ‘other land’ is at a large scale and pace lost for plantation. In fact, in all scenarios, after 2020 or 2030, the loss of ‘other land’ is the fastest responding land use decrease of all, showing thus that savannah is a main part of the biomass marginal after this time under all conditions.

Old forest land: Old forest land is seen to decrease quite significantly under all biomass and CO_2 price conditions. The pace of decrease is sensitive to the CO_2 price, and at zero CO_2 price the decrease is almost twice the decrease at 50 US$/ton CO_2 in 2050. A significant part of the decrease is probably windfall, diseases and fires, which implies a demand insensitive baseline for the decrease. This is sustained by the fact that the decrease, at constant CO_2 price, is seen to be rather insensitive to biomass price, even though there is a small response in terms of larger decrease at increased biomass price.

Grassland: Grassland is seen to keep increasing at low CO_2 prices, while it responds by rapid decrease at increasing CO_2 price. It seems that both new forest plantation and ‘other land’ can increase at the expense of grassland at low biomass price, while at high biomass price, plantation is the dominating displacer of grassland. Moreover, the model shows that the use of grassland for plantation is the first response from 2010 onwards, but under all conditions, the decrease of grassland stops around a scale of supply between 10 and 40 EJ/year, corresponding to 2020 or somewhere between 2020 and 2030. Presumably because it is the most attractive land type as host for expansion of plantation, new forest and also cropland, but also constrained by scale, so the potential for expanding further on grassland is relatively quickly used up in a large scale global biomass demand scenario. Our conclusion is that plantation on grassland is mainly a part of the marginal in the first periods in time, and at larger scale of biomass use, plantation on ‘other land’ like savannah takes over.

Cropland: Cropland is the land type varying the least. It is sensitive to CO_2 price, and at low CO_2 price cropland keeps increasing while at high CO_2 price it is more constant. It is also, even though to a lesser degree, sensitive to biomass price, and higher biomass prices implies less cropland at constant CO_2 price. As the graphs in Figure 1 show the net development, it is difficult to deduct how much plantation on cropland that may take place, because this may be followed by a further ILUC within which cropland is subsequently displacing forest, grassland or other land. But the fact that cropland does show some sensitivity to biomass price indicates that such mechanisms may take place within the models of GLOBIOM.

Figure 2 illustrates, then, the breakdown of these land use developments on the 11 world regions comprised in GLOBIOM. The purpose of this is to show where in the World the land use change is modelled to happen. This is done for the combination of high CO_2 price and high biomass price only, but it is not judged to differ significantly for other combinations. As seen, the predominant increase in plantation is happening in Latin America (= South America) and Sub Saharan Africa, and the predominant decrease in other land, old forest and grassland is also found here. This is no big surprise, as these regions are where the largest areas are found.

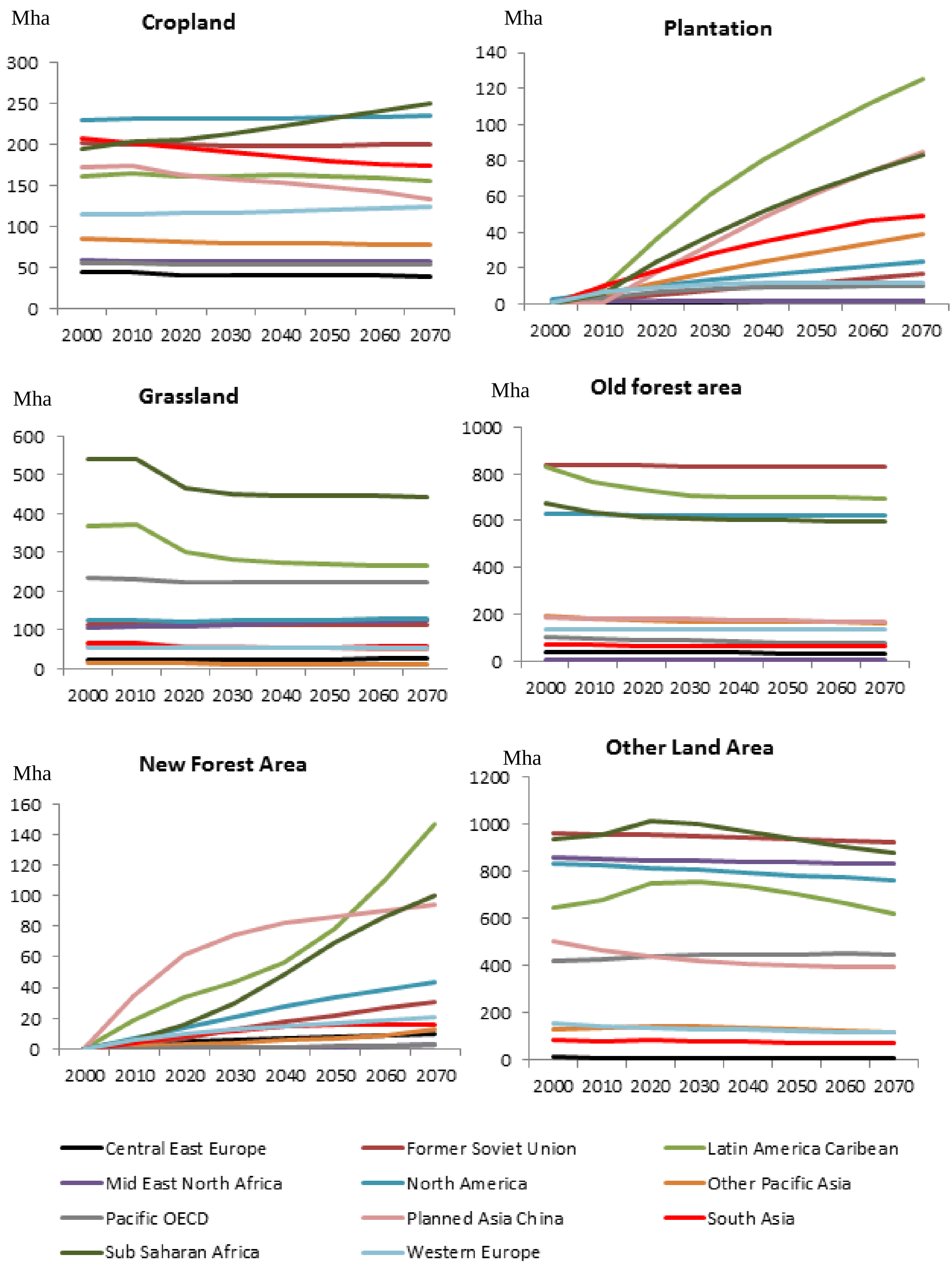

Figure 2 *Development in Land Use in 11 regions of the world, as modelled in the partial equilibrium model GLOBIOM at* CO_2 *price of 50 USD/ton and biomass price of 5 USD/GJ*

As the objective of the stsudy in this project has been to identify the response to an incremental change in biomass demand deriving from a Danish import, is was tried to use the modelled data to illustrate an incremental price level change, thus presumably revealing the difference in land use going from one price level to the next. Figure 3 shows the outcome of this at high CO_2 price and high biomass price.

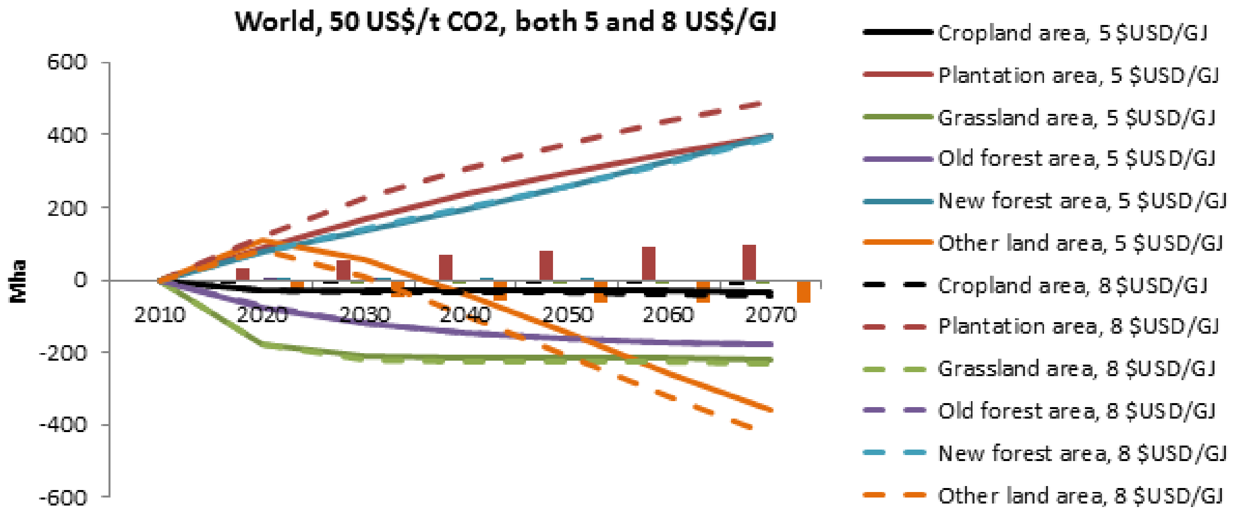

Figure 3 *The difference in land use change (LUC) at biomass price of 5 and 8 USD/GJ – simulating the incremental change in LUC at incremental biomass demand increase*

The change in price level obviously gives rise to a change in land use, and the model hereby reveals which change in land use this causes. As the figure shows, the predominant response to this incremental change is an increase in plantation and a decrease in ‘other land’ indicating that the increased biomass supply happens by establishing plantation on the savannah or similar land types, predominantly in Sub Saharan Africa and Latin America as indicated by Figure 2.

There may, however, be non-land use related responses to the increased biomass price level, as for example intensification and harvest of forest biomass without changes in forest area, i.e. harvest from ‘forest remaining forest’. A data extraction was done to identify the significance of this, as illustrated in Figure 4.

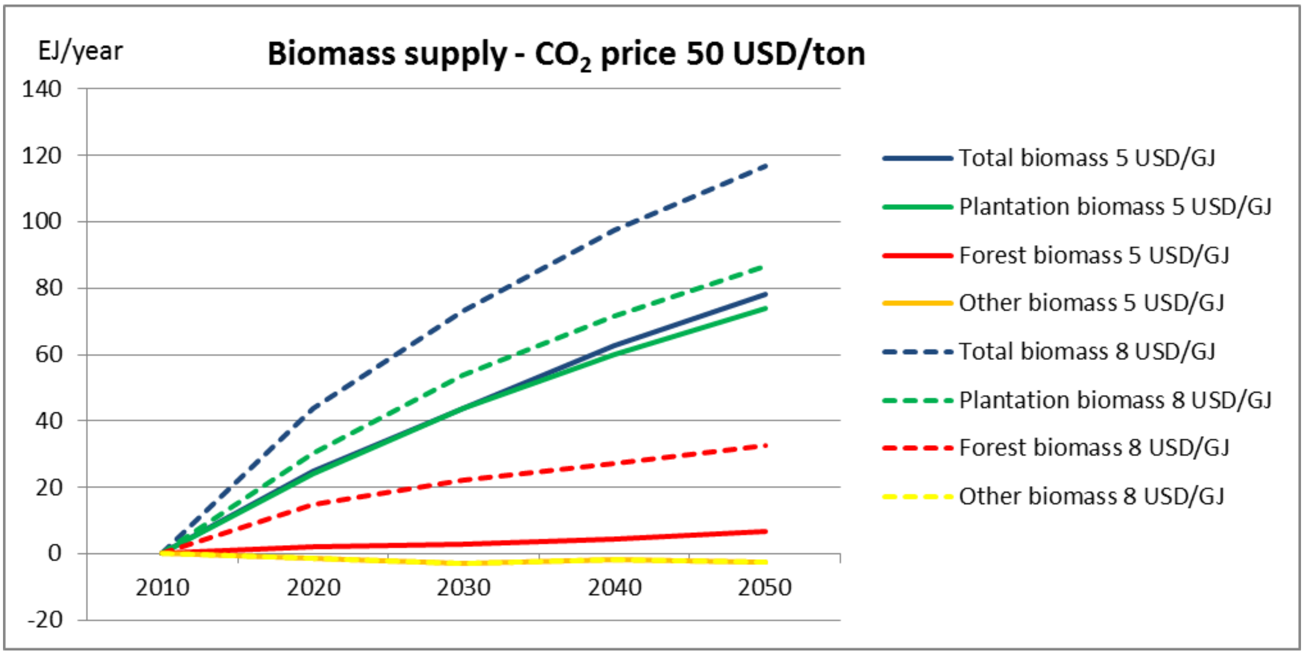

Figure 4 *The difference in biomass supply at biomass price of 5 and 8 US$/GJ – simulating the incremental change in supply at incremental price increase*

Figure 4 shows a case of high CO_2 price, i.e. 50 USD/ton. At this CO_2 price and a biomass price of 5 USD/GJ, the major increase in biomass supply from 2010 onwards derives from plantation, and only a small part come from forest biomass, which here means harvest from forest remaining forest. But at a biomass price of 8 USD/GJ (and CO_2 price still being 50 USD/ton), an increasing part begin to derive from forest biomass, and looking at the increment only, it shows that among two thirds of the increase in biomass supply when going from 5 to 8 USD/GJ in fact derive from forest biomass – according to the data of the SSP2 model run.

1.3.4 Summarizing the potential candidates for biomass marginal supply

Based on the presented models and findings, relevant biomass supply categories are identified, discussed and interpreted in order to establish candidates for the marginal supply in response to a Danish demand of biomass for energy.

First of all, domestic manure and straw biomass is believed to represent marginal supplies in the sense that the marginal is their alternative use – as already described. For manure the avoided alternative is the state-of-the-art Danish conventional manure management, and for straw the avoided alternative is ploughing down. These models are described in Appendix G.

Secondly, domestic wood is considered sold to and purchased from the same international markets as imported wood, thereby having the same marginal. For this biomass, the marginal supplies are divided into supplies representing a smaller scale, shorter term biomass demand and a larger scale, longer term demand.

1.3.5 Small scale bioenergy demand – shorter term wood marginals

This marginal represents decisions with shorter term consequences like decisions on operations and fuel type – not involving investments with a long term return on investment. On the short term, relatively low CO_2 prices are foreseen to prevail on the markets in question, i.e. within the countries potentially supplying wood, like Canada, Russia, USA and Latin America. Looking from the best case to the worst case situation, potential candidates for biomass marginal on the shorter term can be:

<u>2013 – 2020</u>

1. Best case: Biomass from pre-commercial thinnings and harvest residues and from forest intensification
2. Medium case: Plantation on grassland with no or low ILUC
3. Medium case: Plantation on cropland
4. Worst case: Harvest from existing forest, i.e. forest remaining forest

Forest intensification, i.e. harvest from forest landscapes with increasing C-stock at increasing harvest, is a realistic part of the marginal at a smaller scale of demand. However, such harvest of biomass for energy, as a co-product from intensified forestry, is limited by the scale of timber production. As total Roundwood production is around 10 EJ/year, this biomass marginal supply is, thus, no longer realistic as soon as global bioenergy gains a wider scale.

Pre-commercial thinning wood and harvest residues and co-product output from forest intensification are, thus, expected to be available as at least part of the marginal up to a scale of 5-10 EJ/year. Historically, thinning wood has been used in virgin paper making, but paper industry is increasingly moving to plantation of e.g. Eucalyptus. Pellet production is observed to move in, where paper industry is moving out. But the question remains why paper industry moves for plantation for economic reasons (lower cost of wood feedstock), when pellet production is not expected to do so. A probable explanation is that establishing new plantation constitutes a bottleneck (there is a limit to the pace at which it happens) and that the options for new plantation are taken by paper industry for the time being, because paper production implies the higher added value of the two competing customers for new plantation. At some point, however, the bottleneck will be surpassed, and the lower feedstock cost of plantation wood may result in plantation being the marginal. It is difficult to give an estimate of a time horizon within which thinning wood can be judged to be part of the marginal, but maybe up to around 2020 or 2030? The development of where pellet production takes place should be followed.

The GLOBIOM model runs show that plantation on grassland can be a very probable marginal on the shorter term. But also this potential is limited by scale and in time. The decrease of grassland area stops around a scale of supply between 10 and 40 EJ/year, and beyond this plantation on grassland is no longer seen as a large scale contributor to the marginal biomass supply.

Plantation on cropland. As the profit margin of farmers from shifting to energy crops can under some circumstances be higher than from food/feed crops, also on a short term, this may also be a part of a market based marginal. The business case for farmers should be carefully investigated and understood, and a proper structure of incentives established, if it (for reasons of security of food supply) is an aim to avoid plantation on cropland from being part of the marginal woody biomass supply.

Harvest from old forest or plantation on old forest land. As the partial equilibrium model shows, a part of the land use change, especially at low CO_2 prices (as foreseen to prevail on the markets in question on the shorter term), is still decrease in old forest area – unless strong land use governance is assumed.

When purchasing biomass, care can be taken to ensure a specific origin, e.g. thinning wood from a specific forest owner. This helps ensure the origin and direct carbon footprint. However, if thinning wood over time become limited, other customers may be pushed towards other marginals by Danish customers taking the thinning wood. It is may also be that chips or pellets from thinnings and harvest from existing forest are quite closely related, i.e. traded on the same markets or even sold by the same company/forest owner. It may be difficult, even with quite strict control, to prevent forestry biomass from punctual harvest in ‘forest remaining forest’ to enter the market.

Good governance and conscious sourcing of the demand towards pre-commercial thinning and harvest residues is judged able to ensure that such biomass is a predominant part of the marginal up to a global biomass demand of 5-10 EJ/year. But strong and global land use governance is believed necessary to prevent other biomass origins like plantation on cropland or harvest from existing forest to constitute some part of the marginal.

1.3.6 Larger scale bioenergy – longer term wood marginals

Based on the GLOBIOM model, and also based on an understanding of where the larger scale available land types are, it seems that plantation on grassland, savannah and old forest land constitute an aggregated marginal on the long term. Plantation on other land like savannah may be the predominant part of the marginal. The following candidates for the biomass marginal were found probable on the medium to longer term:

<u>2020-2035:</u>

1. Best case: Plantation on grassland with no or low ILUC
2. Best case: Plantation on low C savannah
3. Medium case: Plantation on tropical grassland with high ILUC
4. Medium case: Plantation on high C savannah
5. Worst case: Plantation on forest land

<u>2035-2050:</u>

5. Best case: Plantation on high C savannah
6. Worst case: Plantation on forest land or harvest from forest remaining forest

<u>2050+:</u>

1. Best case: Plantation on high C savannah
2. Worst case: Plantation on forest land or harvest from forest remaining forest

1.4 The ILUC model

As highlighted in the recent study of Warner et al. (2013), two main approaches to model the environmental consequences (most often the GHG consequences only) of ILUC have been used in studies published so far: (i) economic equilibrium modelling; and (ii) deterministic modelling. This study draws on the second approach.

It has been beyond the scope of the present work to elaborate on the details, strengths and drawbacks of these respective approaches. For this, the reader is referred to Warner et al. (2013), as well as to Marelli et al. (2011). Briefly, however, it can be highlighted that the choice of the deterministic approach was essentially motivated by its transparency advantage and by its reliability over time. Further, equilibrium models constructed to study near-term marginal changes were judged less suited for producing the longer term outlooks aimed at in the present study.

The ILUC model considered in this study comprises two main mechanisms:

(i) Transformation of non-cultivated area (nature) to cropland, also referred to as *land expansion* (or new land cultivation).

(ii) Increased yield per land area, also referred to as *intensification*

Land Expansion

To quantify the Carbon Footprint due to land expansion, or new land cultivation, it is necessary to:

i. Identify how much land is converted, where it is converted and which types of land are converted (biome types);

ii. Estimate, for all converted biomes, the releases of C from the vegetation and soil to the atmosphere.

In order to quantify point (i) above, a deterministic approach to ILUC (as e.g. described in Schmidt, 2008) was used. The methodology used as well as calculations are described and presented in Appendix F.

In order to quantify the releases of C due to land conversion (point ii above), the soil and vegetation carbon data from the Woods Hole Research Centre, as published in the “supporting online material” of Searchinger et al. (2008) have been used[1]. From this database, the amount of C in the soil and vegetation of all

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[1] Other databases (i.e. IPCC) could have been used. See Appendix F for a discussion on the implications of this choice.

affected biomes (point i) was extracted. This allowed to calculate the amount of CO_2 emitted (or sequestered) during land conversion, where the following has been considered, based on the standard practices in various studies dealing with ILUC[2]:

- 25% of the C in the soil is released as CO_2 for all types of land use conversion, except when forests are converted to grassland, where 0% is released;

- 100% of the C in vegetation is released as CO_2 for all forest types as well as for tropical grassland conversions[3], while 0% is released for the remaining biome types (e.g. shrub land, non-tropical grassland, chaparral).

It should be noted that the above applies for the calculation of ILUC only, i.e. the situation where non-cultivated land is transformed to cropland. Cases where land is transformed to lignocellulosic plantations (here considered as DLUC) are covered in Appendix A-E. Calculations details for ILUC are presented in Appendix F, for selected ILUC examples.

Intensification

Intensification refers to the increase of crop yields as a response to a change in demand for land. Recent studies on biofuels or increased crop consumption involving economical modelling indicated that the share of the intensification response in replacing the displaced biomass is likely to be of at least 15% (Kløverpris, 2008; Marelli et al., 2011) and may potentially be as high as 70% (Marelli et al., 2011). In this study, a range has been considered regarding the intensification share of the displacement response:

Case 1: Low intensification (and high expansion): in this case, 15% of the change in demand for land is supplied by intensification

Case 2: High intensification (and low expansion): in this case, 70% of the change in demand for land is supplied by intensification[4].

Intensification may be achieved through three main pathways:

Input-driven pathway: this refers to any yield increases obtained through changes in farm inputs (e.g. fertilizers, pesticides, irrigation, etc.). The increases in yield obtained this way may however be reversible.

Innovation-driven pathway: this refers to any yield increases obtained through technological development (e.g. harvesting technologies allowing to recover more

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[2] E.g. Müller-Wenk and Brandão (2010); Laborde (2011); Searchinger et al. (2008).

[3] This is to be seen as a simplifying assumption (personal communication with Miguel Brandão, ILCA, January 2013, and with David Laborde, IFPRI, February 2013). In fact, from the data of Earles et al. (2012), who detailed, for 169 countries, the fate of the above-ground residues when forest are cleared, it can be seen that even after 100 years, it is not exactly 100% of the C that is returned to the atmosphere, although the gap is negligible in most cases.

[4] This, however, does not always apply. For example, such high intensification was considered unlikely for soybean, a N-fixing crop independent of N fertilizers.

biomass, plant breeding, etc.), and is seen as a more permanent effect (Marelli *et al.*, 2011). However, a lag of ca. 20 years is likely before research and development activities actually translate into yield increases (Edwards *et al.*, 2010).

Multi-cropping/cropping-intensity pathway[5]: this consists to grow more than one crop on the same hectare of land for a given year, which in some countries allows a harvest all year-round. This currently represents 18% of the world's cropland, and higher crop prices can be envisioned to increase the profitability of this practice (Marelli *et al.* 2011). This is related to the input-driven pathway, since it has the consequence to involve more input.

In terms of environmental consequences, the input-driven pathway is the one that matters the most, especially when yield increases are obtained through increase use of nitrogen fertilisers (e.g. Melillo et al., 2009). For the purposes of the present study, the environmental implications of innovation-driven intensification will thus be neglected[6].

One challenge for the environmental assessment is then to determine the extent to which intensification is achieved through increased fertilizers. One simple way to address this could be to consider a range (e.g. 50% to 75%). This is the approach adopted in this study.

The proposed way to estimate the environmental consequences of fertilizers-based intensification is to use the approach described in Schmidt (2007), which uses crop yield dose-response figures to determine how much extra N is applied to selected crops likely to be affected by this form of intensification.

All calculations details for intensification are presented in Appendix F, where the amount of crop produced by intensification is presented, along with the GHG releases (and other environmental flows such as NH_3 and NO_3) for each of the cases where intensification is involved.

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[5] Increase use of fallow land could also be included in this intensification category.

[6] Multi-cropping (a form of input-driven intensification) is reflected and accounted for in the case of soybean, see Appendix F. It can also be argued to which extent the innovation-driven intensification should be included in the LCA. The answer, of course, is to the extent that it would not have happened anyway (i.e. to the extent it is demand-driven). Although innovation-driven intensification is excluded of this study for simplification, this question, i.e. the understanding of the extent to which innovation-driven intensification is linked to the demand, could represent a valuable contribution in the iLUC debate.

2 Carbon Footprint calculations

Carbon footprint values herein are reported as CO_2-e/MJ. In the calculation of the carbon footprint of a biomass conversion pathway, including any land use change in forestry and/or agriculture, we sum up all CO_2 emissions and uptakes into a total net emission/uptake and divide them by the total harvested biomass in 20 and 100 years respectively in order to express emissions per MJ biomass harvested. All carbon footprints have, thus, been calculated using both a 20 years' timeframe (GWP20) and a 100 years' timeframe (GWP100), and includes only the warming effect of the emitted Greenhouse Gasses from changes in carbon stocks. For the 20 year average, the conventional GWP20 is used to translate non-CO_2 greenhouse gases emissions into CO_2-equivalents, and for the 100 year average, the GWP100. However, except for pathways including biogas and manure, other GHG than CO_2 is not relevant or of minor importance.

There is an ongoing debate concerning how to account for the timing of GHG emissions. Some argue that timing and the dynamics of emissions mean a lot, due to among other issues the so-called ‘tipping point’ problem, i.e. that high emissions from e.g. C-stock reductions now followed by uptake later on may have higher climate impact than the long term average, because the short term atmospheric GHG increase may lead to cascading effects. Others find that the long term net atmospheric increase is the main cause of climate change and that shorter term variations mean little or nothing. In this 'budget' view it is possible to quantify how much more GHG (CO_2-e) our civilization can emit in order to stay below a two degree Celsius increase.in temperature. The Emission Gap report by UNEP represents this view (UNEP, 2012). This report combines these views by recognizing that both the end point and the emission reduction path that leads to an end point emission level are important. For more on this discussion and implication for bioenergy system analysis see Bentsen & Stupak (2014), section 8 or the latest IPCC Assessment Report (IPCC AR5, 2013).

The dual timeframe allow for discussion of results in relation to both the reduction path and the reference end point in 2100. GWP100 is applied in National GHG inventories submitted by parties to the convention on climate change and the Kyoto Protocol (KP), and thus in member state's reporting and accounting towards EU obligations, yet in IPCC Assessment Reports, GWP20 is recognized in as an alternative (alongside GWP500).

In particular for biomass derived from forests, GWP20 and GWP100 may provide different perspectives due to the importance of long regrowth/rotation cycles on the carbon balance. The dual timeframe for footprints is furthermore introduced to alleviate the current, and by any means fragmented and unconsolidated discussion on 'carbon debt' in the bioenergy constituency. Carbon debt, in short meaning the lag time between the carbon emissions and sequestration in some fuel wood production systems (Dehue, 2013), is however found to be site, species and management specific, for example see Galik et al (2012), Jonker et al (2012), and Lamers and Junginger (2013), and it is not within the scope of this study to analyse forest holding specific GHG balances. This does not in any way preclude that carbon debt could be relevant for particular biomass production systems. For more on geographic scope, see next section.

2.1.1 Counterfactuals

In analysis of carbon footprints several types of counterfactual scenarios could be considered for the fate of the carbon, both at land use and product level. In this study, the alternative to harvest for bioenergy from primary forests is continued unmanaged growth, whereas for all other forest biomass production systems the counterfactual is land use change or continued management. Specific counterfactuals are outlined in appendix A-E.

On product level, alternative non-energy use of the various biomass types mentioned above could be considered. In this study, non-energy use of woody biomass is not considered as a counterfactual directly, thus eventual carbon storage in wood products in the build environment, furniture or likewise is not included in calculations. This does not preclude that some alternative uses of wood may, e.g. through substitution of cement in buildings, altogether deliver more GHG savings than as bioenergy, as demonstrated by some (Sathre & O'Connor, 2010).

2.1.2 Non-GHG climate forcings

Changes to hydrological cycles, albedo, heat exchange, species composition in stands, particle emissions or other biophysical processes caused by changes in land use or management practices driven by bioenergy demand but potentially influencing local meteorological conditions, and if of significant scale also the global energy balance, is, however, not included. For examples of discussions of these aspects see e.g. Cherubini et al. (2012), Bellouin & Boucher (2010) on albedo, Choobari et al. (2014) on dust, Ban-Weiss et al (2011) on heat exchange, Kundzewicz (2008) on links between the hydrological cycle and climate forcing and Bonan (2008A and Bonan 2008B), Hansen et al. (2005), Kabat et al. (2004) or Steffen et al. (2004) for general introduction and overview. The latest IPCC Assessment Report also gives a brief overview of other forcings (IPCC AR5, 2013)

2.1.3 Local to global scale

GHG impacts are site and management specific, as found by a recent literature reviews conducted by Lamers et al (2013) confirming the findings of earlier reviews by Lattimore et al (2009). The land use types used in this study for the identification of biomass marginal are idealized proto-land types, which does not allow for assessing specific geographies or atypical site specific carbon balances. To ensure that these land use types are representative of a wide range of specific conditions, Monte Carlo simulations of 500 specific conditions for each land use types under each climate regime have been undertaken to arrive at a reasonable average number for the carbon stocks. See more in relevant appendix.

2.2 Biomass inventory data

Background (or generic) life cycle inventory datasets were based on the Ecoinvent database v2.2[7] (Ecoinvent, 2010) for production of agricultural inputs such as fertilizers[8,9], capital goods such as agricultural machinery to e.g. harvest the straw, etc.. Foreground (or system-specific) life cycle inventory data includes:

› Danish-specific data for manure management and biogas production (raw and digested, for fattening pig slurry): these are thoroughly detailed in Hamelin et al. (2014), and summarized in Appendix G;

› Danish-specific inventory for wheat straw: these are thoroughly detailed in Hamelin et al. (2012; 2014), and summarized in Appendix G;

However, no background processes for the cultivation and eventual fertilization of woody biomass systems have been considered.

2.2.1 Inventory models for greenhouse gas emissions from land use change and biomass supply

As background for identifying the GHG emission consequence of an incremental biomass supply for a Danish bioenergy policy, models have been established for land use change, LUC at ‘stand level’. Such models show the C-stock change, CO_2 emissions and biomass harvest from various types of forest and plantation. The models comprise:

› Thinnings from managed forests
› Harvest from managed forest
› Forest plantation

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[7] This study was facilitated with the LCA software SimaPro 7.3.3. SimaPro 8, which contains the Ecoinvent v.3.0 database, was not available/functional at the time of carrying out the project. (http://www.pre-sustainability.com/simapro8). Therefore, the study relied on the data from Ecoinvent v.2.2.

[8] Fertilizers are involved in manure-biogas systems (with or without co-digestion with straw), given the interactions between the raw manure or digestate with the mineral fertilizer production

[9] Calcium ammonium nitrate, diammonium phosphate and potassium chloride are considered to be the marginal mineral fertilizers, as described in Hamelin (2013), p. 15-20. The inventory for the fertilizers is from the Ecoinvent database (Nemecek and Kägi, 2007), but the inventory for nitric acid (involved in the production of calcium ammonium nitrate) has been corrected to 0.00248 kg N_2O per kg nitric acid, as explained in Appendix F.

- Plantation on high carbon grassland/savannah
- Plantation on low carbon grassland – with and without indirect land use change, ILUC
- Plantation on marginal land
- Plantation on cropland – including indirect land use change, ILUC
- Domestic biomass residues: straw and manure

The methodological approach followed as well as the used literature references can be found in Appendix A to E.

All of these wooden biomass categories are modelled for both boreal, temperate and tropical climate zones, and the categories involving an ILUC is modelled including a low as well as a high ILUC estimate. The approach followed when modelling ILUC is described in Appendix F.

The domestic residues of straw and manure are modelled as described in Appendix G.

2.2.2 Key aspects and potential range of greenhouse gas emissions from future biomass for energy

Inherently, biogenic emissions are caused by the fact that the carbon stock (C-stock) on the World's land areas decrease, predominantly due to deforestation, including biomass from vegetation above ground as well as below ground and including carbon previously accumulated in the soil. As a major cause of biogenic emissions is the deforestation or decrease in C-stock, an option for reversing the development is, of course, inherently an afforestation or increase in C-stock again. It can be said that the presence of large land areas with low C-stock also represents a potential for CO_2 uptake from the atmosphere by ensuring a C-stock increase again. There is, thus, a potential for increasing the C-stock on areas with low carbon stock and at the same time harvesting more biomass, and large areas with low C-stock exist due to very extensive use of the land, e.g. for grazing of animals. Further, there is also a potential for enhancing the efficiency of the animal production, thus releasing grassland for biomass-for-energy production. But, as mentioned earlier, also drivers for deforestation still exist.

Figure 5 illustrates the change in C-stock when, one the one side, increasing C-stock by establishing a plantation on carbon poor grassland in tropical climate, and, on the other side, decreasing C-stock by establishing a plantation on carbon rich woody savannah.

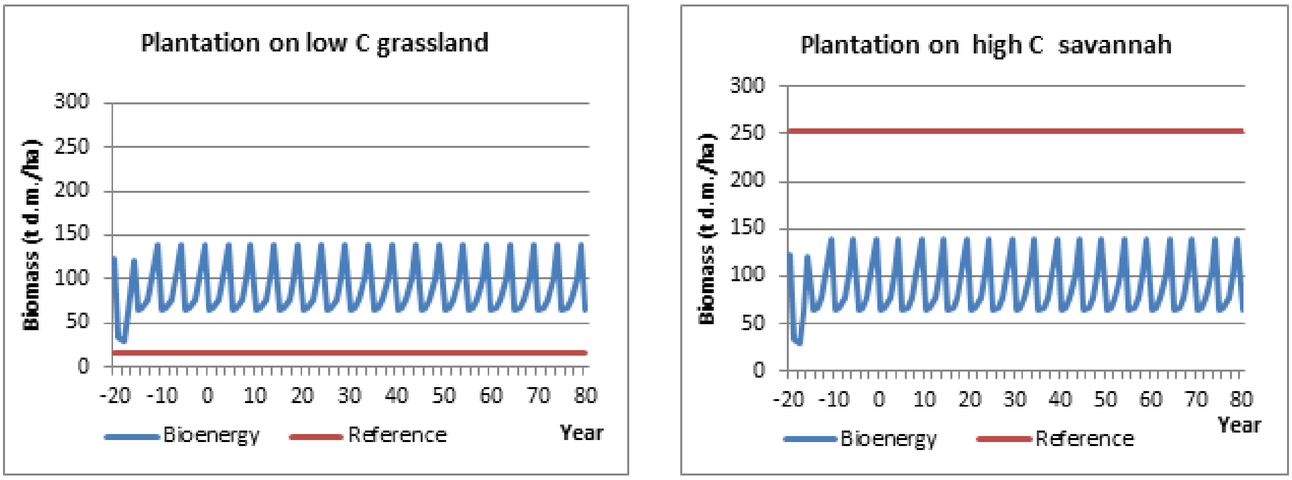

Figure 5 *Changes in C-stock (biomass in ton dry matter (d.m.)/hectare) when establishing a plantation on low carbon stock grassland in the tropics versus on a high C woody savannah. Data, models and assumptions are presented in Appendices A to E*

As evident from Figure 5, there is a huge difference in the consequence for GHG emissions from biomass between producing biomass from plantation on carbon rich land like woody savannah and primary forest or from plantation established on carbon poor grassland. The illustration in Figure 5 shows the change in C-stock in the case of tropical plantation and reference, and the rotation time of the plantation is relatively short, i.e. 5 years between each harvest. In temperate and boreal climate, rotation time of plantation is larger, e.g. up to 20 years, and the C-stock is, therefore, subject to slower variations. The time until the C-uptake from the regrowth of the forest has counteracted the initial emission can, then, be large.

The key aspect of modelling of biogenic GHG emissions from providing biomass for bioenergy is, thus, the net change in carbon stock.

Table 2 presents the outcome of the inventory models.

Table 2 Modelled GHG emissions from individual biomass and LUC categories. CO_2 emission average normalised per harvested (and used for energy) biomass at 20 and 100 years amortisation. Data do not include transport emissions or processing emissions for chips/pellets. *(continued next page)*

	Average emissions at 20 amortisation (g CO_2 per MJ removal)		Average emissions at 100 years amortisation (g CO_2 per MJ removal)	
Residues – thinnings				
Boreal	65		0.02	
Temperate	0.011		0.000	
Tropical	0.009		0.000	
Forest remaining forest (harvest from existing forest)				
Boreal	153		74	
Temperate	222		108	
Tropical	123		41	
Plantation on forest land				
	when utilizing initial removal	when **not** utilizing initial removal	when utilizing initial removal	when **not** utilizing initial removal
Boreal	110	529	53	104
Temperate	181	777	97	194
Tropical	87	383	45	67
Plantation on low C grassland – excluding iLUC from displaced animal feed				
Boreal	-62		-31	
Temperate	-82		-6.6	
Tropical	-15		-3.9	
Plantation on low C grassland – including iLUC from displaced animal feed (low and high estimate)				
	Low	High	Low	High
Boreal	-45	75	-27	-2
Temperate	-78	-9	-6	8
Tropical	-18	83	-5	16
	Average emissions at 20 amortisation (g CO_2 per MJ removal)		Average emissions at 100 years amortisation (g CO_2 per MJ removal)	
Plantation on low C grassland – including iLUC from grassland directly displaced into deforestation				
	when utilizing initial removal	when **not** utilizing initial removal	when utilizing initial removal	when **not** utilizing initial removal
Boreal	110	529	53	104
Temperate	181	777	97	194
Tropical	87	383	45	67
Plantation on high C grassland/savannah – lower and higher C-stock – not using initial removal				
	Lower C-stock	Higher C-stock	Lower C-stock	Higher C-stock
Tropical	14	43	3	9
Low C grassland converted to high C grassland – excluding ILUC from lost animal feed				
Boreal	-41		-5	
Temperate	-77		-6	
Tropical	-18		-3	
Plantation on marginal land				
Boreal	-32		-32	
Temperate	-85		-6.9	
Tropical	-15		-3.9	
Plantation on cropland – excluding iLUC from lost food/feed production				
Boreal	-32		-32	
Temperate	-85		-6.9	
Tropical	-15		-3.9	
Plantation on cropland – including iLUC from lost food/feed production (low and high estimate)				
	Low	High	Low	High
Boreal	-5	110	-24	-3
Temperate	-68	30	-2	17
Tropical	-9	52	-3	10

Table 2 cont. Modelled GHG emissions from individual biomass and LUC categories. CO_2 emission average normalised per harvested (and used for energy) biomass at 20 and 100 years amortisation. Data do not include transport emissions or processing emissions for chips/pellets. (continued)

Straw (Denmark)		
	GWP20 (gCO_2-eq./MJ)	GWP100 (gCO_2-eq./MJ)
Temperate	24	11
Manure (Denmark, fattening pig, 6.9% TS, 5.5% VS)		
	GWP20 (gCO_2-eq./MJ VS)	GWP100 (gCO_2-eq./MJ VS)
Temperate	-164	-73

As shown in Table 2, the CO_2 emissions from the various types of biomass supply are expressed per MJ harvested and used for energy. The models of the forest and plantation biomasses (described in Appendix A - E) account for emissions from any change in carbon stock on the land in question, be it a decrease or an increase, as well as any subsequent cyclic emissions from the forest or plantation.

Emissions from burning/using the biomass for energy purposes are included in the values in the Table, i.e. the values are the net biogenic CO_2 emissions deriving from uptake and releases and thus reflect the changes in stock. Carbon stock changes, be it increase or decrease, appear initially, typically within the first few years, followed subsequently by cyclic emissions and cyclic changes in the carbon stock. The cyclic emissions balance, assuming a steady operation of the forest or plantation subsequent to the initial C-stock change, i.e. uptake and releases are equal – because a net average C-stock is maintained constant. See Figure 5 for illustration. Therefore, the initial C-stock change is the key contributor to the CO_2 emissions or uptake from the biomass. This initial emission/uptake is, then, normalised by the harvested – and used – biomass.

Assuming a long term steady-state cyclic operation of the forest/plantation, including a biomass harvest at every rotation interval, the initial emission/uptake will, of course, be ‘diluted’ more and more when normalised to the harvested biomass. On the very long term, the cyclic emissions dominate completely, and the net emission comes close to zero. In several cases, however, this will take several hundred years.

When doing plantation on forest land or savannah, it may happen that the initial biomass removal is used partly or fully for energy, and it may happen that it is not used. For plantation on forest land, we have modelled both situation, for plantation on savannah, we have assumed the initial biomass removal not used.

On the 20 year horizon, the specific GHG emissions from plantation on high C savannah is 43 g CO_2-eq./MJ and from plantation on forest land it is 87 or up to 383 g CO_2-eq./MJ depending on whether the initial C-stock removal is utilized or not (see Table 2). This implies specific GHG emissions on the 20 year horizon to lie in the range of 43 – 383 g CO_2-eq./MJ as the longer term marginal.

On the 100 year horizon, the specific GHG emissions from plantation on high C savannah is 9 g CO_2-eq./MJ and from plantation on forest land it is 45 or up to 67 g CO_2-eq./MJ depending on whether the initial C-stock removal is utilized or not (see Table 2). This implies specific GHG emissions on the 100 year horizon to lie in the range of 9 – 67 g CO_2-eq./MJ as the longer term marginal.

From another study (Schmidt and Brandao, 2013), we have seen specific emissions og 6.5 to 45 g CO_2-eq./MJ for GWP 100 and 34 to 198 g CO_2-eq./MJ for GWP20. This range matches quite well the range we will get if taking a weighted average of plantation on savannah and forest land on the longer term.

2.2.3 The historic development of biogenic greenhouse gas emissions

In 2000, it was estimated (IPCC, 2000) that approximately 405 ± 60 Gt C during the period 1850-1998 had been emitted as CO_2 into the atmosphere from human activities. These emissions were caused by fossil fuel burning and cement production (67 percent), and land use and land-use change, LUC (33 percent), predominantly from deforestation.

According to IPCC (2007), annual GHG emissions in 2004 amounted to around 49 Gt CO_2-eq./year, of which around 31% were from agriculture and forestry – equal to around 15 Gt CO_2-eq./year from these two sectors together, cf. Figure 6. Likewise, UNEP (2012) estimated the agricultural & forestry emissions in 2010 to be around 11 Gt CO_2-eq./year.

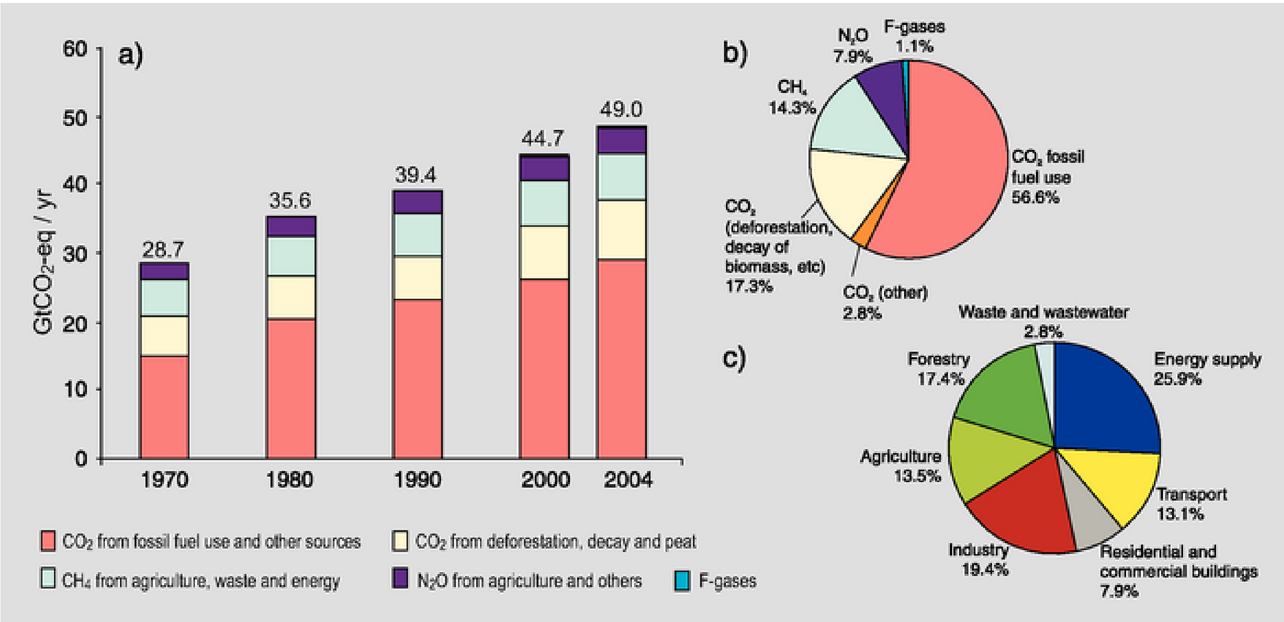

Figure 4-1 (from IPCC (2007). (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004. (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Forestry includes deforestation.)

These agricultural and forestry emissions relate to the way we use the land. In order to understand the efficiency of our historic and present way of using land to provide food, feed and forestry products, the emissions are in the following related to the quantity of acquired products.

Based on data from FAOSTAT from 2011, Chum et al. (2011) finds the global harvest of major forestry and agricultural products to represent an energy equivalent around 80 EJ/year, i.e. a global industrial roundwood production of 15 to 20 EJ/yr, and a global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) of around 60 EJ/yr. Including agricultural residues and the informal sector use of forest residues (mainly for firewood), the total human appropriated part of the global net primary production, HANPP is larger, i.e. 219 EJ/year according to Krausmann et al. (2008). Bang et al. (2013) finds this figure to be 220 EJ/year based on FAOSTAT and other data.

Relating, thus, recent emissions from agriculture and forestry to the total appropriated biomass, HANPP by humans today, we arrive at a specific GHG emission of:

- *15 Gt CO_2-eq./220 EJ HANPP = 68 g CO_2-eq./MJ HANPP in 2004*

- *11 Gt CO_2-eq./220 EJ HANPP = 50 g CO_2-eq./MJ HANPP in 2010*

As illustrated in Figure 6, around 17% of this emission arose from forestry in 2004, including deforestation, while 13% arose from agriculture. Of this GHG emission, CO_2 emissions accounted for around 17% (i.e. almost entirely from forestry), while agricultural CH_4 emissions and N_2O emission accounted for the remaining 13 %. For comparison, combustion of natural gas give rise to around 55 g CO_2-eq./MJ combusted, and total supply chain GHG emissions from natural gas amount to around 78 g/MJ.

This business-as-usual emission profile from agriculture and forestry reflects the total pattern of drivers & barriers, and economic, sociological and technological realities of the World till now. As illustrated, deforestation has been a major source of biogenic emissions, and a key cause of deforestation is believed to be a low cost of land in many countries compared to other production factors in both agriculture and forestry – and accordingly, of course, an equally low degree of governance to avoid exploitation of the economic benefits from using new land by deforestation.

Figure 7 illustrates the development of net forest conversion, being the net result of deforestation and afforestation. As seen from the Figure, a net global reduction in forest area is still taking place.

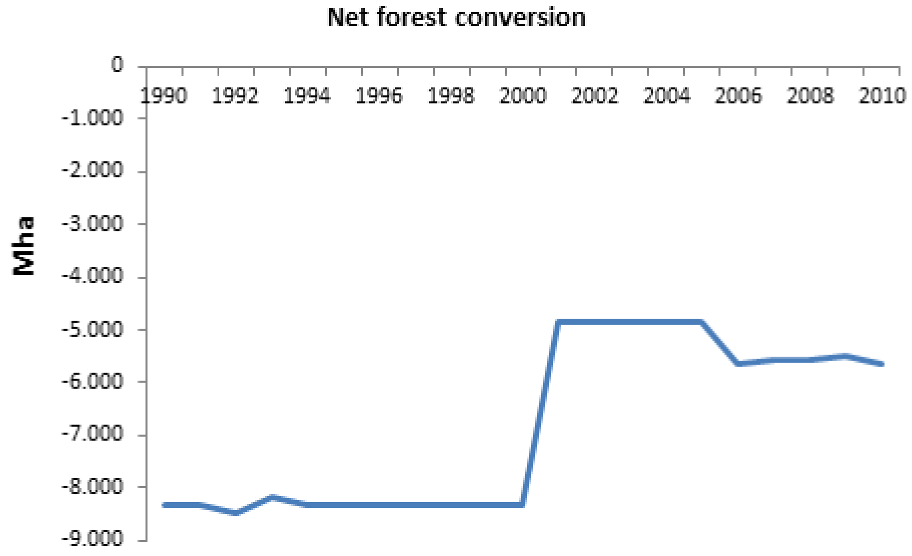

Figure 7 *Net forest conversion as the sum of deforestation and afforestation, retrieved from FAOSTAT (2013)*

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Appendix A Emissions from converting primary forest bioenergy plantations

By David Neil Bird

A.1 Description

A.1.1 Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production comes initially from primary forests and all biomass (including branches and tops) is used for energy. Subsequent to the clearing of the primary forest, a coppice plantation is established.

A.1.2 Reference system

If the reference system, it is assumed that the primary forest is in dynamic equilibrium.

A.2 Model

The model is a combination of the plantation model with the primary forest model. However additional information on the ratio of biomass in the plantation to primary forest is necessary. This has a wide range of values because it depends on the rotation length plantation. Different net calorific values are applied to the biomass from the primary and plantation forests

A.2.1 Correction for cyclicity

A simple correction for cyclicity as previously applied does not work in this example, because the plantation produces less energy per harvest than the clearing of the primary forest. Instead, an inverse operator is calculated so that when it is convolved[10] with the “raw” energy stream the output produces a single pulse of energy at t=0.

The same operator is convolved with the “raw” emissions series to produce the corrected emission series.

[10] See http://en.wikipedia.org/wiki/Convolution for details

A.3 Data

	Boreal	Temperate	Tropical
Plantation biomass (t d.m. / ha)	20 – 200[11]	20 - 200	50-200[12]
Primary forest biomass (t d.m. / ha)	200 - 600[11, 13]	200 - 600[11, 13]	100 – 400[13]
Plantation / Primary	0.1 – 0.5	0.1 – 0.5	0.1 – 0.5

A.4 Results

Given that the exact values of the required parameters above are not known. The emission profile is estimated using the mean of a Monte Carlo simulation using 500 different locations. The provided spreadsheet calculates the mean and standard deviation of emissions profiles in the three biomes. The results are shown in the following diagrams.

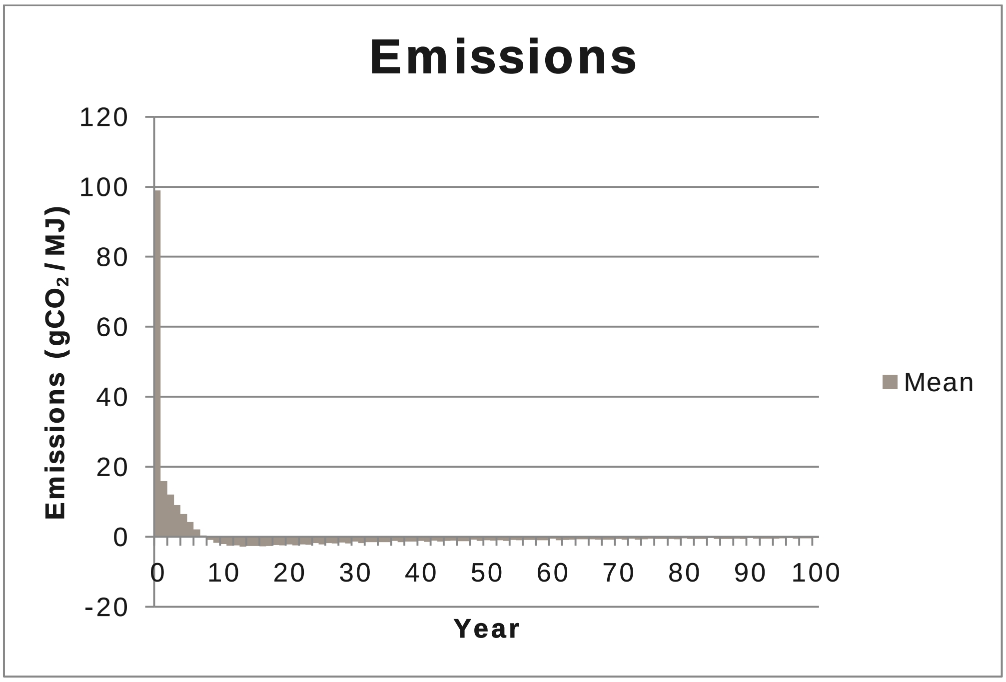

Figure A-1: Emissions from using primary forest converted to bioenergy plantation (boreal biome).

[11] Joint Research Centre. 2013. European forest yield table database

[12] Tiarks A, Nambiar EKS, and Cossalter C. 1998. Site Management and Productivity in Tropical Forest Plantations. CIFOR: Occasional paper no. 16

[13] IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

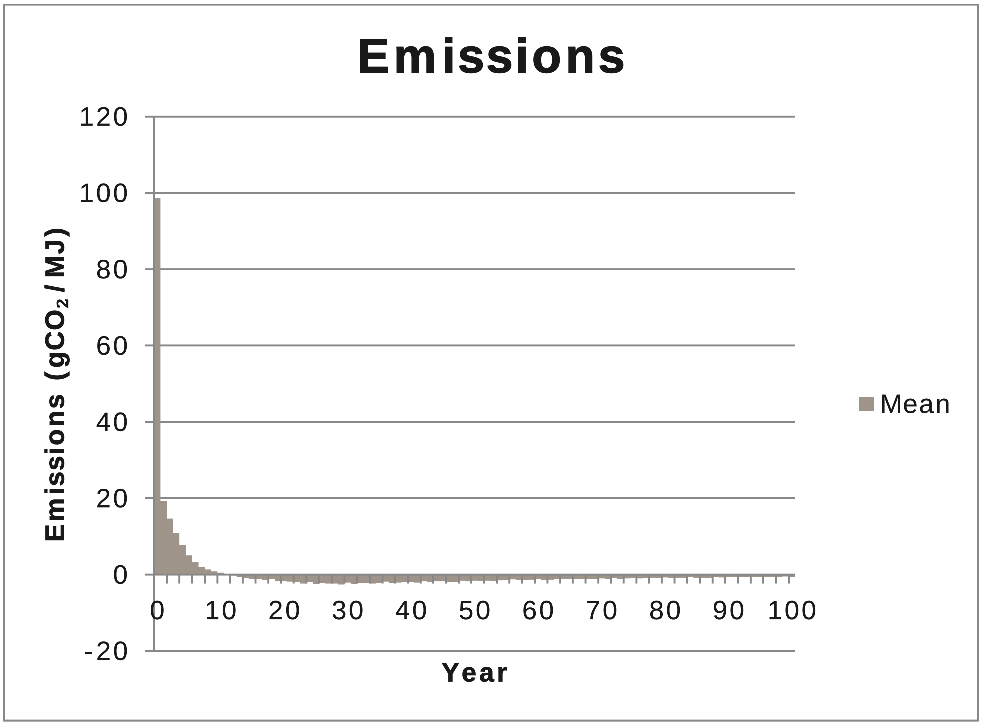

Figure A-2: *Emissions from using primary forest for bioenergy (temperate biome).*

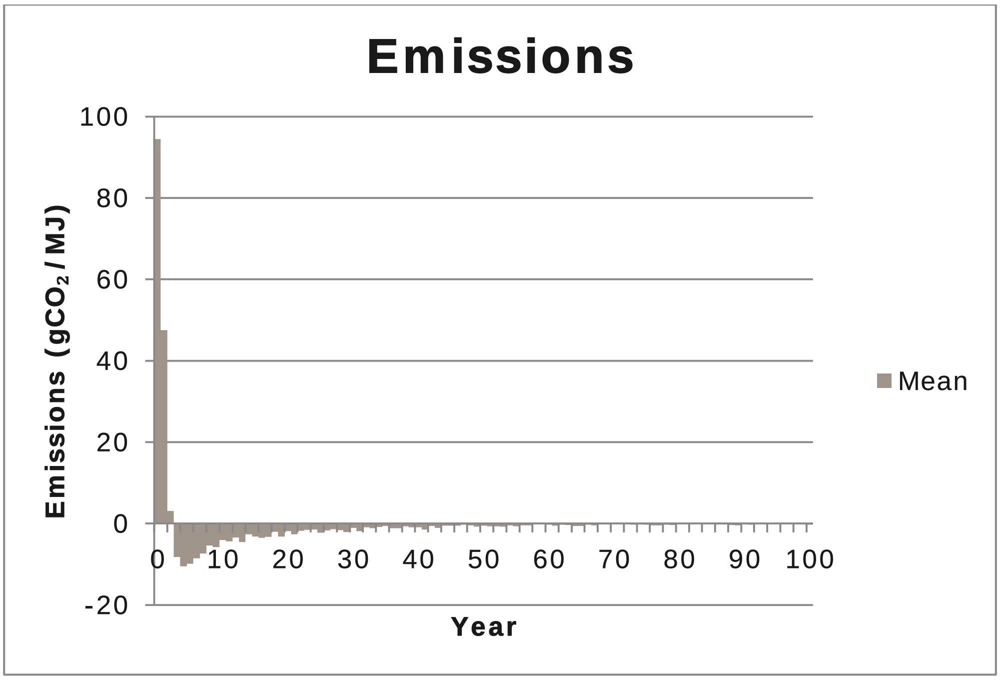

Figure A-3: *Emissions from using primary forest for bioenergy (tropical biome).*

Appendix B Emissions from primary forest remaining primary forest

By David Neil Bird

B.1 Description

B.1.1 Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production comes from primary forests.

1. The biomass is extracted at the "optimal" time when the mean annual increment is a maximum. This assumption may be challenged because it is more likely in forest in developed countries that the forest is older than this age. The assumption makes a pessimistic estimate of the emissions from bioenergy use because the forest will grow more in the reference system.
2. All biomass (including branches and tops) is used for energy. This assumption may also be challenged. When one speaks with foresters the say that this scenario is not very likely since the forest always have more value as lumber than as biomass for energy. They claim that only processing residues will end up as biomass for energy. However, biomass for pulp is already in competition with biomass for energy in Austria (Schwarzbauer 2010)[14].
3. The biomass is not "de-barked". For this reason, the net calorific value used for the conversion of mass to energy will be a weighted mixture of forest residues and clean wood.

B.1.2 Reference system

If the reference system, it is assumed that forest if not harvested for bioenergy would continue to grow. This assumption may also be challenged because the forest will be subject to natural disturbances such as windthrow, fire (boreal forests), and pests.

B.2 Model

B.2.1 Above-ground live biomass (AGB)

To model the biomass growth of the forest a "logistic" curve[15] is used.

[14] Schwarzbauer, P and Stern T. 2010. Energy vs. material: Economic impacts of a "wood-for-energy scenario" on the forest-based sector in Austria — A simulation approach. Forest Policy and Economics, 12, 31–38

[15] Zweitering MH, Jogenburger I, Rombouts FM and van't Riet K. 1990. Modeling of bacterial growth curve. Applied and Environmental Microbiology. 56 / 6, 1875-1881

$$B(t) = \frac{B_o B_{mx}}{B_o + (B_{mx} - B_o)e^{-ct}}$$

Where B_o = biomass at t=0, B_{mx} = maximum biomass and c is a constant that scales the time axis. If we assume that $B_o = 0.01\ B_{mx}$, we can simplify the equation to

$$B(t) = \frac{0.01 B_{mx}}{0.01 + 0.99e^{-ct}}$$

In this situation the maximum of the mean annual increment occurs when ct = 6.26. Therefore

$$c = \frac{6.26}{T_{rotation}}$$

This is the time at which the biomass would be harvested. At this time $B_{harvest} = 0.84\ B_{mx}$

So the biomass equation can be rewritten in terms of the harvest biomass as:

$$B(t) = \frac{0.01 B_{harvest}}{0.84 * (0.01 + 0.99e^{-ct})}$$

B.2.2 Below-ground live biomass (BGB)

I will assume a constant root-to-shot ratio, *R*.

Li et al[16] suggest that fine-root biomass is a proportion of total root biomass using the equation

$$\frac{FR}{R} = 0.072 + 0.354e^{-0.060R}$$

However, this equation is not very conducive to the model formulation used (normalized to harvest biomass), so a simpler formula is applied:

$$FR = kR$$

And calculate an average value from the Li equation for the range of root biomass expected.

B.2.3 Above-ground dead biomass

Litter

Every year the forest produces litter which decays following simple exponential decay. Litter is typically about 4% of above ground biomass. The decay rate of litter is temperature and biome following an equation derived by Brovkin et al (2012)[17]. In this paper they suggest

$$k_{litter} = k_{litter10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

And have studied a global compilation of reports to attain values for $k_{litter10}$ and Q_{10}. They suggest:

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[16] Li Z., Kurz W., Apps S. and Beukema S. l, 2003, Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvements and implications for the estimation of NPP and NEP. Can. J. For. Res. 33: 126-136.

[17] Brovkin V, van Bodegom PM, Kleinen T, Wirth C, Conrwell WK, Cornelissen JHC and Kattge J. 2012. Plant-driven variation in decomposition rates improves projections of global litter stock distribution. Biogeosciences 9, 565-576

Table B-1: Parameters for the estimation of litter decay-rates

Biome	$K_{litter10}$	Q_{10}
Trop. Broadleaved evergreen	0.93	2.75
Trop. Broadleaved raingreen	1.17	2.75
Temp. needleleaved evergreen	0.70	1.97
Temp. broadleaved	0.95	1.37
Boreal needleleaved	0.76	1.97
Boreal broadleaved	0.94	1.37

Dead wood

In addition the forest produces dead wood due to mortality. Typical mortality rates are shown in Table B-2. It is assumed that dead wood is harvested for bioenergy when the stems are harvested.

Table B-2: Average mortality rates

Biome	Average mortality rate (fraction of standing biomass per year)
Tropical forests	0.0177
Evergreen forests	0.0116
Deciduous forests	0.0117

Source[18]

I assume that dead wood will decay exponentially following Brovkin's relationship for wood

$$k_{wood} = k_{wood10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

They have studied a global compilation of reports to attain values for k_{wood10} and Q_{10}. They suggest:

Table B-3: Parameters for the estimation of decay-rate for wood

Biome	k_{wood10}	Q_{10}
Trop. Broadleaved evergreen	0.039	2.75
Trop. Broadleaved raingreen	0.039	2.75
Temp. needleleaved evergreen	0.041	1.97
Temp. broadleaved	0.104	1.37
Boreal needleleaved	0.041	1.97
Boreal broadleaved	0.104	1.37

For the purpose of this study, it is assumed that temperate forests are predominantly broadleaved and boreal forests are predominantly needle leaved.

[18] IPCC. (2003). Good practice guidance for land use, land-use change and forestry. (J. Penman, M. Gytarsky, T. Hiraishi, T. Krug , D. Kruger, R. Pipatti, et al., Hrsg.) Hayama, Kanagawa, Japan: The Institute for Global Environmental Strategies for the IPCC and IPCC National Greenhouse Gas Inventories Programme

B.2.4 Below-ground dead biomass

Below-ground dead biomass comes from two sources: decaying roots post-harvest and fine root litter. The latter is a bit of a problem to model. The IPCC default method has soil organic carbon on a per hectare basis depending on soil type, forest type and management.

Coarse roots post-harvest

I will assume that all dead roots decay following Brovkin's relationship for wood.

Fine roots

Brunner et al[19] have recently published root turnover rates for European forests. They found that fine root turnover = 1.11 mean fine root biomass. This value is used for an estimate of fine root turnover for both temperate and boreal forests.

For tropical forest a relationship based on that derived by Finér et al[20] is used. They found that

$$Ln(FRP) = 0.515 * ln(FR) + 2.51$$

Where FRP= fine-root production and FRB = fine-root biomass. This equation is simplified to

$$FRP \approx FRBe^{0.515}$$

And the fine root turnover

$$FRT = FRP - FRB = FRB * (e^{0.515} - 1) = 0.673$$

Fine-roots are assumed to decay following Brovkin's relationship for wood.

Initial biomass in dead biomass pools

One must estimate the initial biomass in the dead biomass pools. To do so, it is assumed that the forest is in dynamic equilibrium. This means that the initial biomass in each of the dead biomass pools is the same as in the year of harvest.

B.2.5 Emissions per kg biomass harvested

The emissions per kg of biomass in a specific year are given

$$Emission_i = \frac{44}{12} * 0.5 * (Biomass_{i-1} - Biomass_i)$$

Finally, one can this in terms of emissions per MJ of energy through the net calorific value (NCV) since NCV = MJ/kg harvested

B.2.6 Correction for cyclicity

The fits energy produced by this type of land management change occurs at the end of the first rotation. As well, once the land management change has happened the land produces multiple batches of energy. Both these factors must be corrected for,

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[19] Brunner I, Bakker MR, Björk RG, Hirano Y et al. 2013. Fine root turnover rates for European forests revisited: an analysis of data from sequential coring and ingrowth cores. Plant Soil. 362: 357-372

[20] Finér L, Ohashi M, Noguchi K, Hirano Y. 2011. Fine root production and turnover in forest ecosystems in relation to stand and environmental characteristics. Forest Ecology and Management. 262: 2008-2023

if one is to use the emission stream with an energy demand steam. This correction is applied in two steps:

1) the negative of the energy series, time delayed by a rotation is added to the original energy series. This corrects for the cyclic nature; and
2) The resulting time series from the first step is shifted back in time so that the first energy produced occurs at t=0.

The same operations are performed on the emissions series.

B.3 Data

	Boreal	Temperate	Tropical
Rotation length (years)	40 – 140[21]	40 – 120	10 – 70[22]
R-to-S ratio[23]	0.15 – 0.37	0.12 – 0.93	0.29 – 0.81
Fine-root / total roots[24]	17% - 30%	10% - 15%	12% - 20%
Fine-root turnover ($year^{-1}$)	1.11	1.11	0.673
Average temperature (deg. C)	-5 – 5	5 – 16	16 - 30
Annual rainfall (mm)	200 – 2000	500 – 1500	500 – 16000
Net calorific value (MJ/kg)	18.6 – 21.1[25]	18.6 – 20.7	Eucalyptus 19.0 – 19.6

B.4 Results

Given that the exact values of the required parameters above are not known. The emission profile is estimated using the mean of a Monte Carlo simulation using 500 different locations. The provided spreadsheet calculates the mean and standard deviation of emissions profiles in the three biomes. The results are shown in the following diagrams.

The three curves have very similar shape (Figure, Figure, Figure). The differences are caused by the differences in rotation lengths. The time until the bioenergy

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[21] Joint Research Centre. 2013. European forest yield table database

[22] Tiarks A, Nambiar EKS, and Cossalter C. 1998. Site Management and Productivity in Tropical Forest Plantations. CIFOR: Occasional paper no. 16

[23] IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan

[24] Values calculated from the Li equation

[25] Oak Ridge National Laboratory. 2011. Heat Content Ranges for Various Biomass Fuels. http://cta.ornl.gov/bedb/appendix_a/Heat_Content_Ranges_for_Various_Biomass_Fuels.xls Accessed 15 July 2013

system has less emissions than the corresponding fossil energy system that it replaces will also be proportional to rotation length.

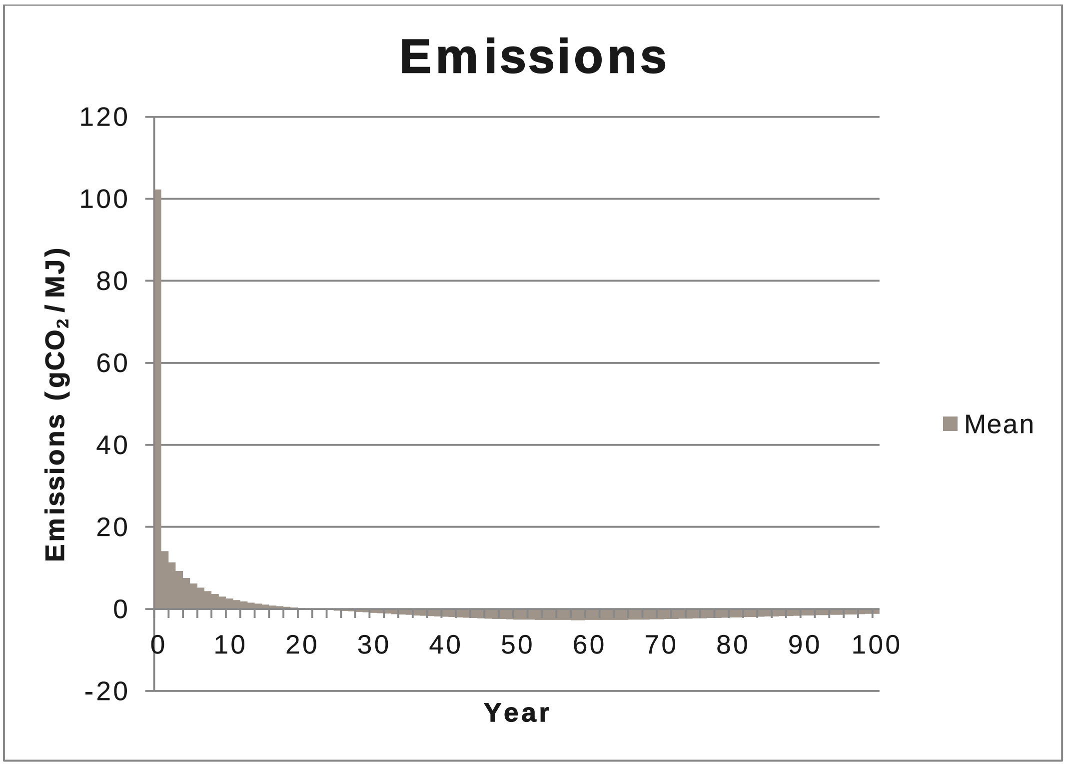

Figure B-1: Emissions from using primary forest for bioenergy (boreal biome).

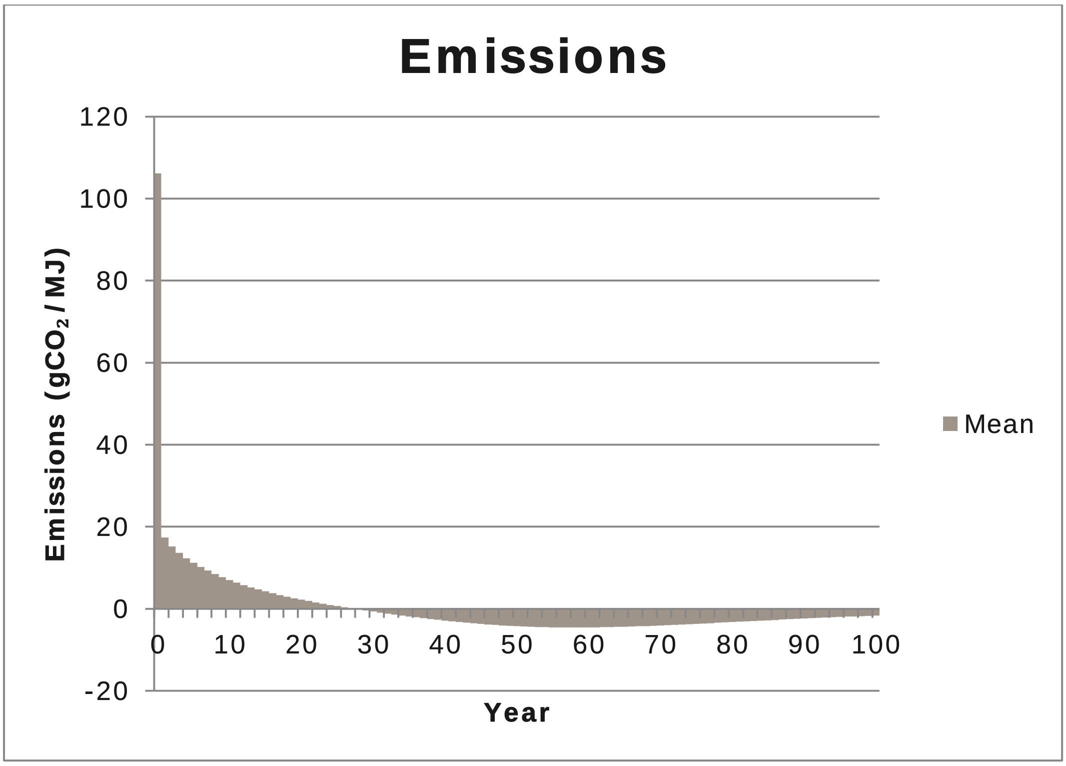

Figure B-2: Emissions from using primary forest for bioenergy (temperate biome).

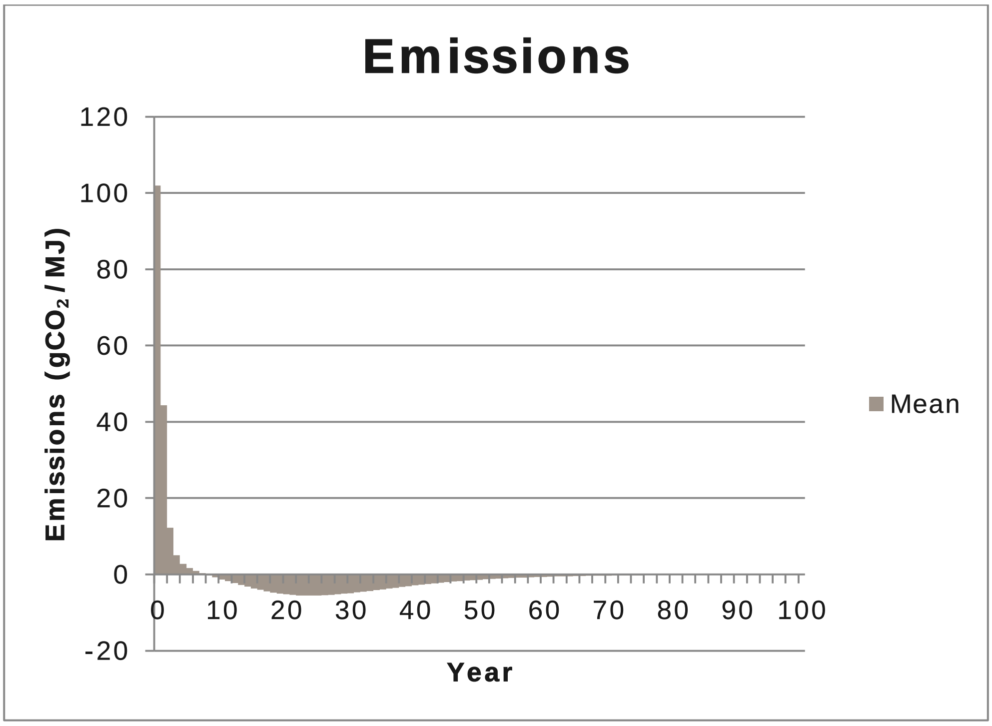

Figure B-3: Emissions from using primary forest for

Appendix C Emissions from new plantations on marginal land and grassland

By David Neil Bird

C.1 Description

C.1.1 Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production comes from short-rotation forests planted specifically for this purpose on marginal land and grassland. All biomass (including branches and tops) is used and the biomass is not “de-barked”. For this reason, the net calorific value used for the conversion of mass to energy will be a weighted mixture of forest residues and clean wood.
The species planted coppices (e.g. willow, poplar, black locust) which means that there is no root die-back at harvest.

C.1.2 Reference system

If the reference system, it is assumed that the marginal and grassland is in steady-state (i.e. there is no net gain or loss of biomass). The lands may be used for other purposes (e.g. subsistence agriculture or grazing) and as such conversion to plantation may cause indirect land use change (iLUC). This is not calculated.

C.2 Model

C.2.1 Above-ground live biomass (AGB)

To model the biomass growth of the plantation a “logistic” curve[26] is used.

$$B(t) = \frac{B_o B_{mx}}{B_o + (B_{mx} - B_o)e^{-ct}}$$

Where B_o = biomass at t=0, B_{mx} = maximum biomass and c is a constant that scales the time axis. If we assume that B_o = 0.01 B_{mx}, we can simplify the equation to

$$B(t) = \frac{0.01 B_{mx}}{0.01 + 0.99e^{-ct}}$$

In this situation the maximum of the mean annual increment occurs when ct = 6.26. Therefore

$$c = \frac{6.26}{T_{rotation}}$$

This is the time at which the biomass would be harvested. At this time $B_{harvest}$ = 0.84 B_{mx}
So the biomass equation can be rewritten in terms of the harvest biomass as:

$$B(t) = \frac{0.01 B_{harvest}}{0.84 * (0.01 + 0.99e^{-ct})}$$

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[26] Zweitering MH, Jogenburger I, Rombouts FM and van’t Riet K. 1990. Modeling of bacterial growth curve. Applied and Environmental Microbiology. 56 / 6, 1875-1881

C.2.2 Below-ground live biomass (BGB)

Since we have assumed that the planted species coppices, we will assume a constant root-to-shot ratio, *R*, during the first rotation and a constant value = $B_{harvest}*R$ thereafter.

C.2.3 Above-ground dead biomass

Every year the plantation produces litter which decays following simple exponential decay. Litter is typically about 4% of above ground biomass. The decay rate of litter is temperature and biome following an equation derived by Brovkin et al (2012)[27]. In this paper they suggest

$$k_{litter} = k_{litter10} Q_{10}^{\left(\frac{T-10}{10}\right)}$$

And have studied a global compilation of reports to attain values for $k_{litter10}$ and Q_{10}. They suggest:

Table C-1: Parameters for the estimation of litter decay-rates

Biome	$K_{litter10}$	Q_{10}
Trop. Broadleaved evergreen	0.93	2.75
Trop. Broadleaved raingreen	1.17	2.75
Temp. needleleaved evergreen	0.70	1.97
Temp. broadleaved	0.95	1.37
Boreal needleleaved	0.76	1.97
Boreal broadleaved	0.94	1.37

C.2.4 Below-ground dead biomass

Below-ground dead biomass (including soil organic carbon) is a bit of a problem. The IPCC default method has soil organic carbon on a per hectare basis depending on soil type, forest type and management.

Marginal lands

As such it is not explicitly dependant on the amount of biomass growing or harvested. A slightly different approach is used. Berhougaray et al (2013) report fine root production as a proportion, k, of net primary productivity (NPP). Therefore:

$$FineRoot_{prod} = \frac{k}{(1-k)} * (\Delta AGB + \Delta BGB)$$

Where $3.9\% \leq k \leq 10\%$

They also estimate fine root biomass turnover rate, t_r, as the ratio of fine root production to mean fine root biomass. Therefore, if we assume that the difference between the production and the mean biomass is the amount that dies per year, we have

[27] Brovkin V, van Bodegom PM, Kleinen T, Wirth C, Conrwell WK, Cornelissen JHC and Kattge J. 2012. Plant-driven variation in decomposition rates improves projections of global litter stock distribution. Biogeosciences 9, 565-576

$$FineRoot_{mort} = \frac{(t_r - 1)}{t_r} * FineRoot_{prod}$$

Where $1.9 \le t_r \le 2.7$
And combining the two equations we arrive at

$$FineRoot_{mort} = \frac{(t_r - 1)k}{t_r(1 - k)} * (\Delta AGB + \Delta BGB)$$

This, it is assumed, will decay exponentially following Brovkin's relationship for wood

$$k_{wood} = k_{wood10} Q_{10}^{(\frac{T-10}{10})}$$

They have studied a global compilation of reports to attain values for k_{wood10} and Q_{10}. They suggest:

Table C-2: Parameters for the estimation of decay-rate for wood

Biome	$\boldsymbol{k_{wood10}}$	$\boldsymbol{Q_{10}}$
Trop. Broadleaved evergreen	0.039	2.75
Trop. Broadleaved raingreen	0.039	2.75
Temp. needleleaved evergreen	0.041	1.97
Temp. broadleaved	0.104	1.37
Boreal needleleaved	0.041	1.97
Boreal broadleaved	0.104	1.37

For the purpose of this study, it is assumed that temperate forests are predominantly broadleaved and boreal forests are predominantly needleleaved.

Grasslands

For grasslands it is assumed that there is no change in soil organic carbon.

C.2.5 Emissions per kg biomass harvested

The emissions per kg of biomass in a specific year are given

$$Emission_i = \frac{44}{12} * 0.5 * (Biomass_{i-1} - Biomass_i)$$

Finally, one can this in terms of emissions per MJ of energy through the net calorific value (NCV) since NCV = MJ/kg harvested

C.2.6 Correction for delayed production and cyclicity

The fits energy produced by this type of land management change occurs at the end of the first rotation. As well, once the land management change has happened the land produces multiple batches of energy. Both these factors must be corrected for, if one is to use the emission stream with an energy demand steam. This correction is applied in two steps:

3) the negative of the energy series, time delayed by a rotation is added to the original energy series. This corrects for the cyclic nature; and

4) The resulting time series from the first step is shifted back in time so that the first energy produced occurs at t=0.

The same operations are performed on the emissions series.

C.3 Data

	Boreal	Temperate	Tropical
Rotation length (years)	10 – 30[28]	3 – 20[29] [30] [31] [32]	3 – 10
R-to-S ratio[33]	0.15 – 0.37	0.12 – 0.93	0.29 – 0.81
Fine-root production / NPP	3.9% - 10%	3.9% - 10%	3.9% - 10%
Fine-root turnover ($year^{-1}$)	1.9 – 2.7	1.9 – 2.7	1.9 – 2.7
Average temperature (deg. C)	-5 – 5	5 – 16	16 - 30
Annual rainfall (mm)	200 – 2000	500 – 1500	500 – 16000
Net calorific value (MJ/kg)	Short Rotation Coppice (SRC): 17.3 – 19.7[34] [35]	SRC: 17.3 – 19.7	Eucalyptus 19.0 – 19.6

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[28] Weih M. 2004. Intensive short rotation forestry in boreal climates: present and future perspectives. Can. J. For. Res. 34: 1369–1378

[29] Drake-Brockman GR. 1996. Establishment and Maintenance Of A Woodfuel Resource. Forestry Research Technical note 17/96. http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/RESOURCES/REF_LIB_RES/PUBLICATIONS/GUIDANCE/ESTABLISHMENT%20AND%20MAINTENANCE%20OF%20A%20WOODFUEL%20RESOURCE%20TDB_TN1796.PDF

[30] Pontailler JY, Ceulemans R, and Guittet J. 1999. Biomass yield of poplar after five 2-year rotations. Forestry 72 / 2, 157-163

[31] Aylott MJ, Casella E, Tubby I, Street NR, Smith P and Taylor G. 2008. Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK. New Phytologist 178: 358–370

[32] Evans S (coordinator), Baldwin M, Henshall P, Matthews R, Morgan G, Poole J, Taylor P, and Tubby I. 2007. Final Report: Yield models for Energy: Coppice of Poplar and willow. Volume A – Empirical Models. Report to DTI (B/W2/00624/00/00URN). Ed: I Tubby and J Poole. 91pp

[33] IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan

[34] McKendry P. 2002. Energy production from biomass (part 1): overview of biomass. Bioresource Technology 83 (2002) 37–46

[35] OMAFRA. 2001. Biomass Burn Characteristics Factsheet. Ontario Ministry of Agriculture and Food. http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm#3. Accessed 17 June 2013

C.4 Results

Given that the exact values of the required parameters above are not known. The emission profile is estimated using the mean of a Monte Carlo simulation using 500 different locations. The provided spreadsheet calculates the mean and standard deviation of emissions profiles in the three biomes. The results are shown in the following diagrams.

There are minor differences between plantation established on marginal land or on grasslands within the same biome. This is due to the increase in soil organic carbon when planted on marginal lands.

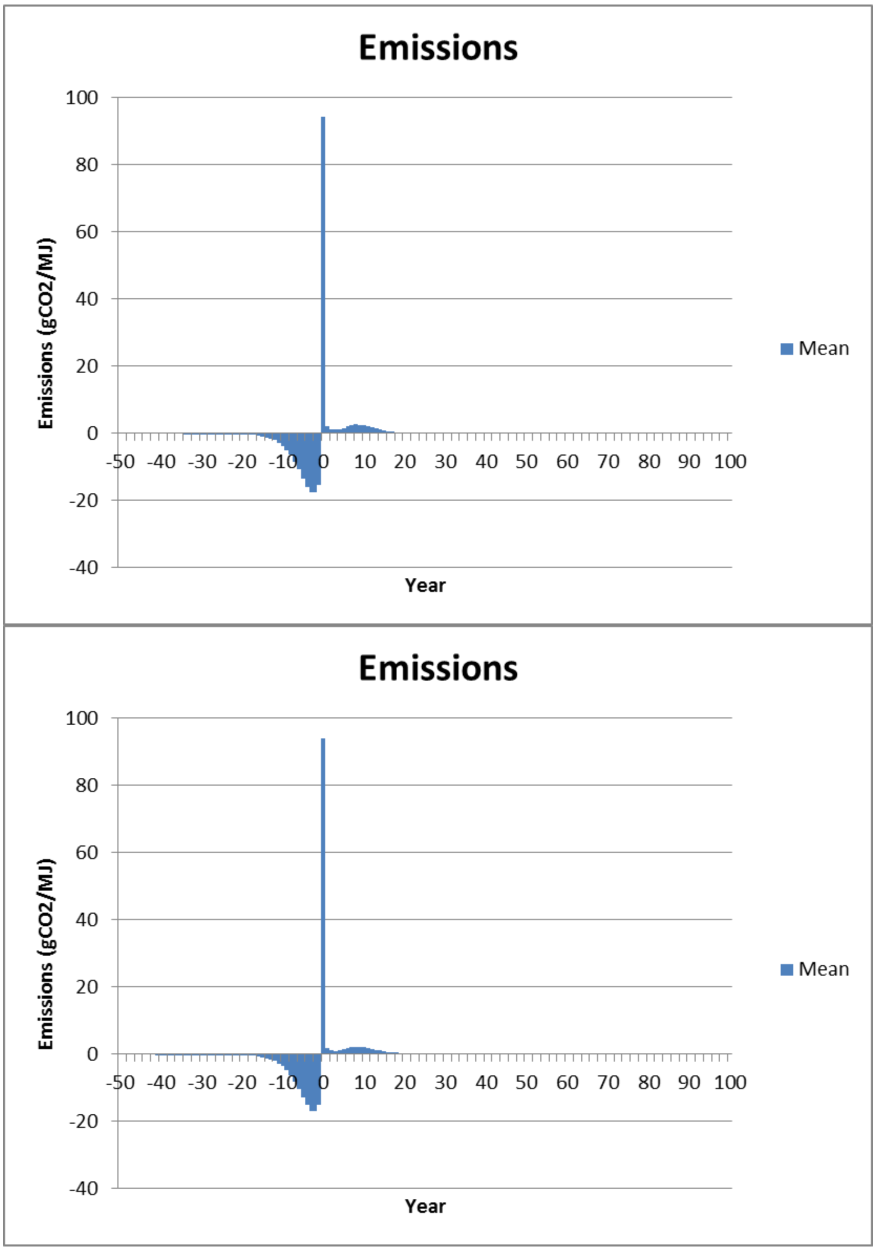


Figure C-1: Emissions from short rotation forestry on marginal lands (boreal biome).

Left image is for on marginal lands. Right image is for grassland. There is a slight net removal on the marginal land due to an increase in soil organic carbon

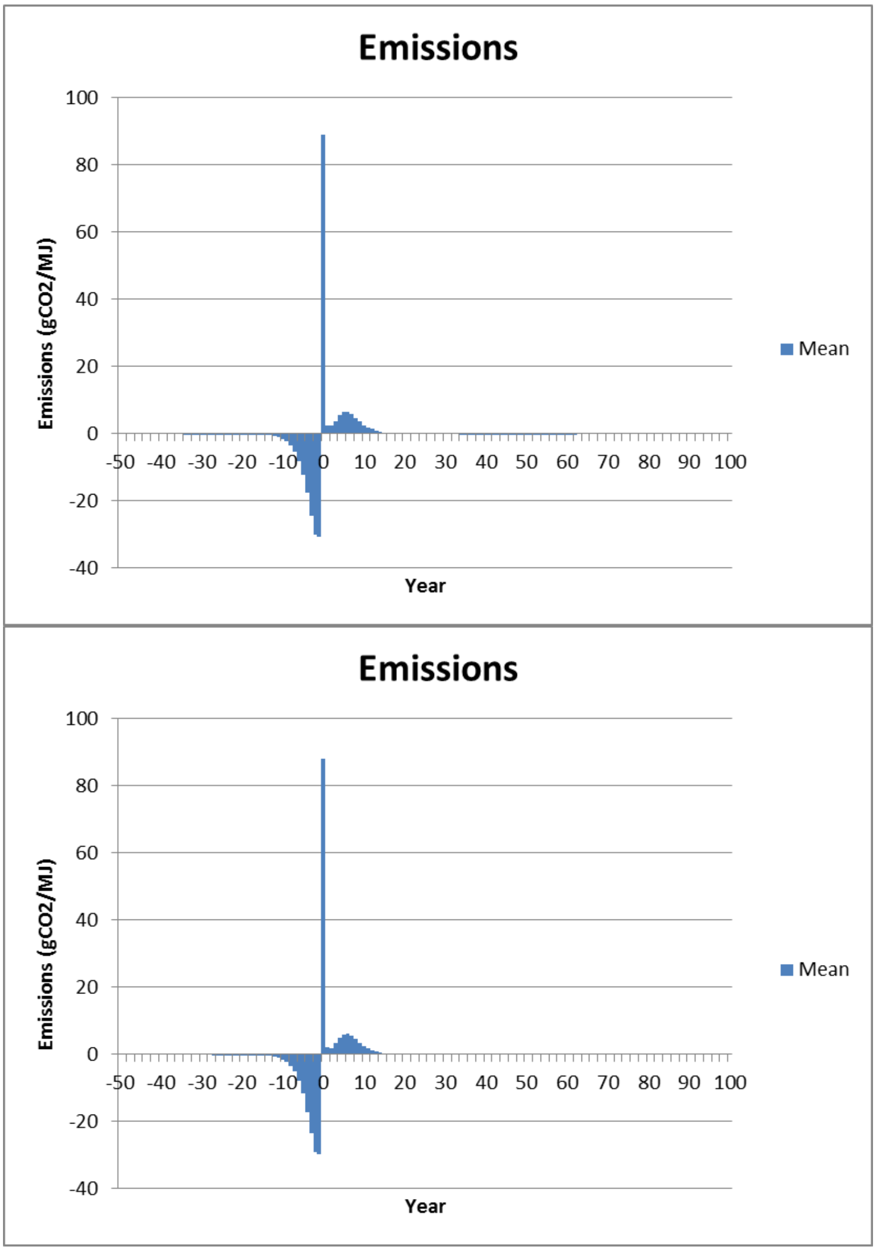
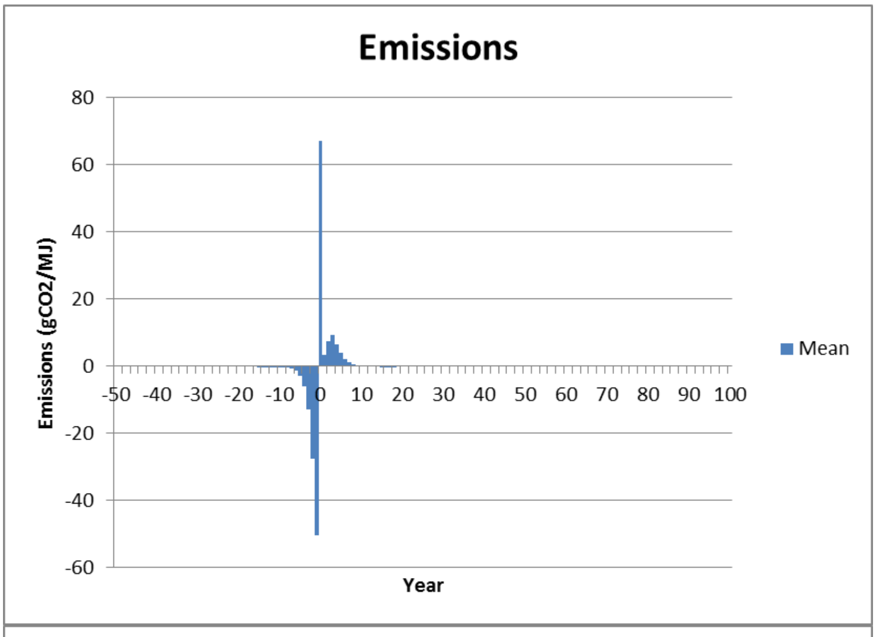


Figure C-2: *Emissions from short rotation forestry on marginal lands (temperate biome). Left image is for marginal lands. Right image is for grassland.*

Left image is for marginal lands. Right image is for grassland. There is a slight net removal on the marginal land due to an increase in soil organic carbon



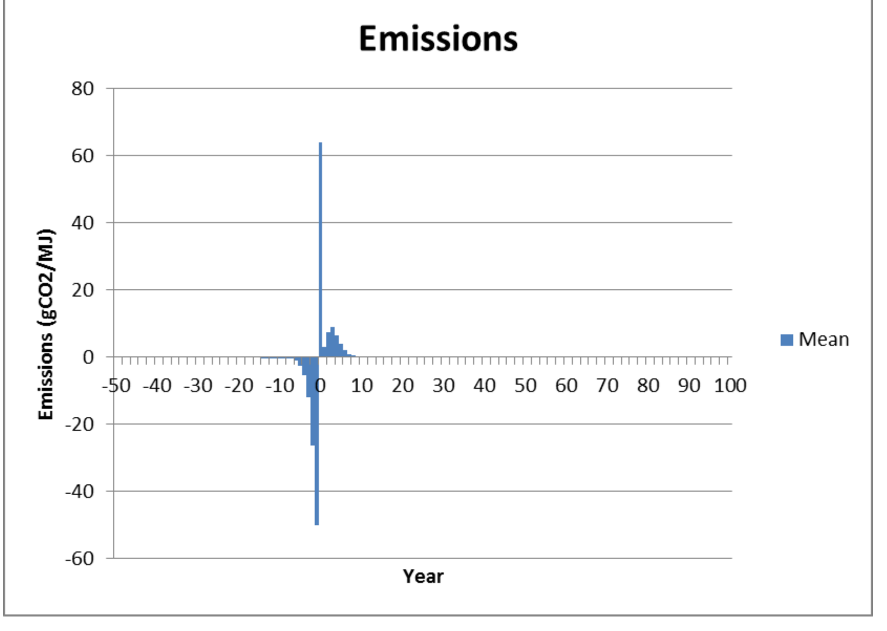


Figure C-3: Emissions from short rotation forestry on marginal lands (tropical biome)

Left image is for marginal lands. Right image is for grassland. There is a slight net removal on the marginal land due to an increase in soil organic carbon.

Appendix D Emissions from the use of forest residues

By David Neil Bird

D.1 Description

D.1.1 Bioenergy system

In the bioenergy system it is assumed that the biomass that is used for bioenergy production is composed of branches, tops, and standing dead wood. The biomass is not “de-barked”. For this reason, the net calorific value used for the conversion of mass to energy must be specifically for forest residues and not for clean wood.

D.1.2 Reference system

If the reference system, it is assumed that the biomass is left on site where it decays following simple exponential decay.

D.2 Model

Therefore the emissions from the use of residues are given by

$$Emission(t) = [B_o\delta(t) - kB_o e^{-kt}] * \frac{44}{12} * 0.5$$

Where the first term is the emission from burning the biomass, B_o[36], and the second term is the displaced emissions from the decay of the biomass (hence the negative sign). The 0.5 is the carbon fraction of dry biomass and the 44/12 is used to convert mass C into mass CO_2.

The emissions in the first year are given by

$$Emission_1 = [B_o e^{-k}] * \frac{44}{12} * 0.5$$

Emissions in year 2 are given by:

$$Emission_2 = Emissions_1(e^{-k} - 1)$$

Emissions in all other years are

$$Emission_j = Emissions_{j-1} e^{-k}$$

The decay constant has been shown to be a function of temperature and rainfall[37]. Moore et al (1999) established a linear relationship between the amount of biomass remaining after three years and rainfall and temperature.

$$\frac{B_3}{B_o} = 0.887 - 0.0163(T - 2.4) - 0.00015(P - 778)$$

Therefore

$$k = -\frac{1}{3}\ln(\frac{B_3}{B_o})$$

However, as this relationship was derived for Canadian forests, another relationship derived by Brovkin et al (2012)[38] is used. In this paper they suggest

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[36] δ(t) is the dirac function. It equals 1 when t = 0, and = 0 when t ≠ 0

[37] Moore et al. (1999). Litter decomposition rates in Canadian forests. Global Change Biology 5, 75-82

$$k_{wood} = k_{wood10} Q_{10}^{(\frac{T-10}{10})}$$

And have studied a global compilation of reports to attain values for k_{wood10} and Q_{10}. They suggest:

Table D-1: Parameters for the estimation of decay-rate

Biome	k_{wood10}	Q_{10}
Trop. Broadleaved evergreen	0.039	2.75
Trop. Broadleaved raingreen	0.039	2.75
Temp. needleleaved evergreen	0.041	1.97
Temp. broadleaved	0.104	1.37
Boreal needleleaved	0.041	1.97
Boreal broadleaved	0.104	1.37

For the purpose of this study, it is assumed that temperate forests are predominantly broadleaved and boreal forests are predominantly needleleaved.

Finally, one can express B_o in terms of emissions per MJ of energy through the net calorific value (NCV) since NCV = MJ/kg
Therefore

$$Eintensity_1 = \frac{e^{-k}}{NCV} * \frac{44}{12} * 0.5$$
$$Eintensity_2 = Eintensity_1 \left(e^{-k} - 1\right)$$
$$Eintensity_j = Eintensity_{j-1} e^{-k}$$

Where *Eintensity* has the units kg CO_2/MJ

D.3 Data

	Boreal	Temperate	Tropical
Average temperature (deg C)	-5 – 5	5 – 16	16 – 30
Annual rainfall (mm)	200 – 2000	500 – 1500	500 – 16000
Net calorific value	18.5 – 20.7[39] [40]	19.0 – 20.0[41]	17.2 – 17.8[44]

[38] Brovkin V, van Bodegom PM, Kleinen T, Wirth C, Conrwell WK, Cornelissen JHC and Kattge J. 2012. Plant-driven variation in deomposition rates improves projections of global litter sotck distribution. Biogeosciences 9, 565-576

[39] European Bioenergy Networks (EUBIONET). 2003. Biomass Co-Firing - An Efficient Way To Reduce Greenhouse Gas Emissions. http://ec.europa.eu/energy/renewables/studies/doc/bioenergy/2003_cofiring_eu_bionet.pdf

[40] Oak Ridge National Laboratory. 2011. Heat Content Ranges for Various Biomass Fuels. http://cta.ornl.gov/bedb/index.shtml. Accessed 17 June 2013

	Boreal	Temperate	Tropical
(MJ/kg)		SRC: 17.3 – 19.7[42] [43]	Eucalyptus 19.0 – 19.6

D.4 Results

Given that the exact climate conditions at the location where the residues are collected and their net calorific value is not known. The emission profile is estimated using the mean of a Monte Carlo simulation using 500 different locations. The provided spreadsheet calculates the mean and standard deviation of emissions profiles in the three biomes. The results are shown in the following diagrams.

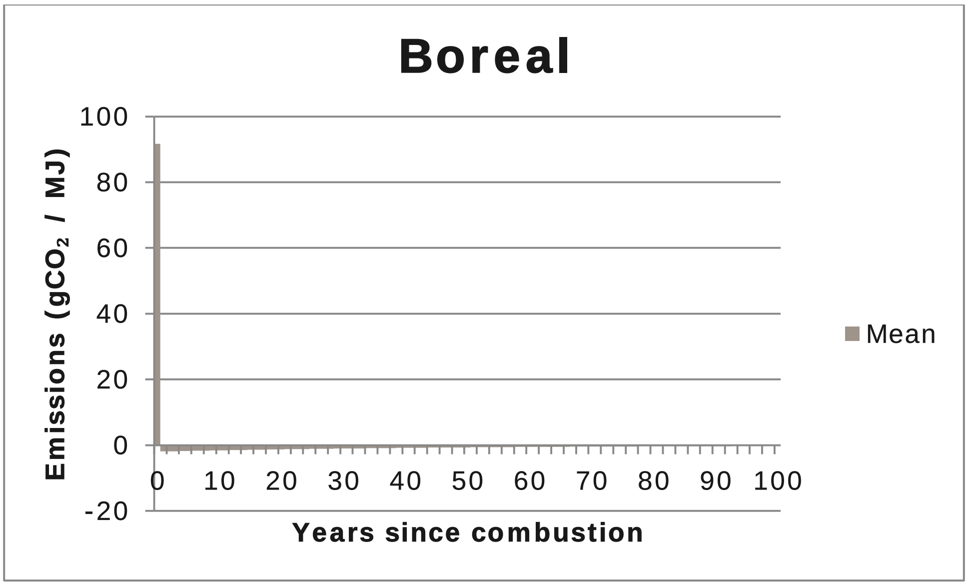

Figure D-1: Emissions from use of boreal residues

[41] Gravalos I, Kateris D, Xyradakis P, Gialamas T et al. 2010. A Study On Calorific Energy Values Of Biomass Residue Pellets For Heating Purposes. FORMEC 2010. Forest Engineering: Meeting the Needs of the Society and the Environment. July 11 – 14, 2010, Padova – Italy
[44] Thek G, Obernberger I. 2010. The Pellet Handbook. Earthscan Ltd. London. 549 pp.
[42] McKendry P. 2002. Energy production from biomass (part 1): overview of biomass. Bioresource Technology 83 (2002) 37–46
[43] OMAFRA. 2001. Biomass Burn Characteristics Factsheet. Ontario Ministry of Agriculture and Food. http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm#3. Accessed 17 June 2013

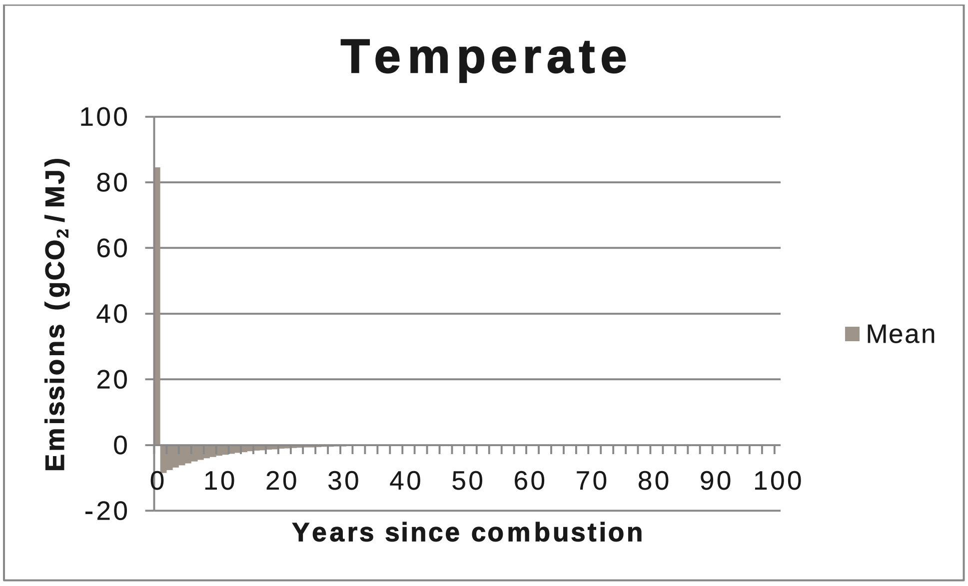

Figure D-2: Emissions from the use of temperate residues

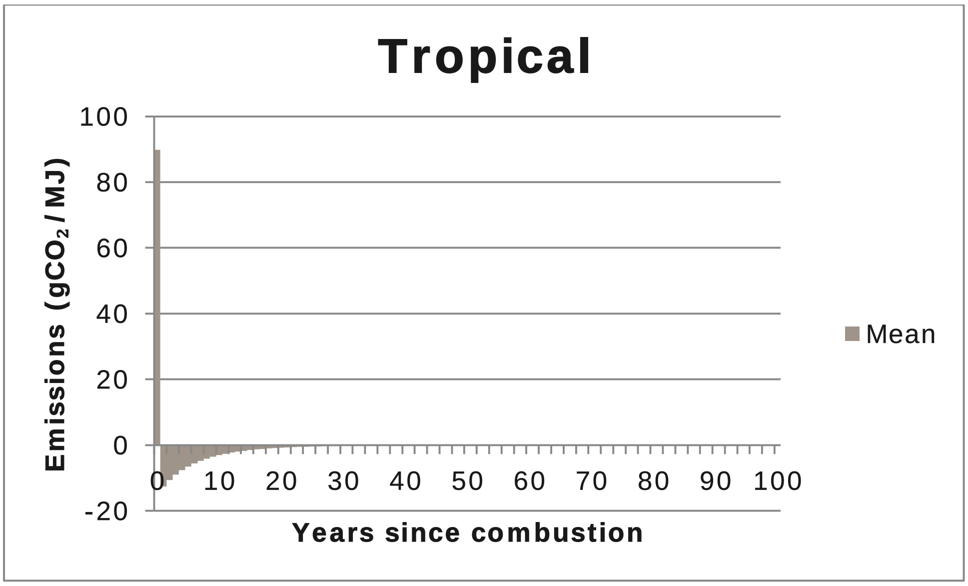

Figure D-3: Emissions from the use of tropical residues

Appendix E Emissions from converting savannah bioenergy plantations

By David Neil Bird

E.1 Description

Reference system

If the reference system, I assume that the savannah[45] is in dynamic equilibrium.

E.2 Model

The model is a combination of the plantation model with the savannah model. However additional information on the ratio of biomass in the plantation to savannah is necessary. This has a wide range of values because it depends on the rotation length plantation. Different net calorific values are applied to the biomass from the primary and plantation forests

E.3 Data

	Plantation	Savannah
Above ground biomass (t d.m. / ha)	50-200[46]	50 – 200[47] Dry forests 133 ± 76[48] Woodlands: 62 ± 28 Savannah: 18 ± 8
Below ground biomass (t d.m. / ha)	15 – 110	15 – 110
Soil organic carbon (tC/ha)	31 – 38[47]	Woodlands: 11.8 ± 5.34 Grassy savannah: 5.65 ± 4.60 Occasionally as high as 115 tC/ha[49]
Total (tC/ha)	**60 - 193**	**36 - 270**
Total (tC/t above ground plantation)	**0.97 - 1.2** Middle value: 1.1	**0.18 – 5.4** Middle value: 3.6

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45 You'll see from the table that there is a large range of values

46 Tiarks A, Nambiar EKS, and Cossalter C. 1998. Site Management and Productivity in Tropical Forest Plantations. CIFOR: Occasional paper no. 16

47 IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan

48 Scholes RJ and Hall DO. 1996. The Carbon Budget of Tropical Savannas, Woodlands and Grasslands http://www.scopenvironment.org/downloadpubs/scope56/Chapter04.html. Accessed 21 October 2013

49 Chen X, Hutley L, Eamus D. 2003. Carbon balance of a tropical savanna of northern Australia. Oecologia 137:405–416

Note: ranges of 30 tC/ha are equal to 0.1 – 1.0 kg biomass/kg harvested. This requires a fine-to-coarse root ratio of as high a 1. For this, I would use a ratio of 1.0 ± 0.5. A more realistic value of between this and typical forests is 0.58 ± 0.5

High carbon savannah is modelled as 127 ton C/ha as total AGB, BGB and soil C, whereas low C is half of that. Plantation C-stock at max value is modelled as 70 ton C/ha.

Appendix F iLUC model

F.1 Approach

A deterministic approach to modelling iLUC, as e.g. described in Schmidt (2008), was used. This section details how emissions were estimated for land expansion (iLUC) and intensification.

F.2 Plantation on grassland

F.2.1 Establishing the model and overall figures needed

Establishing a woody plantation on grassland involves that grassland is displaced.

The starting point for the analysis was to consider that the grass was used as feed for grazing animals. In terms of nutritional value, grass supplies essentially carbohydrates and protein (66% and 20% of the DM, respectively, the rest being ashes and fat; Møller et al. (2000)). For the purpose of this study, it was considered that grass DM supplies 77% carbohydrates and 23% protein (values of Møller, normalized to carbohydrates and protein only).

As a consequence of a new plantation on grassland, the nutritional value that was provided by the grass now has to be supplied by the marginal source of protein and carbohydrates. This is illustrated in Figure F-1 (example for tropical biome), where the boundary conditions considered are shown.

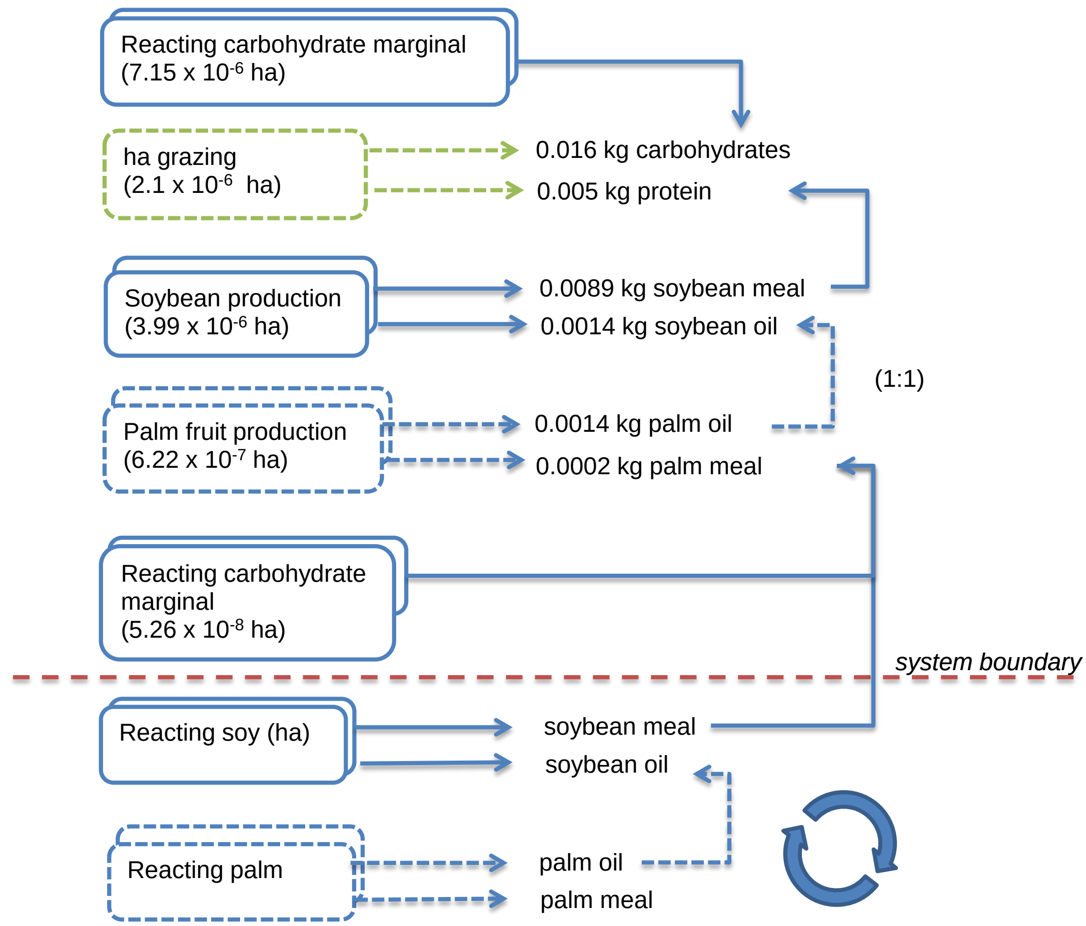

Figure F-1: *Process flow diagram considered for modelling the consequences of establishing a plantation on grassland. The flows are expressed per MJ wood and represent the case of a plantation on tropical biome, for the "high" interval (see text). Full lines represent induced flows and dotted lines avoided flows. The boxes on the second plan represent intensification. The system boundary considered here excludes, for simplicity, the protein share of the palm fruit meal, which would involve a continuous soybean loop. It is therefore assumed that considering this would yield no further information that is significant for decision making. For more details on the soybean loop illustrated herein, see Dalgaard et al. (2008).*

The first step to this analysis is thus to determine how much carbohydrates and protein are displaced, in each biome. This can be done on the basis of the information shown in Table F-1, and the above-mentioned proportions of carbohydrates and protein in grass DM.

Table F-1. LHV and yield considered for the woody plantations as well as the yield of the displaced grass, for each biome

Biome	LHV, wood from plantation (1) (MJ / kg DM)	Yield, wood from plantation (t DM / ha*y)	Yield of grass(5) (t DM / ha*y)
Tropical	19.9	22.8(2)	1.7 – 10.9
Boreal	19.8	4.5(3)	1.3 – 3.0
Temperate	19.5	12.0(4)	1.3 – 4.2

(1) Same data as used for the dLUC model, Appendixes A-E
(2) Considering a mean annual increment of 25 t ha^{-1} y^{-1} (Stape et al., 2010), and a DM content of 91% (Phyllis database; ecn.nl/phyllis2)
(3) Taken as an average of SRC and willow in Finland and Sweden, from Don et al. (2012)
(4) Don et al. (2012; average for Europe); Sannigrahi et al. (2010)
(5) IPCC (2006), page 27, Table 6.4.

Of course, not all of the grass that is generated in a given biome would necessarily be used for grazing, depending on the stocking density, as well as the grazing losses. For the latter, losses of ca. 15% appears as a realistic figure[50]. Therefore, an interval of grass displacement of 50 (low displacement) to 85% (high displacement) has been considered. The upper range is to be seen as a situation with grazing losses only, while the lower range would reflect a situation with a more extensive stocking density. Considering an average consumption of 16 kg DM ha^{-1} d^{-1} for cattle[1], it appears that rather low stocking densities are necessary if the yields presented in Table F-1 are to support grazing (i.e. below 1 cow per ha; except for upper range of the tropical biome where a density slightly above 1.5 cow per ha is obtained). On this basis, a “low” grass displacement below 50% appears difficult to justify, so the lower displacement interval was limited to 50%. These “low” and “high” ranges were used for all biomes, as shown in Table F-2.

Table F-2: Proportion of the grass that is really displaced

	Tropical	Boreal	Temperate
HIGH DISPLACEMENT (%)	85%	85%	85%
LOW DISPLACEMENT (%)	50%	50%	50%

The resulting amount of carbohydrates and protein displaced in all biome is shown in Table F-3.

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[50] Personal communication with Dr. Heiko Georg, Johann Heinrich von Thunen-Institute (vTI), Federal Research Institute for Rural Areas, Forestry and Fisheries, Institute of Organic Farming. October 21st, 2013.

Table F-3: Amount of carbohydrates and protein displaced in all biome(1, 2)

Biome	kg carbohydrate/MJ wood		kg protein/MJ wood	
	HIGH DISPLACEMENT, HIGH GRASS YIELD	LOW DISPLACEMENT, LOW GRASS YIELD	HIGH DISPLACEMENT, HIGH GRASS YIELD	LOW DISPLACEMENT, LOW GRASS YIELD
Tropical	0.015719	0.001442	0.004756	0.000436
Boreal	0.022014	0.005611	0.006661	0.001698
Temperate	0.011722	0.002134	0.003547	0.000646

(1) Numbers are presented with many digits for the transparency of calculation only, but these are not to be seen as significant digits.

(2) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

Considering soybean meal as the marginal protein source (Schmidt, 2007) and a mix of maize, wheat and barley as the marginal carbohydrate source (Hamelin, 2013), the next step consists to determine the amount of soy meal (and co-produced soybean oil) and marginal cereals that are produced as a reaction to the amount of carbohydrates and protein no longer supplied by the grass (Table F-3). This is presented in Table F-4.

Table F-4: Amount of soybean meal, soybeal oil and marginal cereals produced as a reaction to the grass no longer supplied(1, 5)

Biome	Soybean meal(2)		Soybean oil(3)		Cereals(4)	
	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield
tropical (kg DM/ MJ wood)	0.008857048	0.000812573	0.0014	0.000128266	0.018758182	0.001720934
boreal (kg DM/ MJ wood)	0.012403588	0.003161699	0.001957922	0.000499078	0.026269334	0.006696105
temperate (kg DM/ MJ wood)	0.006604903	0.001202573	0.001042592	0.000189828	0.013988404	0.002546908

(1) Numbers are presented with many digits for the transparency of calculation only, but these are not to be seen as significant digits; displ. stands for displacement
(2) 0.54 kg protein per kg soybean meal DM (Møller et al., 2000)
(3) 0.16 kg soybean oil per kg soybean meal (Dalgaard et al., 2008)
(4) 0.84 kg carbohydrate per kg marginal cereal DM (average of spring barley, winter barley, maize and wheat in Møller et al., 2000)

(5) Results can be normalized by ha through multiplying by (1 / 2.21 x 10-6) (tropical biome); (1 / 1.12 x 10-5) (boreal biome) and (4.28 x 10-5) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

Based on an analysis of the historical data available in FAOstat, it appears that soybean meal from Argentina and Brazil is the one most likely to react to an increase in demand for soy (Figure F-2).

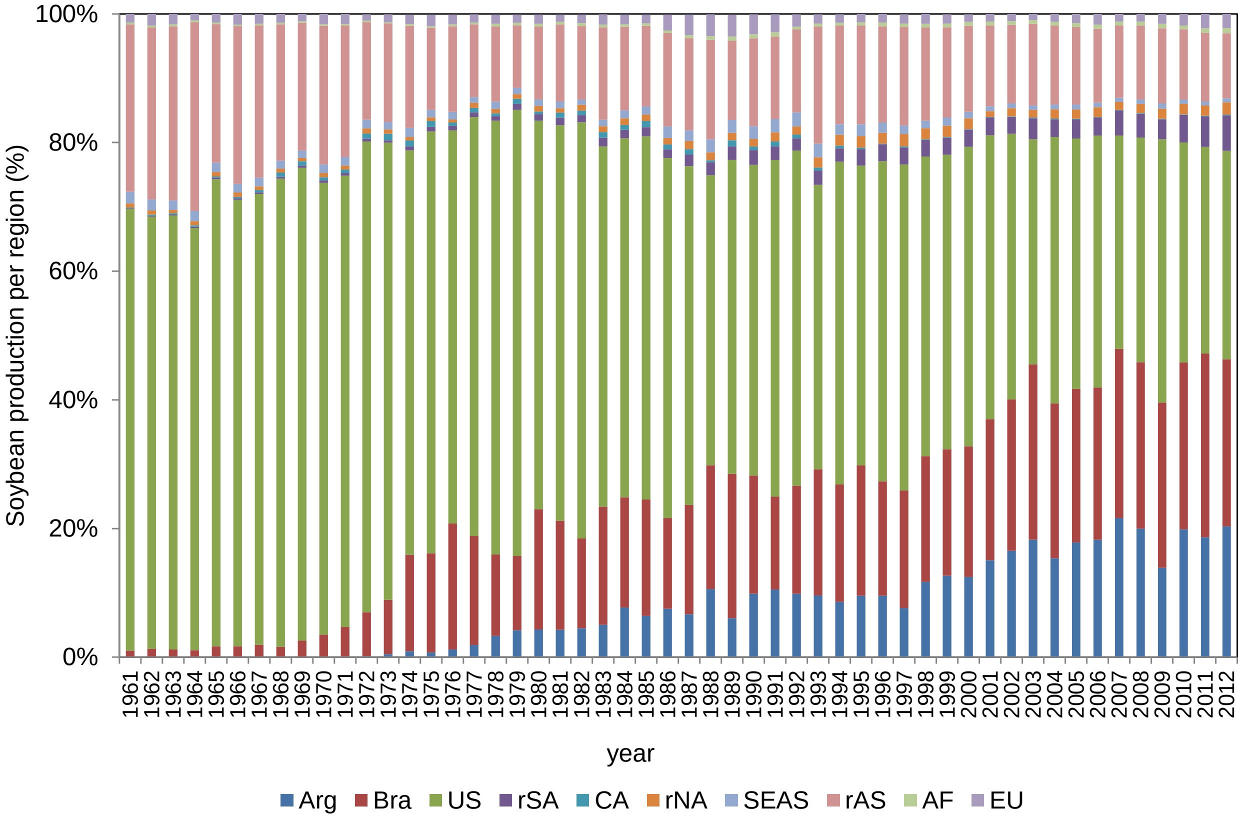

Figure F-2: *Soybean production per region (1961-2012). Data extracted from FAOstat. Arg: Argentina; Bra: Brazil; US: United States; rSA: rest of South America; CA: central America; rNA: rest of North America; SEAS: South-east Asia; rAS: rest of Asia; AF: Africa; EU: Europe.*

Considering, on the basis of Kløverpris (2008), that an increased demand for carbohydrates would lead to land expansion in Sub-Saharan Africa (24%)[51], European Union (EU-15) (24%), Brazil (14%), Former Soviet Union[52] (12%), Australia (9%), Canada (7%), South America (6%)[53] and United States (4%), and considering the major carbohydrate crops (i.e. wheat, maize, rice, barley, sorghum, millet, rye and oats) as well as the regional production volumes of these crops in the last 10 years, a marginal “reacting carbohydrate crop mix” can be derived. This procedure is described in Hamelin (2013), and the results are shown in Table F-5.

Table F-5: *Marginal reacting carbohydrate crop mix*

Crop Country	Maize Botswana	maize Brazil	maize Argentina	wheat France	wheat Kazakhstan	wheat Australia	wheat USA	barley Canada
% in the mix	22%	13%	5%	22%	11%	9%	4%	6%
kg DM/kg FM[(1)]	86%	86%	86%	85%	85%	85%	85%	85%

(1) Møller et al. (2000)

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[51] See Hamelin (2013) for details on how these proportions were derived from the results of Kløverpris (2008).

[52] Excluding Baltic States

[53] Excluding Brazil and Peru

The data for "cereals" in Table F-4 can thus be detailed according to the information presented in Table F-5. This is presented in Table F-6.

Part of the amount of crops shown in Table F-6 will be provided by land expansion (iLUC), and part will be provided by intensification. In this study, a "low" and "high" range was considered for the land expansion share, as shown in Table F-7. These ranges are based on recent studies indicating that the share of the intensification response is likely to be of at least 15% (Kløverpris, 2008; Marelli et al., 2011) and may potentially be as high as 70% (Marelli et al., 2011).

Table F-6: Land conversion, low and high iLUC[1, 2]

	Tropical		Boreal		Temperate	
	high iLUC, low intensif	low iLUC, high intensif	high iLUC, low intensif	low iLUC, high intensif	high iLUC, low intensif	low iLUC, high intensif
Portion supplied by land expansion	85%	30%	85%	30%	85%	30%
Proportion supplied by intensification	15%	70%	15%	70%	15%	70%

(1) Intensif stands for intensification

(2) For soy, 85% land expansion is considered for both "high" and "low" iLUC, as the production cannot be increased much by an increased N supply from mineral fertilizers (soy being a N-fixing crop).

The next step in calculating the area of land expanded and the amount of crop (i.e. soy and marginal cereals) produced by intensification is to determine the yield of these crops. In Table F-8, both the "historical" yield (2001-2010) and the projected yield (2025; from FAPRI outlook[54]) are presented for these crops. Based on Laborde (2011), a ratio of 0.75 between the yield on new cropland and the average yield is considered, and applied to the FAPRI values. The yield considered for this study where the highest value among the "historical yield" and the "FAPRI-adjusted" yield. Of course, it is here intended to use values that would best represent the yield of "the future". When "historical yield" are used (e.g. for soy in Argentina/Brazil), it is thus to be interpreted that it is considered that significant increases in yield for that crop (in that specific region) are unlikely.

[54] http://www.fapri.iastate.edu/tools/outlook.aspx

Table F-7: Amount of soy and marginal cereals produced as a reaction to the grass no longer supplied (kg DM / MJ wood)[(2)]

Biome	Soy[(1)] (Latin America)		maize Botswana		maize Brazil		maize argentina		wheat France		wheat Kazakhstan		wheat Australia		wheat USA		Barley Canada	
	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield	High displ.; High grass yield	Low displ.; Low grass yield
Tropi-cal	1.2 X 10^{-2}	1.1 X 10^{-3}	4.8 X 10^{-3}	4.4 X 10^{-4}	2.8 X 10^{-3}	2.6 X 10^{-4}	1.1 X 10^{-3}	1.0 X 10^{-4}	4.9 X 10^{-3}	4.5 X 10^{-4}	2.4 X 10^{-3}	2.2 X 10^{-4}	2.0 X 10^{-3}	1.8 X 10^{-4}	8.8 X 10^{-4}	8.1 X 10^{-5}	1.3 X 10^{-3}	1.2 X 10^{-4}
boreal	1.7 X 10^{-2}	4.4 X 10^{-3}	6.7 X 10^{-3}	1.7 X 10^{-3}	4.0 X 10^{-3}	1.0 X 10^{-3}	1.5 X 10^{-3}	3.9 X 10^{-4}	6.8 X 10^{-3}	1.7 X 10^{-3}	3.4 X 10^{-3}	8.7 X 10^{-4}	2.8 X 10^{-3}	7.1 X 10^{-4}	1.2 X 10^{-3}	3.2 X 10^{-4}	1.9 X 10^{-3}	4.7 X 10^{-4}
Tempe-rate	9.2 X 10^{-3}	1.7 X 10^{-3}	3.6 X 10^{-3}	6.5 X 10^{-4}	2.1 X 10^{-3}	3.8 X 10^{-4}	8.1 X 10^{-4}	1.5 X 10^{-4}	3.6 X 10^{-3}	6.6 X 10^{-4}	1.8 X 10^{-3}	3.3 X 10^{-4}	1.5 X 10^{-3}	2.7 X 10^{-4}	6.6 X 10^{-4}	1.2 X 10^{-4}	9.9 X 10^{-4}	1.8 X 10^{-4}

(1) Considering 0.87 kg DM per kg FM (Møller et al., 2000), and 0.83 kg soymeal per kg soybean (Dalgaard et al., 2008).

(2) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

Table F-8: Yield of crops considered in this study (t FM per ha per y)

	soy (S. America)	Maize Botswana	maize Brazil	Maize Argentina	wheat France	wheat Kazakhstan	wheat Australia	wheat USA	barley Canada	palm fruit Malaysia / Indonesia
Historical (2001-2010)[(1)]	2.6[(4)]	0.22	3.59	6.52	6.95	1.04	1.55	2.82	2.96	18.98
2025 (FAPRI)[(2)]	3.21[(4)]	1.76[(5)]	5	8.35	5.69[(6)]	2.86[(7)]	2.09	3.16	3.87	34.1[(8)]
FAPRI-adjusted[(3)]	2.40	1.32	3.75	6.26	4.27	2.15	1.57	2.37	2.90	25.58
This study	2.63	1.32	3.75	6.52	6.95	2.15	1.57	2.82	2.96	25.58

(1) FAOstat (faostat.fao.org)
(2) http://www.fapri.iastate.edu/tools/outlook.aspx
(3) Based on Laborde (2011), see text.
(4) Average for Argentina and Brazil.
(5) Figure for "Africa, other"
(6) Figure for European Union
(7) Taken as the average for Ukraine and Russia
(8) Taken from Laborde (2011; Table 2, p.25), as no data for this in FAPRI.

F.2.2 Land expansion/intensification resulting from the protein share of the grass displaced (soy in South America)

Land expanded and amounts from intensification

Based on the figures presented in Tables F- 6-8, the amount of land expanded can be calculated. Results are shown in Table F-9.

*Table F-9: Land expansion for the extra soy needed, in Argentina/Brazil (m^2*y/MJ wood)[1, 2]*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield
Land expanded	0.040	0.004	0.056	0.014	0.030	0.005

(1) Only a "high" land expansion (or iLUC) is considered for soy, see text.

(2) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

From this, the amount of soy that has to be provided by intensification can be calculated as the missing amount (Table F-10).

Table F-10: Amount of soy supplied from intensification (kg FM/MJ wood)[1]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield
Soy supplied by intensification	0.00185	0.00017	0.00259	0.00066	0.00138	0.00025

(1) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to land expansion

In order to quantify the releases of C due to the land conversion presented in Table F-9, the soil and vegetation carbon data from the Woods Hole Research Centre, as published in the “supporting online material” of Searchinger et al. (2008) was used. From this database, the amount of C in the soil and vegetation of all affected land types in the region “Latin America” could be extracted. This allowed the calculation of the CO_2 emitted during land conversion, where the following has been considered:

› 25% of the C in the soil is released as CO_2 for all types of land use conversion, except when forests are converted to grassland, where 0% is released;

› 100% of the C in vegetation is released as CO_2 for all forest types as well as for tropical grassland conversions[55], while 0% is released for the remaining biome types (e.g. shrub land, non-tropical grassland, chaparral).

The results of this calculation are shown in Table F-11.

[55] This is to be seen as a simplifying assumption (personal communication with Miguel Brandão, ILCA, January 2013, and with David Laborde, IFPRI, February 2013). In fact, from the data of Earles et al. (2012), whom detailed, for 169 countries, the fate of the above-ground residues when forest are cleared, it can be seen that even after 100 years, it is not exactly 100% of the C that is returned to the atmosphere, although the gap is negligible in most cases.

Table F-11: CO_2 releases from land expansion in Latin America[3]

					Tropical		Boreal		Temperate	
Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)					25% of soil C; 100% of vegetation C[1]		25% of soil C; 100% of vegetation C[1]		25% of soil C; 100% of vegetation C[1]	
Biomes converted	**% conversion**	Region	C in vegetation (ton/ha)	C in soil (ton/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
					High ILUC	Low ILUC	High ILUC	Low ILUC	High ILUC	Low ILUC
Tropical evergreen forest	3%	LA[2]	200	98	93.78	8.60	131.33	33.48	69.94	12.73
Tropical seasonal forest	22%	LA	140	98	525.71	48.23	736.22	187.66	392.04	71.38
Tropical open forest	47%	LA	55	69	495.00	45.41	693.21	176.70	369.13	67.21
Temperate evergreen forest	3%	LA	168	134	84.17	7.72	117.88	30.05	62.77	11.43
Temperate seasonal forest	1%	LA	100	134	16.73	1.53	23.43	5.97	12.47	2.27
Grassland	24%	LA	10	42	71.51	6.56	100.14	25.53	53.33	9.71
Desert	1%	LA	6	58	2.57	0.24	3.60	0.92	1.92	0.35
TOTAL CO_2 (g CO_2*y/MJ)					**1289.48**	**118.30**	**1805.81**	**460.30**	**961.59**	**175.08**
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ)					**64.47**	**5.92**	**90.29**	**23.02**	**48.08**	**8.75**
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ)					**12.89**	**1.18**	**18.06**	**4.60**	**9.62**	**1.75**

(1) Except exceptions, see text.
(2) LA: Latin America (selected as the closest region in the Woodshole database to represent Argentina and Brazil)
(3) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to intensification

The emissions induced from input-driven intensification were calculated as described in (Schmidt, 2007), where yield responses to an increased level of N-fertilizer application of 5% are presented, for various crops in various regions of the world (Tables 18.2 to 18.4).

As of now, the inventory data of Schmidt (2007) for intensified crop production are used (Table F-12). It is however foreseen to adjust these data, among other the inventory of ammonium nitrate based on an updated inventory for the N_2O emissions related to nitric acid production[56]. The yield data and yield responses will also be adjusted in function of the yields used in this study (Table F-8).

Table F-12: Inventory data considered for intensified crop production (fertilizer-driven), based on Schmidt (2007; Tables 18.6, 18.7, 18.9)

	Ammonium nitrate, as N kg / ha*y	NH_3 kg / ha*y	N_2O kg / ha*y	NO_3 kg / ha*y	CO_2 kg / ha*y	Ammonium sulfate (as N) kg / ha*y	urea (as N) kg / ha*y	yield kg fm/ha*y
Barley, Canada, intensified(1)	70.4	7.8	2.4	60				2858
Soybean, Brazil, intensified	0	0	4.9	0				3341
Palm, Indonesia/Malaysia, intensified (FFB)		18.9	10.4	375	1500	80.3	29.7	19199

(1) Used as a representative for all intensified cereals

Based on Table F-12 and Table F- 10, the emissions induced from the intensification (input-driven) response of soybean can be calculated. Results are presented in Table F-13.

[56] 0.00248 kg N_2O per kg nitric acid based on an average of plants applying catalytic N_2O decomposition in the oxidation reactor (European Commission, 2007, Table 3.12) (instead of the figure of 0.00839 kg N_2O per kg nitric acid presented in the Ecoinvent v.2.2 database). The BAT level for new plants is however stated to a much lower level, i.e. 0.00012 to 0.00060 kg N_2O per kg nitric acid.

Table: F-13: Emissions induced from the intensification response of soybean (multi-cropping), in kg / MJ wood [(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield
NH_3	0	0	0	0	0	0
N_2O	2.71×10^{-6}	2.49×10^{-7}	3.80×10^{-6}	9.67×10^{-7}	2.02×10^{-6}	3.68×10^{-7}
NO_3	0	0	0	0	0	0
CO_2	0	0	0	0	0	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.2.1 Land expansion/intensification resulting from the carbohydrates share of the grass displaced

Land expanded and amounts from intensification

Based on the figures presented in Tables F-6-8, the amount of land expanded can be calculated. Results are shown in Table F-14.

*Table F-14: Land expansion for the extra cereals needed (m^2*y/MJ wood)[(1)]*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Maize, Botswana	0.0309	0.0010	0.0433	0.0039	0.0230	0.0015
Maize, Brazil	0.0064	0.0002	0.0090	0.0008	0.0048	0.0003
Maize, Argentina	0.0014	0.0000	0.0020	0.0002	0.0011	0.0001
Wheat, France	0.0059	0.0002	0.0083	0.0007	0.0044	0.0003
Wheat, Kazakhstan	0.0096	0.0003	0.0135	0.0012	0.0072	0.0005
Wheat, Australia	0.0108	0.0003	0.0151	0.0014	0.0080	0.0005
Wheat, USA	0.0027	0.0001	0.0037	0.0003	0.0020	0.0001
Barley, Canada	0.0038	0.0001	0.0053	0.0005	0.0028	0.0002

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area

of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

From this, the amount of cereals that has to be provided by intensification can be calculated as the missing amount (Table F-15).

Table F-15: Amount of cereals supplied from intensification (kg FM/MJ wood)(1)

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Maize, Botswana	0.00072	0	0.00101	0.00120	0.00054	0.00046
Maize, Brazil	0.00043	0	0.00060	0.00071	0.00032	0.00027
Maize, Argentina	0.00016	0	0.00023	0.00027	0.00012	0.00010
Wheat, France	0.00073	0	0.00102	0.00121	0.00054	0.00046
Wheat, Kazakhstan	0.00036	0	0.00051	0.00061	0.00027	0.00023
Wheat, Australia	0.00030	0	0.00042	0.00050	0.00022	0.00019
Wheat, USA	0.00013	0	0.00019	0.00022	0.00010	0.00008
Barley, Canada	0.00020	0	0.00028	0.00033	0.00015	0.00013
Total	0.00303	0	0.00424	0.00505	0.00226	0.00192

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to land expansion

GHG from land expansion were calculated as described in 2.2.2, and on the basis of the regional repartition presented in Table F-5. The biome converted in each region was selected on the basis of the results from Kløverpris (2008). Results are shown in Table F-16.

Table F-16: CO_2 releases from land due to cereals (carbohydrates displaced from grass)[(3)]

From Kløverpris (2008)					Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)		Tropical 25% of soil C; 100% of vegetation C[(1)]		Boreal 25% of soil C; 100% of vegetation C[(1)]		Temperate 25% of soil C; 100% of vegetation C[(1)]	
Biomes converted	**Reacting crop**	Region [(2)]	Share of biome	Final share	C in vegetation (ton/ha)	C in soil (ton/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
							High	Low	High	Low	High	Low
Savanna (taken as shrub land)	maize	xss	50%	12.0%	4.6	30	12.79	0.41	17.91	1.61	9.54	0.61
African tropical evergreen forest (taken as tropical rain forest)	maize	xss	50%	12.0%	127	190	297.00	9.62	415.93	37.42	221.48	14.23
Tropical evergreen forest	maize	bra	100%	14.0%	200	98	446.56	14.46	625.37	56.26	333.01	21.40
Grassland/steppe (taken as grassland)	maize	xla	50%	3.00%	10	42	4.48	0.14	6.27	0.56	3.34	0.21
Tropical evergreen forest	maize	xla	50%	3.00%	200	98	95.69	3.10	134.01	12.06	71.36	4.59
Temperate evergreen forest	wheat	xeu15	24%	5.76%	160	134	118.47	3.84	165.90	14.93	88.34	5.68
Temperate deciduous forest	wheat	xeu15	24%	5.76%	120	134	93.98	3.04	131.61	11.84	70.08	4.50
Dense shrubland (taken as temperate grassland)	wheat	xeu15	52%	12.48%	7	189	62.68	2.03	87.77	7.90	46.74	3.00
Grassland/steppe (taken as temperate grassland)	wheat	xsu	100%	12.00%	10	189	60.27	1.95	84.40	7.59	44.94	2.89
Savanna (taken as tropical grassland)	wheat	aus	100%	9.00%	18	42	27.26	0.88	38.18	3.43	20.33	1.31
Open shrubland (talen as chaparral)	wheat	usa	100%	4.00%	40	80	8.50	0.28	11.91	1.07	6.34	0.41
Boreal deciduous forest (taken as temperate deciduous forest)	barley	can	100%	7.00%	135	134	16.44	0.53	23.03	2.07	12.26	0.79
TOTAL CO_2 (g CO_2*y/MJ wood)							**1244.117**	**40.284**	**1742.286**	**156.745**	**927.766**	**59.619**
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ wood)							**62.206**	**2.014**	**87.114**	**7.837**	**46.388**	**2.981**
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ wood)							**12.441**	**0.403**	**17.423**	**1.567**	**9.278**	**0.596**

(1) Except exceptions, see text.

(2) With xss: Sub-Saharan Africa, excluding Botswana, Lesotho, Namibia, South Africa and Swaziland; xeu15: EU-15, excluding Denmark; bra: Brazil; xsu: Former Soviet Union, excluding the Baltic States; aus: Australia; can: Canada; xla: South America, excluding Brazil and Peru; usa: United States.

(3) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to intensification

The emissions induced from input-driven intensification were calculated as described in section F.2.2. Results are presented in Table F-17.

Table F-17. Emissions induced from the intensification response of cereals (displaced carbohydrates from grass; input-driven), in kg / MJ wood[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
NH_3	8.27×10^{-6}	0	1.16×10^{-5}	1.38×10^{-5}	6.17×10^{-6}	5.24×10^{-6}
N_2O	2.54×10^{-6}	0	3.56×10^{-6}	4.24×10^{-6}	1.90×10^{-6}	1.61×10^{-6}
NO_3	6.36×10^{-5}	0	8.91×10^{-5}	1.06×10^{-4}	4.74×10^{-5}	4.03×10^{-5}
CO_2	0	0	0	0	0	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.2.2 Land expansion/intensification avoided from the avoided palm plantation (as a result of extra soy oil)

Land expanded and amounts from intensification

Based on the figures presented in Tables F-6 and F-8, the amount of land expanded, palm oil (and fruits) avoided and palm meal displaced can be calculated. Results are shown in Table F-18.

*Table F-18: Land expansion avoided due to the increase for palm fruit avoided (m^2*y/MJ wood)[(6)]*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Amount of palm fruits avoided, kg DM / MJ wood[(1,2)]	6.24×10^{-3}	5.72×10^{-4}	8.73×10^{-3}	2.23×10^{-3}	4.65×10^{-3}	8.47×10^{-4}
Area of increased palm plantation avoided, m^2*y / MJ wood[(3)]	6.22×10^{-3}	2.19×10^{-3}	8.71×10^{-3}	3.06×10^{-3}	4.64×10^{-3}	1.63×10^{-3}
Amount of palm meal avoided, kg DM / MJ wood[(4)]	1.68×10^{-4}	1.54×10^{-5}	2.36×10^{-4}	6.01×10^{-5}	1.26×10^{-4}	2.29×10^{-5}
Amount of carbohydrates to be replaced, kg / MJ wood[(5)]	1.15×10^{-4}	1.06×10^{-5}	1.62×10^{-4}	4.12×10^{-5}	8.61×10^{-5}	1.57×10^{-5}
Amount of palm oil avoided, kg DM / MJ wood[(2)]	1.40×10^{-3}	1.28×10^{-4}	1.96×10^{-3}	4.99×10^{-4}	1.04×10^{-3}	1.90×10^{-4}

(1) Assuming that 1 kg of soybean oil displaces 1 kg palm oil
(2) 0.224 kg palm oil per kg palm fruit (Dalgaard et al., 2008)
(3) 0.333 kg palm fruit DM per kg palm fruit FM (Goh & Härdter, p.194)
(4) 0.027 kg palm meal per kg palm fruit (Dalgaard et al., 2008; figure 1)
(5) 0.686 kg carbohydrate per kg meal (Møller et al., 2000)
(6) Results can be normalized by ha through multiplying by (1 / 2.21×10^{-6}) (tropical biome); (1 / 1.12×10^{-5}) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

From this, the amount of palm fruit no longer provided by intensification can be calculated as the missing amount (Table F-19).

Table F-19: Amount of palm fruit no longer supplied from intensification (kg FM/MJ wood)[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
	0.000935	0	0.001310	0	0.000698	0

(1) Results can be normalized by ha through multiplying by (1 / 2.21×10^{-6}) (tropical biome); (1 / 1.12×10^{-5}) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to land expansion

GHG from land expansion were calculated as described in F.2.2. Results are shown in Table F-20.

Table F-20: CO_2 releases (avoided) from land expansion due to avoided palm fruit(4)

						Tropical		Boreal		Temperate	
Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)						25% of soil C; 100% of vegetation C(1)		25% of soil C; 100% of vegetation C(1)		25% of soil C; 100% of vegetation C(1)	
Biomes converted	**% conversion(2)**	Region	C in vegetation (ton/ha)	C in soil (ton/ha)	Emission factor peat (ton CO_2/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
						High ILUC	Low ILUC	High ILUC	Low ILUC	High ILUC	Low ILUC
Tropical evergreen forest	53%	South & SouthEast Asia	250	120		-340	-120	-476	-167	-253	-89
Tropical seasonal forest	13%	South & SouthEast Asia	150	80		-52	-18	-72	-25	-38	-14
Tropical open forest	4%	South & SouthEast Asia	60	50		-6	-2	-8	-3	-4	-2
Peatland	30%	South & SouthEast Asia			1100(3)	-205	-72	-287	-101	-153	-54
TOTAL CO_2 (g CO_2*y/MJ wood)						-602	-212	-843	-297	-449	-158
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ wood)						-30	-11	-42	-15	-22	-8
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ wood)						-6	-2	-8	-3	-4	-2

(1) Except exceptions, see text.
(2) Based on Laborde (2011; footnote p.53), it can be assumed that 30% of the palm extension would occur on peatland. The repartition given by Searchinger et al. (2008), which does not involve peatland, has thus been adjusted accordingly.
(3) Based on Laborde (2011; footnote p.53): 55 t CO_2/ha*y, 20y annualization
(4) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to intensification

The emissions induced from input-driven intensification were calculated as described in section F.2.2. Results are presented in Table F-21. Negative signs indicate that the intensification is avoided.

Table F-21: Emissions avoided from the intensification response of avoided palm fruit), in kg / MJ wood[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
NH_3	-9.12×10^{-7}	0	-1.29×10^{-6}	0	-6.87×10^{-7}	0
N_2O	-5.07×10^{-7}	0	-7.10×10^{-7}	0	-3.78×10^{-7}	0
NO_3	-1.83×10^{-5}	0	-2.56×10^{-5}	0	-1.36×10^{-5}	0
CO_2	-7.31×10^{-5}	0	-1.02×10^{-4}	0	-5.45×10^{-5}	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.2.3 Land expansion/intensification resulting from the induced demand for carbohydrates (as a result of missing palm meal)

Based on the figures presented in Tables 5, 6, 8 and 18, the amount of land expanded can be calculated. Results are shown in Table F-22.

*Table F-22: Land expansion for the extra cereals needed, as a reaction to the missing palm meal (m^2*y/MJ wood)[(1)]*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Maize, Botswana	2.27×10^{-4}	2.08×10^{-5}	3.18×10^{-4}	8.10×10^{-5}	1.69×10^{-4}	3.08×10^{-5}
Maize, Brazil	4.72×10^{-5}	4.33×10^{-6}	6.61×10^{-5}	1.69×10^{-5}	3.52×10^{-5}	6.41×10^{-6}
Maize, Argentina	1.4×10^{-5}	9.58×10^{-7}	1.46×10^{-5}	3.73×10^{-6}	7.79×10^{-6}	1.42×10^{-6}
Wheat, France	4.36×10^{-5}	4.00×10^{-6}	6.11×10^{-5}	1.56×10^{-5}	3.25×10^{-5}	5.92×10^{-6}
Wheat, Kazakhstan	7.07×10^{-5}	6.48×10^{-6}	9.90×10^{-5}	2.52×10^{-5}	5.27×10^{-5}	9.60×10^{-6}
Wheat, Australia	7.91×10^{-5}	7.26×10^{-6}	1.11×10^{-4}	2.82×10^{-5}	5.90×10^{-5}	1.07×10^{-5}
Wheat, USA	1.95×10^{-5}	1.79×10^{-6}	2.74×10^{-5}	6.98×10^{-6}	1.46×10^{-5}	2.65×10^{-6}
Barley, Canada	2.79×10^{-5}	2.56×10^{-6}	3.91×10^{-5}	9.97×10^{-6}	2.08×10^{-5}	3.79×10^{-6}

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

From this, the amount of cereals that has to be provided by intensification can be calculated as the missing amount (Table F-23).

Table F-23: Amount of cereals supplied from intensification, as a result of the missing palm meal (kg FM/MJ wood) [(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
Maize, Botswana	5.29×10^{-6}	4.85×10^{-7}	7.41×10^{-6}	1.89×10^{-6}	3.94×10^{-6}	7.18×10^{-7}
Maize, Brazil	3.12×10^{-6}	2.87×10^{-7}	4.38×10^{-6}	1.12×10^{-6}	2.33×10^{-6}	4.24×10^{-7}
Maize, Argentina	1.20×10^{-6}	1.10×10^{-7}	1.68×10^{-6}	4.29×10^{-7}	8.96×10^{-7}	1.63×10^{-7}
Wheat, France	5.35×10^{-6}	4.91×10^{-7}	7.49×10^{-6}	1.91×10^{-6}	3.99×10^{-6}	7.26×10^{-7}
Wheat, Kazakhstan	2.68×10^{-6}	2.45×10^{-7}	3.75×10^{-6}	9.55×10^{-7}	2.00×10^{-6}	3.63×10^{-7}
Wheat, Australia	2.19×10^{-6}	2.01×10^{-7}	3.7×10^{-6}	7.81×10^{-7}	1.63×10^{-6}	2.97×10^{-7}
Wheat, USA	9.73×10^{-7}	8.93×10^{-8}	1.36×10^{-6}	3.47×10^{-7}	7.25×10^{-7}	1.32×10^{-7}
Barley, Canada	1.46×10^{-6}	1.34×10^{-7}	2.04×10^{-6}	5.21×10^{-7}	1.09×10^{-6}	1.98×10^{-7}
Total	2.23×10^{-5}	2.04×10^{-6}	3.12×10^{-5}	7.95×10^{-6}	1.66×10^{-5}	3.02×10^{-6}

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to land expansion

GHG from land expansion were calculated as described in section F.2.2. Results are shown in Table F-24.

Table F-24: CO_2 releases from land expansion due to cereals (carbohydrates displaced from no longer available palm meal)[3]

From Kløverpris (2008)					Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)		Tropical: 25% of soil C; 100% of vegetation C[1]		Boreal: 25% of soil C; 100% of vegetation C[1]		Temperate: 25% of soil C; 100% of vegetation C[1]	
Biomes converted	**Reacting crop**	Region [2]	Share of biome	Final share	C in vegetation (ton/ha)	C in soil (ton/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
							High	Low	High	Low	High	Low
Savanna (taken as shrub land)	maize	xss	50%	12.0%	4.6	30	0.094	0.009	0.132	0.034	0.070	0.013
African tropical evergreen forest (taken as tropical rain forest)	maize	xss	50%	12.0%	127	190	2.182	0.014	3.056	0.779	1.627	0.296
Tropical evergreen forest	maize	bra	100%	14.0%	200	98	3.281	0.014	4.595	1.171	2.447	0.445
Grassland/steppe (taken as grassland)	maize	xla	50%	3.00%	10	42	0.033	0.009	0.046	0.012	0.025	0.004
Tropical evergreen forest	maize	xla	50%	3.00%	200	98	0.703	0.014	0.985	0.251	0.524	0.095
Temperate evergreen forest	wheat	xeu15	24%	5.76%	160	134	0.870	0.010	1.219	0.311	0.649	0.118
Temperate deciduous forest	wheat	xeu15	24%	5.76%	120	134	0.690	0.010	0.967	0.246	0.515	0.094
Dense shrubland (taken as temperate grassland)	wheat	xeu15	52%	12.48%	7	189	0.461	0.006	0.645	0.164	0.343	0.063
Grassland/steppe (taken as temperate grassland)	wheat	xsu	100%	12.00%	10	189	0.443	0.006	0.620	0.158	0.330	0.060
Savanna (taken as tropical grassland)	wheat	aus	100%	9.00%	18	42	0.200	0.010	0.281	0.072	0.149	0.027
Open shrubland (talen as chaparral)	wheat	usa	100%	4.00%	40	80	0.062	0.006	0.087	0.022	0.047	0.008
Boreal deciduous forest (taken as temperate deciduous forest)	barley	can	100%	7.00%	135	134	0.121	0.001	0.169	0.043	0.090	0.016
TOTAL CO_2 (g CO_2*y/MJ wood)							**9.141**	**0.111**	**12.801**	**3.263**	**6.816**	**1.241**
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ wood)							**0.457**	**0.006**	**0.640**	**0.163**	**0.341**	**0.062**
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ wood)							**0.091**	**0.001**	**0.128**	**0.033**	**0.068**	**0.012**

(1) Except exceptions, see text.

(2) With xss: Sub-Saharan Africa, excluding Botswana, Lesotho, Namibia, South Africa and Swaziland; xeu15: EU-15, excluding Denmark; bra: Brazil; xsu: Former Soviet Union, excluding the Baltic States; aus: Australia; can: Canada; xla: South America, excluding Brazil and Peru; usa: United States.

(3) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

GHG related to intensification

The emissions induced from input-driven intensification were calculated as described in section F.2.2. Results are presented in Table F-25.

Table F-25: Emissions induced from the intensification response of cereals (displaced carbohydrates from no longer available palm meal; input-driven), in kg / MJ wood[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	LOW iLUC (high intensif), LOW displ, LOW grass yield
NH_3	6.08×10^{-8}	5.57×10^{-9}	8.15×10^{-8}	2.17×10^{-8}	4.53×10^{-8}	8.25×10^{-9}
N_2O	1.87×10^{-8}	1.72×10^{-9}	2.62×10^{-8}	6.67×10^{-9}	1.39×10^{-8}	2.54×10^{-9}
NO_3	4.67×10^{-7}	4.29×10^{-8}	6.55×10^{-7}	1.67×10^{-7}	3.49×10^{-7}	6.35×10^{-8}
CO_2	0	0	0	0	0	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.2.4 Final iLUC / intensification figures for plantation of grassland

The final iLUC and intensification figures (i.e. summing up the effect over the whole system, as illustrated in Figure F-1) occurring as a result of a plantation on grassland are presented in Table F-25.

The intensification figures shown in Table F-25 present the net global warming impact in g CO_2 eq. per MJ wood, considering IPCC AR4's GWP_{100}[57]. Further, the figures presented in Tables F-13, F-17, F-21 and F-25 are for the input-driven (here fertilizer) share of intensification. Here, it was considered that this effect would account for a maximal of 75% of the intensification response, the rest of the share being considered GHG-negligible (e.g. improved breeds, irrigation, mechanization improvement, etc.). Accordingly, the GHG figures from the above-mentioned Tables were multiplied by 75%.

[57] Involving, among others, a factor of 289 kg CO_2 eq. per kg N_2O. AR4 stands for assessment report 4.

Table F-26: Final iLUC/intensification aggregated GHG figures for plantation on grassland, in g CO_2 eq. per MJ wood)[1,2, 4]

	ILUC						INTENSIFICATION			TOTAL (ILUC + INTENSIFICATION)					
	20 years annualization[3]			100 years annualization[3]						20 years annualization[3]			100 years annualization[3]		
	Tro	Bor	Tem	Tro	Bor	Tem	Tro	Bor	Tem	Tro	Bor	Tem	Tro	Bor	Tem
HIGH	97	136	72	19	27	14	1	1	1	98	137	73	20	29	15
LOW	-3	16	4	-1	3	1	0	1	0	-3	17	4	0	4	1

(1) all figures were calculated with IPCC AR4's GWP_{100}
(2) Tro: tropical; Bor: boreal; Tem: temperate
(3) The same approach as applied and described in Chapter 5.3.2
(4) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of grass displaced because of the plantation, in ha grass*y per MJ wood. They were obtained from the data in Table F-1: (1/LHV wood) * (1/yield wood) * (1/1000).

F.3 Plantation on cropland

Establishing a woody plantation on cropland involves that a crop is displaced. In order to determine how much land expansion would take place as a result of such cropland displacement, a deterministic approach was used, as in section F.2.

The starting point for the analysis was to consider wheat as the crop displaced, in all biomes. This involves that it is considered that it is this crop that farmers would give up, if less land is available. Wheat is thus here considered as a representative of the crop with the lowest marginal returns. It can be argued whether this is a realistic choice of not. Yet, based on an analysis of historical data in FAOstat, it appears that cereals and coarse grains do respond more strongly to a price change than most other crops. Further, according to Weidema, (2003), this, i.e. wheat as the marginal displaced crop, is a realistic case for EU (along with barley). One important aspect of this choice, for the present analysis, of course lies in the crop yield. In fact, the higher is the yield of the crop displaced, the higher is the nutritional value (e.g. carbohydrates) displaced, and thus the higher is the iLUC likely to be. For this reason, an important yield range was selected for the wheat displaced in each biome.

In terms of nutritional value, wheat supplies essentially carbohydrates (84% of the DM, based on Møller et al., 2000). As a consequence of a new plantation on grassland, the nutritional value that was provided by the wheat now has to be supplied by the marginal source of carbohydrates. This is illustrated in Figure F-3 (example for tropical biome), where the boundary conditions considered are shown.

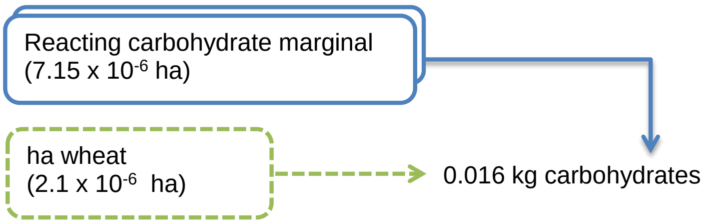

Figure F-3: Process flow diagram considered for modeling the consequences of establishing a plantation on grassland. The flows are expressed per MJ wood and represent the case of a plantation on tropical biome, for the "high" interval (see text). Full lines represent induced flows and dotted lines avoided flows. The boxes on the second plan represent intensification.

The first step to this analysis is thus to determine how much carbohydrates are displaced, in each biome. This can be done on the basis of the information shown in Table F-27.

Table F-27: LHV and yield considered for the woody plantations as well as the yield of the displaced wheat, for each biome

Biome	LHV, wood from plantation (1) (MJ / kg DM)	Yield, wood from plantation (t DM / ha*y)	Yield of wheat(5) (t DM / ha*y)
Tropical	19.9	22.8(2)	2.4 – 9.0
Boreal	19.8	4.5(3)	1.8 – 3.8
Temperate	19.5	12.0(4)	3.1 – 8.0

(1) Same data as used for the dLUC model, Appendixes A-E
(2) Considering a mean annual increment of 25 t ha^{-1} y^{-1} (Stape et al., 2010), and a DM content of 91% (Phyllis database; ecn.nl/phyllis2)
(3) Taken as an average of SRC and willow in Finland and Sweden, from Don et al. (2012)
(4) Don et al. (2012; maximal range of average yields reported for Europe); Sannigrahi et al. (2010)
(5) Selected based on the FAPRI outlook. For tropical, the lower interval represents the yield of Africa and Australia in 2010, while the higher interval represents the yield of Egypt in 2025. For boreal, the lower interval represents the yield of Russia in 2010, while the higher interval represents the yield of Canada in 2025. For temperate, the lower interval represents the yield of Ukraine in 2010, while the highest interval represents the yield of Denmark today, taken from Hamelin et al. (2012). This higher interval was selected as above the values predicted in FAPRI (yet, it should be realistic to consider such high yields in the future for wheat, if these are already achieved today in Denmark, where allowed fertilization levels are below the economical optimum). For all cases, a DM content of 85% was considered for wheat (i.e. 0.85 kg DM per kg FM).

The resulting amount of carbohydrates and protein displaced in all biome is shown in Table F-28.

Table F-28: Amount of carbohydrates displaced in all biome(1, 3)

Biome	kg carbohydrate/MJ wood(2) HIGH wheat yield	kg carbohydrate/MJ wood(2) LOW wheat yield
Tropical	0.016727	0.004373
Boreal	0.035603	0.017468
Temperate	0.028776	0.011172

(1) Numbers are presented with many digits for the transparency of calculation only, but these are not to be seen as significant digits.
(2) 0.84 kg carbohydrates per kg DM were considered, based on Møller et al. (2000).
(3) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

As in the case of plantation on grassland, the amount of reacting marginal cereals can now be calculated (Table F- 29).

Table F-29: Amount of marginal cereals produced as a reaction to the wheat no longer supplied[1, 3]

Biome	Cereals[2] HIGH wheat yield	LOW wheat yield
tropical (kg DM/ MJ wood)	0.019961148	0.005218601
boreal (kg DM/ MJ wood)	0.042485195	0.020844299
temperate (kg DM/ MJ wood)	0.034338999	0.013331611

(1) Numbers are presented with many digits for the transparency of calculation only, but these are not to be seen as significant digits; displ. stands for displacement

(2) 0.84 kg carbohydrate per kg marginal cereal DM (average of spring barley, winter barley, maize and wheat in Møller et al., 2000)

(3) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

Based on the same approach as presented in section F. 2.3, and on the distribution and marginal cereal yields presented in Tables F-5 and F-8 respectively, the amount of extra marginal cereal needed can be calculated (Table F-30), as well as the amount of land expansion (Table F-31) and the amount of cereals produced by intensification (Table F-32).

The GHG from land expansion and intensification were also calculated as described in section F.2.3, and results are presented in Table F-33 and F-34, respectively.

Table F-30: Amount of marginal cereals produced as a reaction to the wheat no longer supplied (kg DM / MJ wood)[(1)]

Biome	Maize Botswana		maize Brazil		Maize Argentina		Wheat France		wheat Kazakhstan		wheat Australia		wheat USA		barley Canada	
	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield	High wheat yield	Low wheat yield
Tropi-cal	5.11×10^{-3}	1.33×10^{-3}	3.02×10^{-3}	7.89×10^{-4}	1.16×10^{-3}	3.03×10^{-4}	5.17×10^{-3}	1.35×10^{-3}	2.58×10^{-3}	6.75×10^{-4}	2.11×10^{-3}	5.53×10^{-4}	9.39×10^{-4}	2.46×10^{-4}	1.41×10^{-3}	3.68×10^{-4}
boreal	1.09×10^{-2}	5.33×10^{-3}	6.42×10^{-3}	3.15×10^{-3}	2.47×10^{-3}	1.21×10^{-3}	1.10×10^{-2}	5.39×10^{-3}	5.50×10^{-3}	2.70×10^{-3}	4.50×10^{-3}	2.21×10^{-3}	2.00×10^{-3}	9.81×10^{-4}	3.00×10^{-3}	1.47×10^{-3}
Tempe-rate	8.78×10^{-3}	3.41×10^{-3}	5.19×10^{-3}	2.02×10^{-3}	2.00×10^{-3}	7.75×10^{-4}	8.89×10^{-3}	3.45×10^{-3}	4.44×10^{-3}	1.73×10^{-3}	3.64×10^{-3}	1.41×10^{-3}	1.62 X 10-3	6.27 X 10-4	2.42×10^{-3}	9.41×10^{-4}

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

*Table F-31: Land expansion for the extra cereals needed (m^2*y/MJ wood)[(1)]*

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield
Maize, Botswana	3.29 X 10-2	3.03 X 10-3	7.00 X 10-2	1.21 X 10-2	5.66 X 10-2	7.75 X 10-3
Maize, Brazil	6.84 X 10-3	6.31 X 10-4	1.46 X 10-2	2.52 X 10-3	1.18 X 10-2	1.61 X 10-3
Maize, Argentina	1.51 X 10-3	1.40 X 10-4	3.22 X 10-3	5.58 X 10-4	2.60 X 10-3	3.57 X 10-4
Wheat, France	6.32 X 10-3	5.83 X 10-4	1.34 X 10-2	2.33 X 10-3	1.09 X 10-2	1.49 X 10-3
Wheat, Kazakhstan	1.02 X 10-2	9.45 X 10-4	2.18 X 10-2	3.77 X 10-3	1.76 X 10-2	2.41 X 10-3
Wheat, Australia	1.15 X 10-2	1.06 X 10-3	2.44 X 10-2	4.22 X 10-3	1.97 X 10-2	2.70 X 10-3
Wheat, USA	2.83 X 10-3	2.61 X 10-4	6.03 X 10-3	1.04 X 10-3	4.87 X 10-3	6.67 X 10-4
Barley, Canada	4.05 X 10-3	3.73 X 10-4	8.61 X 10-3	1.49 X 10-3	6.96 X 10-3	9.54 X 10-4

(1) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

Table F-32: Amount of cereals supplied from intensification (kg FM/MJ wood)[(1)]

Biome of plantation	Tropical		Boreal		Temperate	
	“HIGH”	“LOW ”	“HIGH”	“LOW ”	“HIGH”	“LOW ”
Detail of the High/low interval	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield	High iLUC (low intensif), HIGH wheat yield	Low iLUC (high intensif), LOW wheat yield
Maize, Botswana	7.66E-04	0	1.63E-03	3.73E-03	1.32E-03	2.39E-03
Maize, Brazil	4.53E-04	0	9.63E-04	2.21E-03	7.79E-04	1.41E-03
Maize, Argentina	1.74E-04	0	3.71E-04	8.48E-04	2.99E-04	5.43E-04
Wheat, France	7.75E-04	0	1.65E-03	3.78E-03	1.33E-03	2.42E-03
Wheat, Kazakhstan	3.87E-04	0	8.25E-04	1.89E-03	6.67E-04	1.21E-03
Wheat, Australia	3.17E-04	0	6.75E-04	1.54E-03	5.45E-04	9.88E-04
Wheat, USA	1.41E-04	0	3.00E-04	6.87E-04	2.42E-04	4.39E-04
Barley, Canada	2.11E-04	0	4.50E-04	1.03E-03	3.64E-04	6.59E-04
Total	3.22E-03	0	6.86E-03	1.57E-02	5.55E-03	1.00E-02

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

Table F-33: CO_2 releases from land expansion due to cereals (carbohydrates displaced from wheat no longer produced at the plantation location)[3]

From Kløverpris (2008)					Data from Woodshole database, in Searchinger et al. 2008 (SI) (Appendix D of Searchinger et al.)		Tropical: 25% of soil C; 100% of vegetation C[1]		Boreal: 25% of soil C; 100% of vegetation C[1]		Temperate: 25% of soil C; 100% of vegetation C[1]	
Biomes converted	**Reacting crop**	Region [2]	Share of biome	Final share	C in vegetation (ton/ha)	C in soil (ton/ha)	CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)		CO_2 from land conversion (g*y/MJ)	
							High	Low	High	Low	High	Low
Savanna (taken as shrub land)	maize	xss	50%	12.0%	4.6	30	13.6	1.3	29.0	5.0	23.4	3.2
African tropical evergreen forest (taken as tropical rain forest)	maize	xss	50%	12.0%	127	190	316.1	29.2	672.7	116.5	543.7	74.5
Tropical evergreen forest	maize	bra	100%	14.0%	200	98	475.2	43.8	1011.4	175.1	817.5	112.0
Grassland/steppe (taken as grassland)	maize	xla	50%	3.00%	10	42	4.8	0.4	10.1	1.8	8.2	1.1
Tropical evergreen forest	maize	xla	50%	3.00%	200	98	101.8	9.4	216.7	37.5	175.2	24.0
Temperate evergreen forest	wheat	xeu15	24%	5.76%	160	134	126.1	11.6	268.3	46.5	216.9	29.7
Temperate deciduous forest	wheat	xeu15	24%	5.76%	120	134	100.0	9.2	212.8	36.9	172.0	23.6
Dense shrubland (taken as temperate grassland)	wheat	xeu15	52%	12.48%	7	189	66.7	6.2	142.0	24.6	114.7	15.7
Grassland/steppe (taken as temperate grassland)	wheat	xsu	100%	12.00%	10	189	64.1	5.9	136.5	23.6	110.3	15.1
Savanna (taken as tropical grassland)	wheat	aus	100%	9.00%	18	42	29.0	2.7	61.7	10.7	49.9	6.8
Open shrubland (talen as chaparral)	wheat	usa	100%	4.00%	40	80	9.0	0.8	19.3	3.3	15.6	2.1
Boreal deciduous forest (taken as temperate deciduous forest)	barley	can	100%	7.00%	135	134	17.5	1.6	37.2	6.4	30.1	4.1
TOTAL CO_2 (g CO_2*y/MJ wood)							**1324**	**122**	**2818**	**488**	**2278**	**312**
TOTAL ANNUALIZED CO_2 (20 y) (g CO_2/MJ wood)							**66.2**	**6.1**	**140.9**	**24.4**	**113.9**	**15.6**
TOTAL ANNUALIZED CO_2 (100 y) (g CO_2/MJ wood)							**13.2**	**1.2**	**28.2**	**4.9**	**22.8**	**3.1**

(1) Except exceptions, see text.

(2) With xss: Sub-Saharan Africa, excluding Botswana, Lesotho, Namibia, South Africa and Swaziland; xeu15: EU-15, excluding Denmark; bra: Brazil; xsu: Former Soviet Union, excluding the Baltic States; aus: Australia; can: Canada; xla: South America, excluding Brazil and Peru; usa: United States.

(3) Results can be normalized by ha through multiplying by (1 / 2.21 x 10^{-6}) (tropical biome); (1 / 1.12 x 10^{-5}) (boreal biome) and (4.28 x 10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

Table F-34: Emissions induced from the intensification response of cereals (displaced carbohydrates from no longer available wheat at plantation location; input-driven), in kg / MJ wood (1)

Biome of plantation	Tropical		Boreal		Temperate	
	"HIGH"	"LOW "	"HIGH"	"LOW "	"HIGH"	"LOW "
Detail of the High/low interval	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield	High iLUC (low intensif), HIGH displ, HIGH grass yield	High iLUC (low intensif), LOW displ, LOW grass yield
NH_3	6.08×10^{-8}	5.57×10^{-9}	8.15×10^{-8}	2.17×10^{-8}	4.53×10^{-8}	8.25×10^{-9}
N_2O	1.87×10^{-8}	1.72×10^{-9}	2.62×10^{-8}	6.67×10^{-9}	1.39×10^{-8}	2.54×10^{-9}
NO_3	4.67×10^{-7}	4.29×10^{-8}	6.55×10^{-7}	1.67×10^{-7}	3.49×10^{-7}	6.35×10^{-8}
CO_2	0	0	0	0	0	0

(1) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

The final iLUC/intensification figures for this scenario are summarized in Table F-35. These were calculated as in the grassland case, i.e. considering that the fertilizer-driven response accounts for 75% of the intensification response.

Table F-35: Final iLUC/intensification aggregated GHG figures for plantation on cropland, in g CO_2 eq. per MJ wood)(1,2, 3, 4)

	ILUC						INTENSIFI-CATION			TOTAL (ILUC + INTENSIFICATION)					
	20 years annualization(3)			100 years annualization(3)						20 years annualization(3)			100 years annualization(3)		
	Tr	Bo	Te	Tr	Bo	Te	Tr	Bo	Te	Tr	Bo	Te	Tr	Bo	Te
HIGH	66	141	114	13	28	23	1	1	1	67	142	115	14	29	24
LOW	6	24	16	1	5	3	0	3	2	6	27	17	1	8	5

(1) all figures were calculated with IPCC AR4's GWP_{100}
(2) Tr: tropical; Bo: boreal; Te: temperate
(3) The same approach as applied and described in Chapter 5.3.2
(4) Results can be normalized by ha through multiplying by ($1 / 2.21 \times 10^{-6}$) (tropical biome); ($1 / 1.12 \times 10^{-5}$) (boreal biome) and (4.28×10^{-5}) (temperate biome). These factors corresponds to the area of wheat displaced because of the plantation, in ha wheat*y per MJ wood. They were obtained from the data in Table F-27: (1/LHV wood) * (1/yield wood) * (1/1000).

F.4 Limitations

The main limitation of the approach used for estimating land expansion and intensification lies in the data quality and assumption. Particularly critical (sensitive) data are[58]:

- Future yields:
  - Of the plantation
  - Of the grass / crop displaced*
  - Of the reacting marginal crops
- The stock of soil and vegetation C used[59,60]
- The assumptions regarding the identification of the marginal crops
- The proportions considered for:
  - “high” and “low” expansion*
  - “high” and “low” grass displacement*
  - How much of the intensification response is due to an increase of N-fertilizers

Further, it should be highlighted that the environmental impacts due to the fertilization of the plantation itself have not been included anywhere in this study (although this is not related with the iLUC and intensification calculations). This should be taken into account when interpreting the results as absolute values. Similarly, the impacts related to the harvest and transport of the woody biomass were also excluded, although this can be expected to be of more minor importance (at least in comparison to the global warming contribution from ILUC/intensification).

One other weak point of the approach presented herein relates to the carbohydrates portion of the feedstock to be replaced (here modelled as a corresponsing increased demand for carbohydrates). For this, a mix carbohydrate marginal was derived from the results of Kløverpris (2008). On the basis of that same study, it was considered that land expansion would occur according to specific proportions in specific biomes. This could be seen as a slight inconsistency, since the study of Kløverpris (2008) is based on economic equilibrium modelling. Instead, the same

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[58] Parameters marked with a * are those that were taken into account through the use of range.

[59] For instance, the peatland emission factor used is 55 t CO_2 per ha per y, while recent studies suggested higher values (for example, Marelli et al., 2011, proposed 86 t CO_2 per ha per y)

[60] C stock data from the Woods Hole database, as published in Searchinger et al. (2008), were used for ILUC. Yet, for the DLUC calculations (Appendixes A-E), IPCC data were used. Ideally, the same C stock database should have been used. However, it should be highlighted that important uncertainty exists in relation to both these databases. Nevertheless, using another data source for C stock would change the value of the absolute ILUC figures derived.

approach as used for the protein share could have been used, i.e. determining a single marginal carbohydrate crop and the region from which it is likely to come from based on historical data and best available knowledge. The impact of this (i.e. the method to determine the affected biomes for land expansion due to the carbohydrate share of the increased demand) on the results is however foreseen to be rather insignificant, but the actual sensitivity of the ILUC results to this have not been tested.

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Appendix G Straw and manure inventory

Introduction

This appendix presents the inventory data considered for:

- The conventional manure management of fattening pig slurry
- Wheat straw management (with and without ploughing)
- Mono-digestion of fattening pig slurry (excluding use of the biogas, and energy input data)
- Co-digestion of fattening pig slurry and wheat straw (excluding use of the biogas, and energy input data)

The reason why the energy input and use of biogas are excluded from the 2 latter is that these parameters will be dependent upon the scenario considered for the marginal energy. Similarly, these data do not include any specific energy pathway for of the use of wheat straw, and are simply “cradle-to-gate”, the gate being the harvest of the straw.

G.1 Biogenic CO_2

Soils have an equilibrium C content which is the result of a balance between inflows (e.g. plant matter from above- and below- ground residues, manure, etc.) and outflows (e.g. decomposition, erosion, leaching of soluble C, etc.) to the soil pool. If outflows are greater than inflows, soil C decreases, while soil C increases if inflows are greater than outflows.

When manure (or digesate) and straw are applied/plough down to/into land, part of the C in it enters the soil C pool, and part ends up emitted as CO_2. This was modelled on a year per year basis, with the dynamic soil C model C-TOOL, developed to calculate the soil carbon dynamics in relation to the Danish commitments to UNFCCC (Petersen, 2010a; Petersen et al., 2002).

In the inventory tables presented here (i.e. Tables 6-8, which are to be used for the full bioenergy pathways), it is, however, only the net biogenic CO_2 flows that are presented (sequestration in soils or loss of native soil C), as this is in conformity to the structure of the bioenergy pathways.

G.2 Characterized results

Tables 5-8 also present, besides emission flows themselves, some characterized results for the following impact categories:

- Global warming (time horizon of 20 y an 100 y)
- Aquatic eutrophication (when N is the limiting element for growth)

The methodology used for the former is the one described in IPCC AR4 (Forster et al., 2007), while the methodology used for the latter is the Danish EDIP 2003 life cycle impact assessment method (Hauschild, 2005).

The characterization factors shown in Table 1 were used:

Table G-1: Characterization factors used for the global warming and eutrophication impact

	Global warming, 100 y	Global warming, 20 y	Eutrophication-N
CO_2	1 kg CO_2 eq. / kg CO_2	1 kg CO_2 eq. / kg CO_2	
N_2O	298 CO_2 eq. / kg N_2O	289 CO_2 eq. / kg N_2O	
CH_4	25 CO_2 eq. / kg CH_4	72 CO_2 eq. / kg CH_4	
NH_3			0.1886 kg N eq. / kg NH_3
NO_X			0.096 kg N eq. / kg NOx
NO_3			0.1357 kg N eq. / kg NO_3

G.3 Conventional manure management

The reference pig slurry management considered in this study is based on the reference system described in Hamelin et al. (in press; Supporting Information, p. S2-S4), and assume the same pre-conditions. It a nutshell, this process consists to store the excreted manure (first in the housing system, then in an outdoor storage facility) until it can be applied on land, where it is used as a source of N, P and K fertilizer. By using manure as a fertilizer, it involves that marginal mineral N, P and K fertilizers do not need to be produced and used.

As in Hamelin et al. (in press), outdoor storage is assumed to take place in a concrete tank, covered by a straw floating layer and slurry is applied to fields with a trail-hose slurry tanker. The same reference crop rotation as described in Hamelin et al. (in press; Table S63) is considered here.

The reference slurry composition is based on the Danish manure standards (Poulsen, 2011). Table 2 presents the slurry composition considered, and Table 3, the life cycle inventory data considered for reference slurry management (emission flows). State-of-the-art mass balances were performed to ensure consistency between the slurry composition, and the emission flows. Based on Table 2, there is 1.002 tonne of manure ex-housing (i.e. manure as it leaves the housing unit) per tonne manure ex-animal (i.e. manure as “freshly” excreted). It is the slurry ex-housing (or ex pre-tank) which is the input into the digester[61].

When manure is used for biogas, its conventional storage and application on land is avoided (as well as the mineral fertilizer replacement that it would have generated). Table 4 shows the aggregated environmental impact of this for some selected flows and characterized impacts, per kg VS.

Table G-2: Reference pig slurry composition (from Hamelin et al., in press)

Parameter	Slurry ex-animal[a]	Slurry ex-housing[b]	Slurry ex-storage[c]	Source and assumptions
Mass ($t\ pig^{-1}$)	0.47	0.47[d]	0.48	Data needed to ensure correspondence between each manure stage. Values ex-animal and ex-storage based on Poulsen (2011). Value ex-housing based on mass balance[d]. A net water addition of 0.02 m^3 per tonne manure is considered during outdoor storage.
Total N ($kg\ t^{-1}$)	6.00	5.26	5.03	N ex-animal from Poulsen (2011). Losses considered (during housing and during storage): NH_3, N_2O, N_2, NO. Details on N losses are in Table 3. The N from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 0.009 kg per tonne manure ex-animal and 0.011 kg per tonne manure ex-storage, respectively.
P ($kg\ t^{-1}$)	1.21	1.21	1.19	P ex-animal from Poulsen (2011). No losses considered during housing and storage. The P from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 0.001 kg per tonne manure ex-animal and 0.002 kg per tonne manure ex-storage, respectively.
K ($kg\ t^{-1}$)	2.83	2.85	2.83	K ex-animal from Poulsen (2011). No losses considered during housing and storage. The K from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 0.02 kg per tonne manure ex-animal and 0.03 kg per tonne manure ex-storage, respectively.
DM ($kg\ t^{-1}$)	74.8	68.7	66.0	DM ex-storage from Poulsen (2011). Losses during storage: 5 % of the ex-housing values; losses during housing: 10 % of the ex-animal value. Assumptions for losses during storage and housing based on (Poulsen, 2008).
VS ($kg\ t^{-1}$)	60.7	54.6	52.1	VS are assumed to constitute 79 % of the DM content. Losses considered during storage and housing (absolute values) are the same as for DM (i.e. it is assumed that all DM lost was VS).
C ($kg\ t^{-1}$)	34.5	34.2	31.6	C ex-storage = 47.9 % of DM ex-storage for pigs, based on the ratio C: DM obtained by (Knudsen and Birkmose, 2005). Losses considered (during housing and during storage): CH_4 and CO_2. Details on C losses are in Table 3. The C from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 0.75 kg per tonne manure ex-animal and 0.95 kg per tonne manure ex-storage, respectively.
Cu ($g\ t^{-1}$)	31.0	31.0	30.4	Cu ex-storage = 0.0453 % of DM ex-storage, based on the ratio Cu: DM obtained by (Knudsen and Birkmose, 2005). No losses considered during housing and storage. The Cu from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 4.92 mg per tonne manure ex-animal and 6.25

[61] The slurry is pumped from the pre-tank before to be transferred to a biogas plant. Since it remains there rather temporarily, the manure is assumed to have the same composition as it leaves the animal house – towards the pre-tank – and as it leaves the pre-tank.

Parameter	Slurry ex-animal[a]	Slurry ex-housing[b]	Slurry ex-storage[c]	Source and assumptions
				mg per tonne manure ex-storage, respectively.
Zn ($g\ t^{-1}$)	90.8	90.7	89.1	Zn ex-storage = 0.135 % of DM ex-storage, based on the ratio Zn: DM obtained by (Knudsen and Birkmose, 2005). No losses considered during housing and storage. The Zn from straw addition[e] in-house and as a floating layer during outdoor storage is estimated as 75.5 mg per tonne manure ex-animal and 95.9 mg per tonne manure ex-storage, respectively.
NH_4-N ($kg\ t^{-1}$)	4.20	3.94	3.07	Value ex-storage based on Poulsen (2011). Value ex-housing assuming 0.75 kg NH_4-N per kg manure ex-housing (Poulsen, 2008), and value ex-animal assuming 0.70 kg NH_4-N per kg manure ex-animal (EMEP/EEA, 2010).

[a] All values of this column are expressed per tonne slurry ex-animal. [b] All values of this column are expressed per tonne slurry ex-housing. [c] All values of this column are expressed per tonne slurry ex-storage. [d] The non-rounded value ex-housing is 0.47089 t pig^{-1}, and considers a net water addition in-house of 3.57 kg water per pig, the straw addition described below and DM losses as in this Table. [e] The N, P and K addition from straw added in the stable considers, based on (Poulsen, 2008), an addition of 3 kg of straw per animal per year, 3.3 rotations per year, and the above-mentioned amount of manure ex-animal and ex-housing, yielding a total of 0.0019 t straw per tonne manure ex-housing. For the floating layer, the amount considered is based on (Wesnæs et al., 2009), i.e. 2.5 kg per tonne manure ex-housing. The straw DM content is 85 % (Møller et al., 2000). The N, P, K, Cu and Zn content of straw per kg of DM is 0.00528 kg, 0.0009 kg, 0.015 kg, 3 mg and 46 mg, respectively, based on (Møller et al., 2000). The C content is taken as 0.4563 kg C per kg DM, based on an average of 13 values from the Biolex database (FORCE Technology, 2013).

Table G-3: Life cycle inventory data for the reference manure management (from Hamelin et al., in press). All values in kg (per t manure ex-animal, ex-housing or ex-storage).

Substances	Life cycle stage			Comments		
	in-house per tonne ex-animal manure	outdoor storage per tonne ex-housing manure	Field[c] per tonne ex-storage manure	in-house	outdoor storage	field
NH_3-N	0.71	0.099	0.60	0.17 kg NH_3-N per kg TAN[a] (Poulsen, 2008), with 0.7 kg TAN/kg N (EMEP/EEA, 2010).	2.5 % of TAN[a] ex-housing (Poulsen, 2008); the N ex-housing being estimated according to (Poulsen, 2008), i.e.: N ex-animal minus NH_3-N losses in-house (and not accounting for other losses).	12% of N applied (Hansen et al., 2008) (this is an average for application by trail hose tanker, excluding illegal dates).
NH_3-N, at application			0.015			0.5% of TAN applied, for application by trail hoses, (Hansen et al., 2008).
N_2O-N	0.012	0.030	0.050	0.002 kg N_2O-N per kg N ex-animal (IPCC, 2006a) (pit storage below animal)	0.005 kg N_2O-N per kg N ex-animal (IPCC, 2006a) (liquid/slurry storage)	1% of N applied, (IPCC, 2006b).
NO-N (representing NO_x)	1.96×10^{-4}	1.84×10^{-4}	0.005	0.0001 kg NO per kg TAN ex-animal (EMEP/EEA, 2010).	0.0001 kg NO per kg TAN ex-housing (EMEP/EEA, 2010).	0.1 × N_2O-N, based on (Nemecek and Kägi, 2007).
NO_3-N	0	0	1.68	No leaching from housing, based on (Hamelin et al., 2011).	No leaching from outdoor storage, based on (Hamelin et al., 2011).	Based on Danish $NLES_4$ model (Kristensen et al., 2008).
N_2-N	0.013	0.012		0.003 kg NO per kg TAN ex-animal (EMEP/EEA, 2010).	0.003 kg NO per kg TAN ex-housing (EMEP/EEA, 2010).	
CO_2-C	0.36*	1.20*	31.3* (31.1)*	1.83 kg CO_2 per kg CH_4[b]	1.83 kg CO_2 per kg CH_4[b]	Based on the Danish dynamic soil C model C-TOOL (Petersen, 2010a; Petersen et al., 2002).
CH_4-C	0.54	1.80	0	IPCC algorithm (IPCC, 2006a); MCF of 3% and B_0 of 0.40 kg CH_4/kg VS, with the density of CH_4 at 0°C.	IPCC algorithm (IPCC, 2006a); MCF of 10% and B_0 of 0.40 kg CH_4/kg VS, with the density of CH_4 at 0°C.	Assumed negligible, based on (Hamelin et al., 2011).
P leaching	0	0	0.060			5% of surplus, based on (Hamelin et al., 2012). See details in Hamelin et al. (in press), p. S65-66.
indirect N_2O-N (volatilization)	7.14×10^{-3}	9.91×10^{-4}	0.006	1% of N loss as NH_3 and as NO_x, (ex-animal) (IPCC, 2006b).	1% of N loss as NH_3 and as NO_x, (ex-housing) (IPCC, 2006b).	1% of N loss as NH_3 and as NO_x, (ex-storage) (IPCC, 2006b).
indirect N_2O-N (leaching)	0	0	0.013	0.75% of N lost through leaching (ex-animal) (IPCC, 2006b).	0.75% of N lost through leaching (ex-animal) (IPCC, 2006b).	0.75% of N lost through leaching (ex-animal) (IPCC, 2006b).

[a] Ammonium-N (NH_4^+-N) and compounds readily broken down to NH_4^+-N are referred to as total ammoniacal N (TAN).
[b] Details on how this figure was derived are available in Hamelin et al. (in press), p. S60-61.
[c] For CO_2-C, the amount shown is for a 100 y annualization, while the amount between parenthesis is for a 20 y annualization

*These releases are presented for transparency only, but only the net biogenic CO_2 flows were considered in this study (Table 4)

Table G-4: Inventory data for avoided conventional fattening pig slurry management, expressed per kg VS manure

Cradle : Manure ex-housing (see remark a)
Gate : Application of raw manure on land (including the avoided mineral fertilizers substituted by applying manure)
Processes included : Outdoor storage; manure spreading (application process itself and field processes); (avoided) production of mineral N, P and K**; (avoided) application of mineral N, P and K‡
Remark : a) Process considers that the conventional management of <u>1 tonne manure ex-animal</u> is avoided (housing stage excluded, as independent of whether manure is used for biogas or not)
kg VS, slurry ex pre-tank: 54.6 kg VS/t ex pre-tank (used to express values per kg VS) (Table 2)
Slurry ex pre-tank : 1002 kg slurry ex pre-tank per 1000 kg slurry ex-animal (can be derived from Table 2)

Substance / parameter	Unit	System expansion process: Conventional manure management (outdoor storage, spreading, mineral fertilizers avoided)δ	Total, for use in bioenergy pathways (avoided conventional manure management)†
CO_2, biogenic*	kg / kg VS	-2.10×10^{-2} (3.58×10^{-2})	2.10×10^{-2} (-3.58×10^{-2})
CO_2, fossil	kg / kg VS	-2.00×10^{-1}	2.00×10^{-1}
CH_4, biogenic	kg / kg VS	4.39×10^{-2}	-4.39×10^{-2}
CH_4, fossil	kg / kg VS	-4.31×10^{-4}	4.31×10^{-4}
N_2O	kg / kg VS	2.50×10^{-3}	-2.50×10^{-3}
NO_3-	kg / kg VS	$-1.99 \times 10\text{-}^{10}$	$1.99 \times 10\text{-}^{10}$
NH_3	kg / kg VS	1.56×10^{-2}	-1.56×10^{-2}
NO_x	kg / kg VS	-7.59×10^{-4}	7.59×10^{-4}
SO_2	kg / kg VS	-5.84×10^{-4}	5.84×10^{-4}
GWP_{100}*	kg CO_2 eq. / kg VS	1.61×10^{0} (1.60×10^{0})	-1.61×10^{0} (-1.60×10^{0})
GWP_{20}*	kg CO_2 eq. / kg VS	3.63×10^{0} (3.61×10^{0})	-3.63×10^{0} (-3.61×10^{0})
Eutrophication (N)	kg N eq. / kg VS	-2.59×10^{-4}	2.59×10^{-4}

* Annualization over 100 years, whenever it applies. In parenthesis are the values for a 20 years annualization, for the **net** C flow (i.e. soil C changes) involved as a result of manure spreading.

** 3.8 kg CAN (as N), 0.59 kg DAP (as N), 1.56 kg K_2O (as K) avoided, as a result of manure spreading. All calculations details to determine the exact quantity of avoided mineral fertilizers is available in Hamelin et al. (in press), Supporting Information, Table S64. CAN, DAP and K_2O are considered to be the marginal mineral fertilizers, as described in Hamelin (2013), p. 15-20. The inventory for the fertilizers is from the Ecoinvent database (Nemecek and Kägi, 2007), but the inventory for nitric acid has been corrected to 0.00248 kg N_2O per kg nitric acid, as explained in Appendix F.

‡ Modeled with the Ecoinvent database (process "fertilizing, by broadcaster"), but diesel consumption adjusted for soil JB3 of the Danish classification system (sandy soil), as described in Hamelin et al. (2012)

†Values from previous column multiplied by -1, as the process is avoided.

δ The inventory for outdoor storage and spreading (field processes part) is as detailed in Table 3.

G.4 Straw

The straw reference used in this study is represented by winter wheat straw (as being the most abundant in Denmark) with a yield of 3.09 t DM per ha (Hamelin et al., 2012)[62].

The harvest process involves swath, baling and loading (of the bales), and these were modelled as described in (Hamelin et al., 2012). The straw composition considered is shown in Table G-5.

Table G-5: Straw composition

	Straw "as harvested"
Unit	kg/1 000.0 kg straw "as harvested"
Total mass	1 000.0
DM	850.0[a]
VS	810.6[c]
Total N	4.49[a]
Phosphorus (P)	0.77[a]
Potassium (K)	12.75[a]
Carbon (C)	382.50[b]
Cupper (Cu)	0.003[a]
Zinc (Zn)	0.039[a]

[a] Based on (Møller et al., 2000);
[b] Based on (Petersen, 2010a), 0.45 kg C/kg DM;
[c] Taken as 95 % of DM, according to (Møller et al., 2004; Triolo et al., 2011; Wang et al., 2009).

If not used for bioenergy, it is considered that straw would have been incorporated to the soil instead. Part of the C of the straw would have entered the soil C pool, building up soil C stock, while most of it would have end up as a CO_2 emission to the atmosphere.

The net difference between straw harvest and incorporation was modelled on the basis of the wheat life cycle inventory presented in Hamelin et al. (2012)[63], where the flows of C and N are presented for systems with and without the harvest of the straw. According to this, the soil C change is:

- Straw removal system[64]: -79.8 (-132.5) kg C per ha per y
- Straw incorporation system: 51.1 (128) kg C per ha per y

Additional inventory details are presented in Table G- 6.

[62] Sandy soil (JB3), ”wet” climate (964 mm per y).
[63] Same soil type as above, case without application of manure (as manure, being a waste product from another activity, cannot be a marginal fertilizer)
[64] Value annualized over 100 y, unless presented between parenthesis

Table G-6: Inventory data for wheat straw

Cradle : Straw is generated
Gate : Harvest of straw
LHV straw : 16.8 MJ / kg DM (0.85 kg DM per kg FM)
Yield straw : 3.09 t DM / ha
(1 tonne of wheat straw)

Substance / parameter	Unit	Additional emissions due to harvesting of straw instead of ploughing, biogenic flows only(2)	Straw harvest (swath, baling and loading)(8)	Avoided stubble harrowing(8, 9)	Total, for use in bioenergy pathways
CO_2, biogenic(1)	kg / MJ_{straw}	1.28×10^{-2} (2.55×10^{-2})	0	0	1.28×10^{-2} (2.55×10^{-2})
CO_2, fossil	kg / MJ_{straw}	-	1.02×10^{-3}	-5.12×10^{-4}	5.07×10^{-4}
CH_4, biogenic	kg / MJ_{straw}	Negligible(3)	0	0	0
CH_4, fossil	kg / MJ_{straw}	-	2.44×10^{-6}	-6.72×10^{-7}	1.77×10^{-6}
N_2O	kg / MJ_{straw}	-6.87×10^{-6}(4)	2.65×10^{-8}	-1.58×10^{-8}	-6.86×10^{-6}
NO_3-	kg / MJ_{straw}	0(5)	1.71×10^{-8}	-7.77×10^{-9}	9.36×10^{-9}
NH_3	kg / MJ_{straw}	0(6)	1.77×10^{-8}	-1.00×10^{-8}	7.68×10^{-9}
NO_x	kg / MJ_{straw}	9.64×10^{-6}(7)	8.33×10^{-6}	-3.55×10^{-6}	1.44×10^{-5}
SO_2	kg / MJ_{straw}	-	1.75×10^{-6}	-7.51×10^{-7}	1.00×10^{-6}
Global warming impact (100 y horizon)	kg CO_2 eq. / MJ_{straw}	1.07×10^{-2} (2.34×10^{-2})	1.09×10^{-3}	-5.37×10^{-4}	1.13×10^{-2} (2.40×10^{-2})
Global warming impact (20 y horizon)	kg CO_2 eq. / MJ_{straw}	1.08×10^{-2} (2.35×10^{-2})	1.24×10^{-3}	-5.82×10^{-4}	1.15×10^{-2} (2.40×10^{-2})
Eutrophication (N)	kg N eq. / MJ_{straw}	9.25×10^{-7}	8.06×10^{-7}	-3.44×10^{-7}	1.39×10^{-6}

(1) Annualization over 100 years, whenever it applies. In parenthesis are the values for a 20 years annualization, for the net C flow (i.e. soil C changes) involved as a result of straw harvesting.
(2) Value represent the emission (or changes in soil C) in the wheat system when straw is incorporated minus emission (or changes in soil C) when straw is harvested. Soil C changes and emissions considered for the wheat system are as described in Hamelin et al. (2012), where all inventory data are available.
(3) The CH_4 sink as a result of microbial oxidation is considered negligible in annual crop systems and has not been included in this study, for the reasons explained in Hamelin (2013), p. 56.
(4) In Hamelin et al. (2012), N_2O were calculated based on the IPCC guidelines (IPCC, 2006b). In this case, only "direct" N_2O applies (because NH_3 and NO_3 are the same whether straw is incorporated or not, see below), and this is calculated as 0.01 kg N_2O-N per kg N in straw.
(5) Many studies reported, from a short-term perspective, a decrease in NO_3 losses with increasing straw incorporation (e.g. Beaudoin et al., 2005; Gabrielle and Gagnaire, 2008), due to a temporary immobilization of mineral N by soil microflora. When the microbes die, this immobilized N is

remobilized and as a result, the net effect is simply to postpone the straw-N losses by a few years. For this reason, the empirical model used in this study for predicting nitrate leaching (N-LES4) does not consider any effects from the straw incorporation (Kristensen et al., 2008). In the longer term, however, an increase in soil organic matter through incorporation of straw may lead to higher levels of NO_3 leaching than shown here.

(6) NH_3 due to straw degradation was, in Hamelin et al. (2012), considered insignificant, on the basis of de Ruijter et al. (2010). This part of the inventory should be reviewed, although this flow is expected to be rather small.

(7) Hamelin et al. (2012) used, based on Haenel et al. (2010) an emission factor of 0.007 kg NO-N per kg N, for crop residues (where NO-N was used to represented NOx)

(8) Inventory for these was drawn from the Ecoinvent database. For the exact process used, see Hamelin et al. (2012), Appendix 2 (available online free of charges).

(9) The negative sign applies as the process is “avoided”.

G.5 Mono- and co-digestion of fattening pig slurry and straw

Tables G-7 and G-8 present the necessary inventory data for mono-digestion of fattening pig slurry and co-digestion of fattening pig slurry with straw, respectively. Figures G-1 and G-2 illustrate the system boundary considered for these 2 systems. In both cases, the use of the biogas is not included within the inventory data, as the idea is to use these data as an input to a given energy conversion pathway.

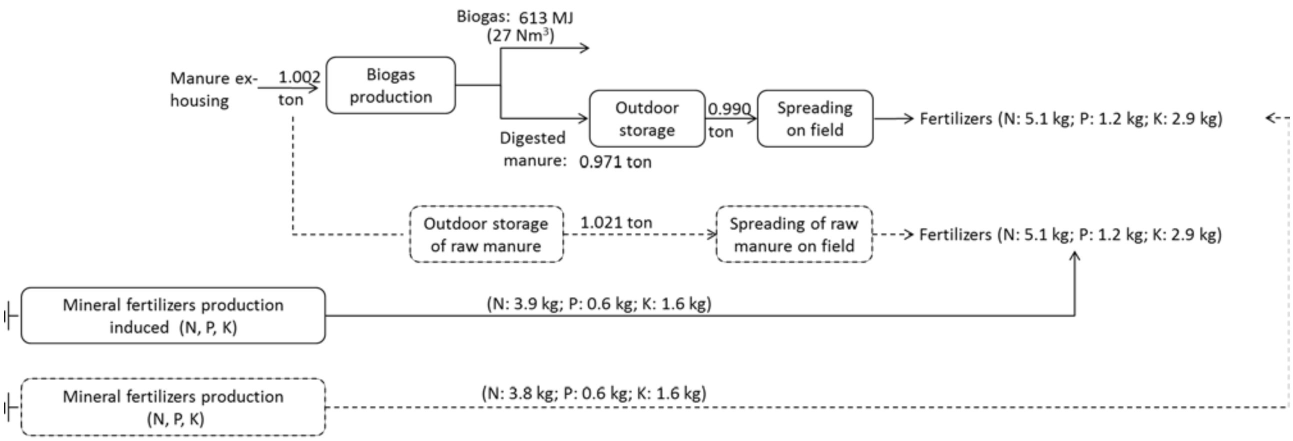

Figure G-1: System boundary considered for the inventory data of mono-digestion of fattening pig slurry. Dotted lines indicate an avoided process while full lines indicate an induced process.

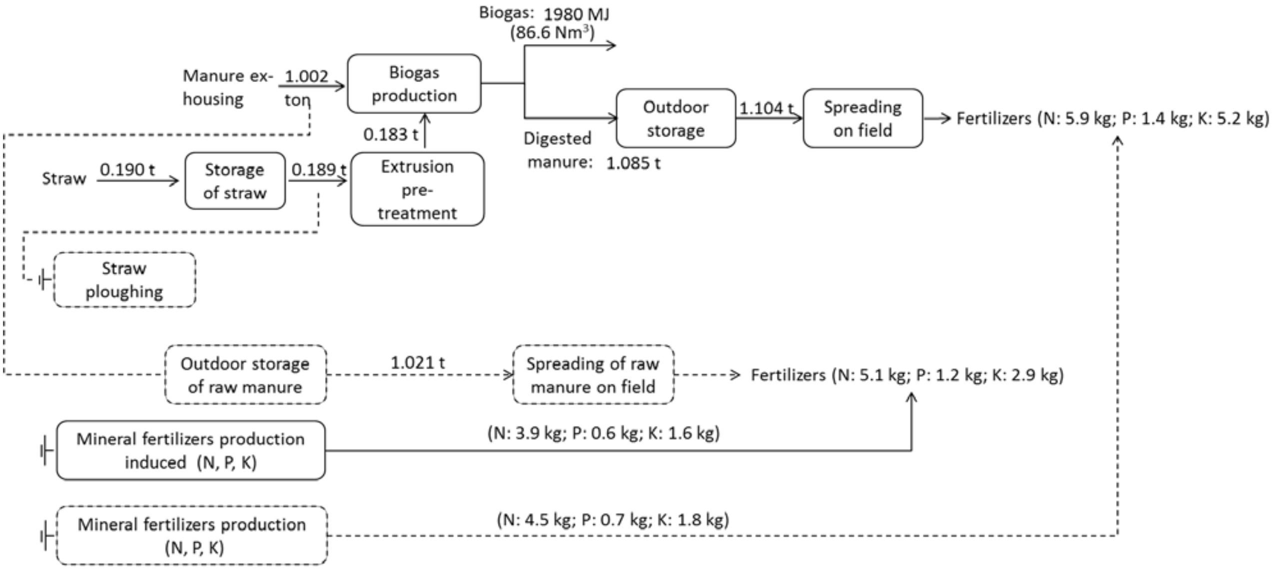

Figure G-2: System boundary considered for the inventory data of mono-digestion of fattening pig slurry. Dotted lines indicate an avoided process while full lines indicate an induced process.

The inventory data presented in Tables G-7 and G-8 are essentially based on a recent study (Hamelin et al., 2014), although a few modifications from this were performed:

- The internal energy consumption needed for the anaerobic digestion process was taken out, as this is adjusted in the pathway assessment, depending on the scenario used for the energy marginal;

- Only the net biogenic CO_2 emissions are accounted for (although the mass balances still take into account the losses of biogenic CO_2 occurring at each individual process

Table G-7: Manure-biogas (mono-digestion of fattening pigs slurry) inventory, all process up to biogas production (use of the biogas, and thereby the energy replaced, are not included)

Cradle : Manure excretion
Gate : a) for the biogas part: biogas
b) for the digestate part: application on land and substitution of mineral fertilizers
Remark : a) This process draws on Hamelin et al. (2014).
b) This process does **not** include the internal energy consumption, nor the use of the biogas.
Amount of manure ex-animal : 1 tonne
kg VS, slurry ex pre-tank : 54.6 kg VS/t ex pre-tank (used to express values per kg VS) (Table G-2)
Slurry ex pre-tank : 1002 kg slurry ex pre-tank per 1000 kg slurry ex-animal (can be derived from Table G-2)
CH_4 yield, pig slurry : 319 Nm^3 CH_4 per t VS (based on Hamelin et al., 2014)
LHV of CH_4 : 35.9 MJ per Nm^3 CH_4 (Energinet.dk and DEA, 2012)

Substance / parameter	Unit	Biogas production (fugitive losses) (3)	Digestate handling (storage, field application and avoided mineral fertilizers)(9)	Avoided conventional slurry handling (outdoor storage, spreading, mineral fertilizers avoided)(2)	Total pathway, excluding energy input and biogas use
CO_2, biogenic(1)	kg / MJ biogas	0	8.29×10^{-3} (1.54×10^{-2})	1.83×10^{-3} (-3.12×10^{-3})	1.01×10^{-2} (1.85×10^{-2})
CO_2, fossil	kg / MJ biogas	0	-2.07×10^{-2}	1.75×10^{-2}	-3.26×10^{-3}
CH_4, biogenic	kg / MJ biogas	2.00×10^{-4}	9.76×10^{-4}(4)	-3.84×10^{-3}	-2.66×10^{-3}

Substance / parameter	Unit	Biogas production (fugitive losses) (3)	Digestate handling (storage, field application and avoided mineral fertilizers)(9)	Avoided conventional slurry handling (outdoor storage, spreading, mineral fertilizers avoided)(2)	Total pathway, excluding energy input and biogas use
CH_4, fossil	kg / MJ biogas	0	-4.31×10^{-5}	3.77×10^{-5}	-5.47×10^{-6}
N_2O	kg / MJ biogas	0	1.60×10^{-4}(5)	-2.18×10^{-4}	-5.89×10^{-5}
NO_3-	kg / MJ biogas	0	-1.99×10^{-11}(6)	1.74×10^{-11}	-2.52×10^{-12}
NH_3	kg / MJ biogas	0	1.38×10^{-3}(7)	-1.37×10^{-3}	1.08×10^{-5}
NO_x	kg / MJ biogas	0	-8.73×10^{-5}(8)	6.63×10^{-5}	-2.10×10^{-5}
SO_2	kg / MJ biogas	0	-1.14×10^{-4}	5.10×10^{-5}	-6.32×10^{-5}
Global warming impact (100 y horizon)	kg CO_2 eq. / MJ biogas	5.00×10^{-3}	5.86×10^{-2} (6.57×10^{-2})	-1.41×10^{-1} (-1.39×10^{-1})	-7.70×10^{-2} (-6.87×10^{-2})
Global warming impact (20 y horizon)	kg CO_2 eq. / MJ biogas	1.44×10^{-2}	1.01×10^{-1} (1.08×10^{-1})	-3.17×10^{-1} (-3.15×10^{-1})	-2.02×10^{-1} (-1.93×10^{-1})
Eutrophication (N)	kg N eq. MJ biogas	0.00×10^{0}	1.89×10^{-3}	2.26×10^{-5}	1.92×10^{-3}

(1) Annualization over 100 years, whenever it applies. In parenthesis are the values for a 20 years annualization, for the net C flow (i.e. soil C changes) involved as a result of manure/digestate spreading. Soil C changes were calculated with the dynamic soil C model C-TOOL.

(2) As in Table G-2, but units are different

(3) Fugitive losses of CH_4 during the digestion process: 1% of the methane content of the biogas is assumed to be emitted to the environment, based on recent studies (Börjesson and Berglund, 2006; Jungbluth et al., 2007). This is judged to be realistic for future state-of-the-art biogas plants to be built.

(4) For storage: IPCC algorithm (IPCC, 2006a); MCF of 10% and B_0 of 0.400 kg CH_4/kg VS. To this, an “emission reduction potential” factor of 60 % is applied, accounting for the lower emissions of digestates (Nielsen et al., 2009); At field, biogenic CH_4 are considered negligible, as for raw manure application

(5) Storage: Storage: Calculated as for raw manure; At field: Calculated as for raw manure (Table G-3)

(6) Based on the N-LES4 model, as described in Hamelin et al. (2014), p. S65-66.

(7) Calculated as for raw manure (Table G-3), but for storage, it was considered that TAN is 77% of the total N, and for field application, 79% of the total N

(8) Calculated as for raw manure (Table G-3), but for storage, it was considered that TAN is 77% of the total N

(9) Processes related to the production and application of marginal mineral fertilizers were taken from the Ecoinvent database, with the same specifications as indicated in Table G-4 for raw manure

Table G-8: Co-digestion of fattening pig slurry with wheat straw, all process up to biogas production (use of the biogas, and thereby energy replaced, not included)

Cradle : Straw generation
Gate : a) for the biogas part: biogas
b) for the digestate part: application on land and substitution of mineral fertilizers
Remark : a) This process draws on Hamelin et al. (2014)
b) This process does **not** include the internal energy consumption, nor the use of the biogas.
LHV straw : 16.8 MJ / kg DM (0.85 kg DM per kg FM)
Yield straw : 3.09 t DM / ha
Amount of manure ex-animal in input mixture : 1 tonne (1002 kg slurry ex pre-tank per 1000 kg slurry ex-animal)
Amount of straw ex-storage in input mixture : 0.1886 tonne (990.7 kg straw ex-storage per kg straw ex-harvest; Hamelin et al., 2014)
CH_4 yield, extruded straw : 263 Nm^3 / t VS (Hamelin et al., 2014)
LHV of CH_4 : 35.9 MJ per Nm^3 CH4 (Energinet.dk & DEA, 2012)

Substance / parameter	Unit	Biogas production (fugitive losses) (3)	Digestate handling (storage, field application and avoided mineral fertilizers(9))	Straw handling (harvest, storage, and extrusion pre-treatment)(10)	Additional emissions due to straw harvest instead of ploughing(11) (20 y annualization)	Avoided conventional slurry handling (outdoor storage, spreading, mineral fertilizers avoided) (2)	Total pathway, excluding energy input and biogas use
CO_2, biogenic(1)	kg / MJ_{straw}	0	-1.33×10^{-2} (-2.19×10^{-2})	0	1.29×10^{-2} (2.57×10^{-2})	4.90×10^{-4} (7.90×10^{-4})	1.19×10^{-3} (5.79×10^{-3})
CO_2, fossil	kg / MJ_{straw}	0	-5.61×10^{-3}	2.00×10^{-3}	-5.18×10^{-4}	4.06×10^{-3}	-6.92×10^{-5}
CH_4, biogenic	kg / MJ_{straw}	1.50×10^{-4}	7.26×10^{-4}(4)	0	0	-8.92×10^{-4}	-1.66×10^{-5}
CH_4, fossil	kg / MJ_{straw}	0	-1.17×10^{-5}	6.66×10^{-6}	0	8.76×10^{-6}	3.76×10^{-6}
N_2O	kg / MJ_{straw}	0	4.29×10^{-5}(5)	7.28×10^{-8}	-6.96×10^{-6}	-5.08×10^{-5}	-1.48×10^{-5}
NO_3-	kg / MJ_{straw}	0	3.27×10^{-3}(6)	4.07×10^{-8}	-7.86×10^{-9}	-2.83×10^{-3}	4.38×10^{-4}
NH_3	kg / MJ_{straw}	0	3.70×10^{-4}(7)	5.49×10^{-6}	-1.01×10^{-8}	-3.18×10^{-4}	5.80×10^{-5}
NO_x	kg / MJ_{straw}	0	-2.40×10^{-5}(8)	9.40×10^{-6}	6.16×10^{-6}	1.54×10^{-5}	7.00×10^{-6}
SO_2	kg / MJ_{straw}	0	-3.08×10^{-5}	3.38×10^{-6}	-7.60×10^{-7}	1.19×10^{-5}	-1.63×10^{-5}
Global warming impact (100 y horizon)	kg CO_2 eq. / MJ_{straw}	3.74×10^{-3}	1.17×10^{-2} (3.20×10^{-3})	3.28×10^{-3}	1.03×10^{-2} (2.31×10^{-2})	-3.27×10^{-2} (-3.24×10^{-2})	-3.65×10^{-3} (9.49×10^{-4})
Global warming impact (20 y horizon)	kg CO_2 eq. / MJ_{straw}	1.08×10^{-2}	4.48×10^{-2} (3.63×10^{-2})	3.66×10^{-3}	1.03×10^{-2} (2.32×10^{-2})	-7.37×10^{-2} (-7.34×10^{-2})	-4.13×10^{-3} (4.66×10^{-4})
Eutrophication (N)	kg N eq. / MJ_{straw}	0	5.10×10^{-4}	1.94×10^{-6}	5.88×10^{-7}	-4.42×10^{-4}	7.10×10^{-5}

(1) Annualization over 100 years, whenever it applies. In parenthesis are the values for a 20 years annualization, for the net C flow (i.e. soil C changes) involved as a result of manure/digestate spreading. Soil C changes were calculated with the dynamic soil C model C-TOOL.

(2) As in Table G-2, but units are different

(3) Fugitive losses of CH_4 during the digestion process: 1% of the methane content of the biogas is assumed to be emitted to the environment, based on recent studies (Börjesson and Berglund, 2006; Jungbluth et al., 2007). This is judged to be realistic for future state-of-the-art biogas plants to be built.

(4) For storage: IPCC algorithm (IPCC, 2006a); MCF of 10% and B_0 of 0.475 kg CH_4/kg VS. To this, an "emission reduction potential" factor of 60 % is applied, accounting for the lower emissions of digestates (Nielsen et al., 2009); At field, biogenic CH_4 are considered negligible, as for raw manure application

(5) Storage: Calculated as for raw manure; At field: Calculated as for raw manure (Table G-3)

(6) Based on the N-LES4 model, as described in Hamelin et al. (2014), p. S65-66.

(7) Calculated as for raw manure (Table G-3), but for storage, it was considered that TAN is 77% of the total N, and for field application, 79% of the total N

(8) Calculated as for raw manure (Table G-3), but for storage, it was considered that TAN is 77% of the total N

(9) Processes related to the production and application of marginal mineral fertilizers were taken from the Ecoinvent database, with the same specifications as indicated in Table 4 for raw manure.

(10) Harvest process is as in Table G-6; storage process considers that 1.1% of the initial DM is lost on the basis of (Kreuger et al., 2011), and NH_3-N losses of 0.077 kg per t of harvested straw (Hamelin et al., 2014, p.S28-S30); extrusion pre-treatment only considers an input of 14.5 kWh per t of straw ex-storage, which has here been taken as coal-based electricity (on the basis of the Ecoinvent process "electricity, hard coal, at power plant/NORDEL U"). The latter should of course be made consistent with the pathway scenario considered.

(11) Biogenic flows, as in Table G-6, plus avoided stubble harrowing (Table G-6)

G.6 Limitation

One clear limitation of the inventories presented in this Appendix, in the perspective of direct use for the modeling of several energy pathways, lies in the use of the data from the Ecoinvent v2.2 database for background processes. In fact, many of these processes require electricity/heat/fuel input, and these often involve fossil fuels, and as such may not necessarily always be consistent with the pathways under analysis, especially for the scenarios with 100% renewable energy.

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Appendix H The GLOBIOM model

The function and characteristics of these SSPs are:

- SSP1: SUSTAINABILITY
  - economic growth: high (global GDP per capita reach 20 000 USD by 2050)
  - demographic growth: low (from current 7 B to 8 B in 2050); European population is highest here
  - education level: high
  - technological growth: fast
  - developed vs developing countries: convergence
  - international cooperation: high
  - sustainability concerns: high
  - to reflect better management of domestic waste in developed countries, consumption per capita assumed almost constant (for developed countries)
  - animal protein demand reduced in regions where more than 75 g protein/cap/d are consumed for animal and vegetable products, but min of 25 is ensured (from animal)
  - red meat reduced to 5 g protein/cap/d
  - developing countries: protein intake at 75 g protein/cap/d ensured, reduction of root consumption at a level of 100 kcal/cap/d

- SSP2: BAU
  - Demographic growth (from current 7 B to 9 B in 2050)
  - Future diet follow projections of (FAO 2006) for 2050

- SSP3: FRAGMENTATION
  - economic growth: slow (global GDP per capita < 10 000 USD by 2050)
  - demographic growth: high (from current 7 B to 10 B in 2050); European population is lowest here
  - low food demand per capita

Crop yields

- Econometric relationship between crop yield and GDP per capita established:
  - Crop yield from FAOSTAT fitted to GDP per capita over 1980-2009
  - Countries grouped based on world bank economic groups
  - Estimation carried out for each of the 18 crops of the database separately

- N utilization vs. yield:
  - SSP2: Proportional increase of N utilization to yield growth (elasticity = 1)
  - SSP1: decreasing N intensity (elasticity = 0.75)
  - SSP3: increasing N intensity (elasticity = 1.25)

(permanent increase of 1% in crop price result in an increase of 1%, 0.75% and 1.25% (respectively) of N utilization)

Results of the runs of the baseline SSPs. All results for 2050, relative to 2000

	SSP1	**SSP2**	**SSP3**
Calorie comsumpt per capita, 2050	No change	+14%	+3%
Crop consumption	+12%	+10%	
Livestock consumption	+19%	+37%	
Demand for 1st gen biofuels	9% of all crop production, in terms of calories (largest)		
Crop price index, world	0.97	1.03	1.13
Land cover	Tot expansion ≈ **275 Mha**	175 Mha additional cropland 300 Mha additional grassland 150 Mha additional for short rotation tree plantations (total expansion = **625 Mha**: 35% in forest; 65% in other natural land) = 4.4 Mha deforestation/y	Tot expansion ≈ **575 Mha**
Yield change 2000-2050	+52	+70%	+55
N comsumpt	+40%	+60%	+61%
Irri water	+5%	+12%	+13%
GHG	-14%	+34	

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