Inventory report for modelling direct land use changes of perennial and annual crop in Denmark

Version 0. Presented for the CEESA WP5 report.

Lorie Hamelin

Institute of Chemical Engineering, Biotechnology and Environmental Technology, Faculty of Engineering,
University of Southern Denmark, Campusvej 55, 5230 Odense M., Denmark.

January 2011

This document is currently under progression. Therefore, it should be noted that this is not the final version.

Table of Contents

1. General description

This study discusses the perspective of agricultural biomass (energy crops and crops residues) in a 100 % renewable energy system in Denmark for 2050. Using agricultural biomass as part of the Danish energy strategy involves changes in the land use allocation in Denmark, resulting in perturbations of the biogeochemical flows between the land and the atmosphere.

The goal of this study is to provide life cycle inventory (LCI) data in order to model the direct environmental consequences of turning one hectare of Danish land to bioenergy production.

This report presents the inventory of all substances flows for the cultivation of one hectare of miscanthus (autumn and spring harvested), willow, spring barley, spring barley combined with a catch crop, winter wheat, sugar beet, rye grass and silage maize. This inventory is based on the conditions encountered on the field as of today.

For each of these crops, two climate are considered (“wet” and “dry”) as well as two soil types (sand [JB3] and sandy loam [JB6]) and two initial soil C content (“high C” and “low C”). Moreover, two residues management practices are considered (“with harvest” and “without harvest”). This applies for harvestable residues only.

Emissions of CO_2 due to soil carbon changes are accounted for. Changes in soil C are limited in duration, until a new equilibrium is established. In this project, two timescale are used for the time needed for the establishment of this equilibrium: 20 years and 100 years.

Figure 1 presents the overview of the data structure for this life cycle inventory. As illustrated, a total of 432 combinations are considered, for which the output flow of substances through the different pre-storage agricultural activities are determined.

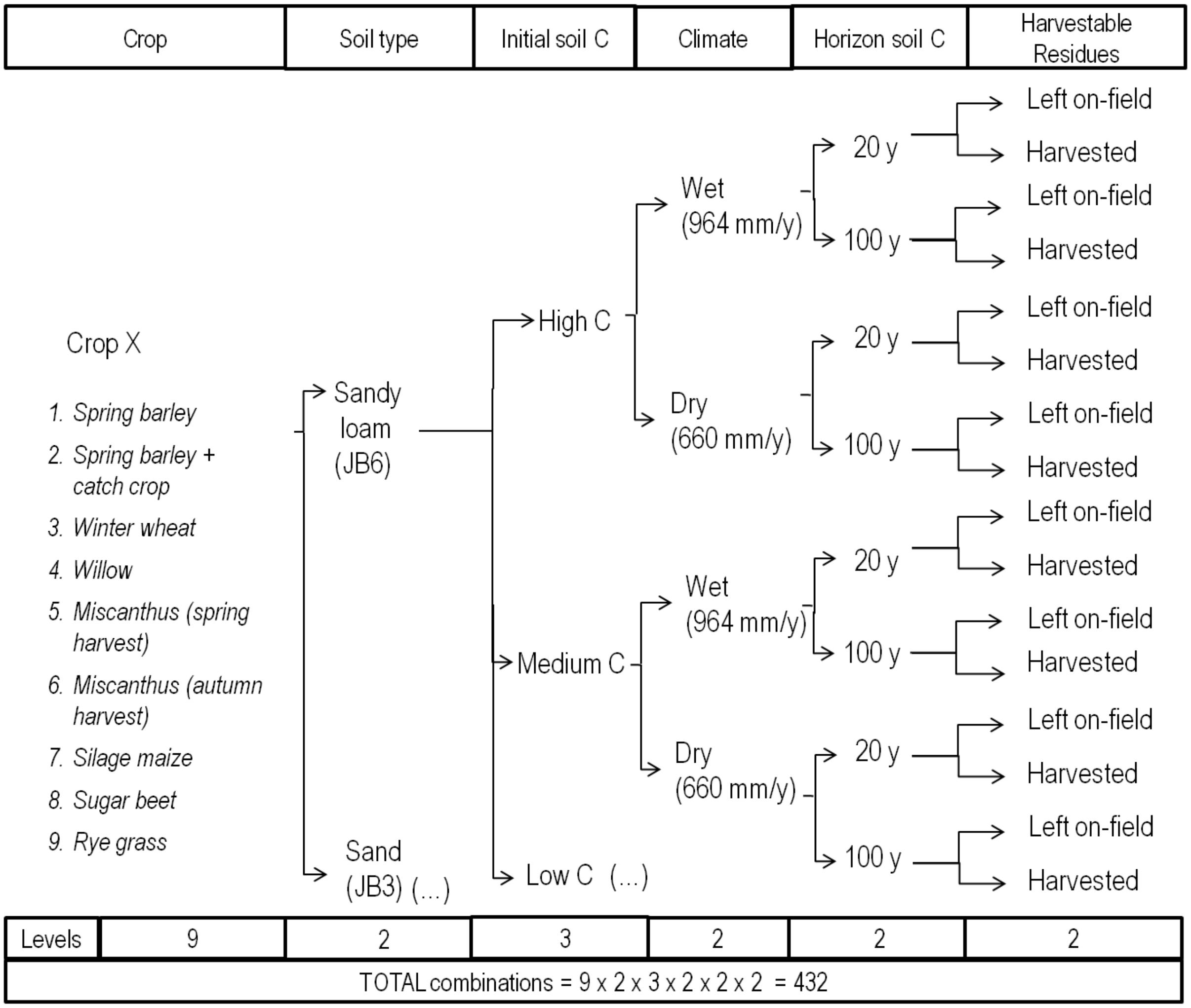

Figure 1. Simplified illustration of the different combinations considered in the life cycle inventory.

As the estimation of some data require defining a specific spatial location (ex. N leaching), the “wet climate” scenarios are based on conditions at Jyndevad, considering an annual precipitation of 964 mm. The “dry climate” scenarios are based on conditions at Roskilde, considering an annual precipitation of 660 mm.

2. Overview of the life cycle of selected crops

2.1 Perennial and annual selected crops

Ideal biomass for bioenergy should provide a high energy output for a minimum of input (in terms of energy, resources and money). Such biomass-for-bioenergy issued from energy crops may be divided into two categories: biomass coming from annual crops and biomass coming from perennial crops. Perennial crops refer to crops whose life cycle are at least 2 years, so these crops do not need to be sown annually, as opposed to annual crops. The present study includes a mix of perennial and annual crops, as shown in Table 1.

Table 1. Perennial and annual crops included in the study

Crop included in the study	Annual or perennial	Photosynthesis type	Duration of the plantation considered in this project (year)	Number of cycles for C horizon considered	
				20 y	100 y
Spring barley	Annual	C_3	1	20	100
Spring barley + catch crop	Annual	C_3	1	20	100
Winter wheat	Annual	C_3	1	20	100
Miscanthus (spring harvest)	Perennial	C_4	20	1	5
Miscanthus (autumn harvest)	Perennial	C_4	20	1	5
Willow	Perennial	C_3	24	24/21	100/21
Silage maize	Annual	C_4	1	20	100
Sugar beet	Annual	C_3	1	20	10
Perennial rye grass	Perennial	C_3	2	10	50

During photosynthesis, CO_2 is converted into organic compounds using water and energy from sunlight. The main organic compounds formed are cellulose/starch ($[C_6H_{10}O_5]_n$), hemi-cellulose ($[C_5H_8O_4]_n$), lignin ($[C_{10}H_{12}O_3]_n$) as well as energy storage and building material compounds (e.g. lipids, carbohydrates, proteins). Cellulose occurs as a principal structural component of the cell walls of plants and is a polymer of glucose (large number of monomer) while hemi-cellulose is an oligomer (only a few monomer) of C_5 and C_6 sugars. In contrast to cellulose, hemicelluloses present a structure giving them little resistance to hydrolysis. Cellulose is constituted of microfibrils that are attached to each other by, among other, hemicelluloses, and that are covered by lignin. Lignin is a highly cross-linked polymer very stable and very resistant to chemical and biological degradation (Taherzadeh and Karimi, 2008).

The chemical composition of the selected biomass therefore influences the conversion route to energy. For example, while sugar and starch are suitable for fermentation, lignin is very resistant to biochemical conversion and thereby more suitable for combustion (to produce heat and power instead of a liquid fuel). On the other hand, protein is essentially a component for food/feed, which renders crops with high protein content likely to be prioritized for food and feed. Table 2 presents the chemical composition of all selected crops, except willow and miscanthus, which are presented in table 3 with a particular focus on the lignin, hemicellulose and cellulose content. **These values should be seen as indicative rather than as absolute**. In table 2, the composition of wheat straw, barley straw and sugar beet top is also presented.

Table 2. Chemical composition of the selected crop, including straw and beet top and excluding willow and miscanthus[1]

Crop	DM (%)	Composition				
		Carbohydrates (% of DM)			Protein (% of DM)	Lipid (% of DM)
		Sugar (mono- and di-saccharide)	Starch	Lignine, Hemicellulose, Cellulose		
Spring barley	85	2.0	60.9	20.7	11.2	2.9
Spring barley straw	85	0.0	0.0	89.6	4.0	1.9
Winter wheat	85	3.2	68.0	12.9	11.9	2.2
Winter wheat straw	85	0.0	0.0	91.7	3.3	1.9
Silage maize	31	2.0	29.0	53.9	8.7	2.2
Sugar beet (without top)	22	69.4	0.0	16.4	5.9	0.3
Sugar beet top	12	12.0	0.0	47.9	16.4	4.6
Perennial rye grass	18	13.0	0.0	53.1	20.0	3.9

[1] All data are taken from Møller et al. (2000). The balance (to obtain a total of 100 %) corresponds to the ashes. The values for perennial rye grass correspond to "varigt enggræs" and for silage maize, the values corresponds to "Majs ensilage, middle FK".

Table 3. Content of lignine, hemicelluloses and cellulose in miscanthus and willow

Crop	Unit	Lignine	Hemicellulose	Cellulose	Comment[1]
Miscanthus (spring harvest)	g/kg DM	98.01	293.89	454.71	1
Miscanthus (autumn harvest)	g/kg DM	80.81	295.20	393.13	1
Willow	% of DM	23.7	31.2	44.2	2

[1] 1. Values from Hodgson et al. (2010). The values considered here are the mean for all Miscanthus species in the geographic location "Denmark", in table 4 to 9;

2. Values from Villegas et al. (2009). These values represent the mean of the 6 values presented for "young salix" (all young trees for both willow species and for site 1, site 2 and site 3). The lignine corresponds to the total lignine.

The crops selected are those which are likely to respond to an eventual change in demand of biomass-for-energy in Denmark (the production of some may increase, and some may be simply displaced). In fact, different LCA carried out in Europe identified, based on Weidema (2003), spring barley as the crop displaced by an increased demand for other crops (e.g. Schmidt, 2008; Dalgaard et al., 2007). This is because Weidema (2003) highlights spring barley as the crop with the lowest gross margin. However, this is based on statistics from 1992 and 1997. Recent outlook from Ireland (O'Mahony and O'Donovan, 2010; Clancy and Thorne, 2010) and from the UK (HGCA, 2010) tend to confirm spring barley as the crop with the lowest gross margin. Assuming spring barley as the displaced crop also makes sense on an agronomic point of view, since it is consistent with the assumption that displaced cropland (from food market to energy market), comes from the lower quality soils (i.e lower productivity land), leading to soils where spring barley is actually cultivated.

Similarly, winter wheat and grassland were identified by St.Clair et al. (2008) as potential land uses to be displaced in the UK. It is important to include these potential displaced crops in the database in the perspective of fully assessing the consequences of changes in the use of agricultural land in Denmark. Oilseed crops are not included as they have been proven to represent a land utilisation alternative yielding fairly low benefits compared to other land use options (Hedegaard et al., 2008).

For perennials, the overall life cycle duration of the crops was fixed at 20 years for miscanthus (18 cuts; 1 year establishment: 1 year preparation before planting) and 21 years for willow (6 cuts; 3 years harvest cycle; 1 year establishment; 1 year preparation before planting). The preparation before planting refers to the herbicides applied in the year before planting and the establishment refer to the first year of growth where no harvest is performed. For perennial ryegrass, the lifetime was fixed at 2 years.

As shown in Figure 1, the effect of combining a catch crop with spring barley is also investigated. The catch crop is a non-commercial crop grown to catch available N in the soil during the autumn period (i.e. just after harvest of the main crop, when temperature and light conditions still allow some plant growth), thereby allowing to prevent (or to reduce) N leaching (Thorup-Kristensen et al., 2003).

2.2 Miscanthus lifecycle considered in this study

The Miscanthus specie typically used as a bioenergy crop in Europe, Miscanthus x Ginganteus, is sterile (Christian et al., 2008; DEFRA, 2007) and requires vegetative propagation to produce new plants (this is however not the case for Miscanthus sinensis, which does produce viable seeds). Yet, this is expensive, which means that the crop must remain productive for several years to ensure that the plantation pays off (Christian and Riche, 1999). The average duration of a plantation reported in the literature oscillates around 20 years. Styles et al. (2008), for example, used a 16 years cycle (14 cuts) for miscanthus, though they recognize that the lifetime they used may be a little conservative. Ercoli et al. (1999) as well as Lewandowski et al. (1995) also mentions a lifetime of 15 years for miscanthus while Schhneckenberger and Kuzyakov (2007) refer to a range of 15 to 25 years and Heaton et al. (2004) to a range of 10 to 20 years. Similarly, DEFRA (2007) as well as Atkinson (2009) mentions a lifetime of 15 to 20 years and Lewandowski and Heinz (2003) refer to an estimated life of about 20 years for a miscanthus plantation. Monitored long-term experiments however do not go beyond 15 years of data (e.g. Clifton-Brown et al., 2007; Christian et al., 2008).

Such a life time requires, in the year prior to planting (year 1 of the life cycle), site preparation operations (i.e. herbicides application and tillage operations) to ensure a good establishment. The first year after planting (year 2 of the life cycle), also called the establishment period, no harvest is perform. After that, stems, once lignified, can be harvested every year until the end of the plantation life cycle (year 3 to year 20, in this study). However, in Denmark, only 40 to 60 % is harvested on the first harvest year, and full harvest is reached on the subsequent years. In this study, it is assumed that 60 % is harvested the first harvest year (year 3) and 100 % thereafter. Herbicides are applied every year until the first harvest (year 1, 2 and 3). Then, one treatment each 4th year to clean up for certain problematic weed species is applied.

Miscanthus is a C4 photosynthesis grass, meaning that the first product of photosynthesis is a four-carbon organic acid, instead of a three-carbon molecule as for most crops in the temperate zone. This results, among others, in a more efficient conversion of CO_2 and consequently in a higher rate of sugar formation, in comparison to C3 photosynthesis plants. Miscanthus species have in fact high yields of ligno-cellulose (Clifton-Brown et al., 2007). Greater water efficiency is also a typical advantage of C_4 species (Atkinson, 2009).

New shoots are formed from the rhizome system every year and emerge during spring. In Denmark, this may occur as late as late April (Jørgensen, 1997). Lower leaves start to dry during mid to late summer, and nutrients are moved back to rhizome during autumn (DEFRA, 2007). Miscanthus can in fact store around 30 % of its total dry matter in root and rhizomes (Bullard et al., 1995). Miscanthus is harvested when stems are dead (Christian et al., 2008), whether in autumn or in spring. During winter, there are significant losses of leaves and tops, consequently involving lower DM yield when miscanthus is harvested in spring. However, delaying harvest to spring leaves time for the stems to dry to a lower moisture content (around 20 to 30 %, based on a personal communication with Uffe Jørgensen, 2010), thus involving lower energy requirements for drying. Moreover, delayed harvest allows a lower mineral concentration in the harvested biomass as a result of nutrients relocation from shoots to rhizomes (especially N and K), leaves losses (especially N) and leach of soluble ions from ripening plant material (K and Cl) (Jørgensen, 1997; Lewandowski and Heinz, 2003). This lower mineral concentration of the biomass allows a better combustion quality, which is of importance when combustion is the conversion route to energy. The carbon from the leaves and tops losses can contribute to soil C pool replenishment. Based on Lewandowski and Heinz (2003), spring harvest is also more suitable on an economical perspective than autumn harvest, due to the high cost of the whole stem harvester required for autumn harvest and because it allows to save on drying costs. On the other hand, the energy gain obtained through higher yields when miscanthus is harvested in autumn may compensate the energy needed to dry the biomass, even in spite of the relatively high water content (which may reach around 60 to 70 %, based on Jørgensen, 1996). Moreover, if CHP is the privileged conversion route, spring harvest involves the need for storage capacity (which implies associated costs) as most of the heat demand is in the winter months and is very low during summer months.

Because both harvest periods lead to different trade-offs and because this may influence the conversion route of the harvested biomass, both autumn and spring harvest are included in this life cycle inventory for miscanthus.

2.3. Willow life cycle considered in this study

Ledin (1996) mentions that a willow plantation can be used between 20 to 30 years. Nordh (2005) mentions an expected lifespan for a commercial plantation of 25 years, involving 6 to 7 harvests before ending the plantation. Styles et al. (2008), in their life cycle assessment, used a 23 years cycle (7 cuts) for willow. Brandão et al. (2010) assumed a 16-years rotation, though they mentioned that the productive period vary between 15 to 30 years. For the present study,an overall life cycle of 21 years is judged representative of Nordic conditions. As for miscanthus, the year prior the planting (year 1 of the life cycle), herbicides are applied to control perennial weeds. For the first harvest cycle, one extra year is often needed, i.e. the first harvest occurs 4 years after the plantation year, which is on year 2. This is what has been considered in this project (first harvest year 6). Herbicides are applied on year 1, 2, 3 and 6 (after first harvest) and then a systemic herbicide (glyphosate) is applied every other rotations. Fertilisation is performed the year after planting (year 3) and then on every harvest year (after the harvest) as well as the year after each harvest. Under Danish conditions, in practice, slurry spreading is only possible in harvest years.

2.3. Perennial ryegrass

Perennial ryegrass is a C3 crop. No establishment period is involved for this crop, so harvest is performed every year. In this study, a 2 years lifetime was assumed (i.e. sowing every 2 years).

2.4 Summary of the activities over the life cycle of each crop

Summary of specific information for willow and miscanthus about herbicides and fertiliser application as well as harvest is provided on table 4. An overview of life cycle activities included for all selected crops as well as their occurrence for a 20 and a 100 year period is presented in table 5.

Table 4. Summary of occurrence of plant protection, fertilisation and harvesting activities for miscanthus and willow.

Year	Miscanthus	Year	Willow
1	Herbicide application. No fertilisation.	1	Herbicide application. No fertilisation.
2	Fertiliser application. Planting. Herbicide application.	2	Herbicide application. Planting
3	Fertiliser application. First harvest (60 %). Herbicide application.	3	Fertiliser application (100 % mineral). Herbicide application.
4-20	Year 3 repeated, but full harvest. An herbicide treatment each 4th year (year 4, 8, 12 and 16).	6	First harvest. Fertiliser application (100 % slurry). Herbicide application.
		7	Fertiliser application (100 % mineral)
		9	Second harvest. Fertiliser application (100 % slurry).
		10	Fertiliser application (100 % mineral)
		12	Third harvest. Fertiliser application (100 % slurry). Herbicide application.
		13	Fertiliser application (100 % mineral)
		15	Fourth harvest. Fertiliser application (100 % slurry).
		16	Fertiliser application (100 % mineral)
		18	Fifth harvest. Fertiliser application (100 % slurry). Herbicide application.
		19	Fertiliser application (100 % mineral)
		21	Final harvest

Table 5. Overview of the different processes included in the life cycle and their frequency of occurrence for a 20 years and a 100 years period.

Crop	Operation	Description	Frequency for a 20 years period	Frequency for a 100 years period
Annuals	Propagation	Production of the seeds to be planted.	20	100
	Soil preparation	Includes all tillage activities.	20	100
	Liming	Production and application of lime, including the "consumption" of machinery needed. Once every 5 years.	4 (20 rotations)	20 (100 rotations)
	Sowing	Sowing of the seeds, including the "consumption" of machinery needed.	20	100
	Plant protection	Production and application of plant protection products, including the "consumption" of machinery needed.	20	100
	Fertilisation	Production of mineral fertilisers and application of organic and mineral fertilisers, including the "consumption" of machinery needed.	20	100
	Irrigation	Irrigation of crops, including energy and infrastructure needed.	20	100
	Harvest	Harvest of crops, including the "consumption" of machinery needed.	20	100
Miscanthus/willow	Propagation	Production of rhizomes/cuttings. Once per 20 years for miscanthus, and once per 21 years for willow.	1 (Miscanthus) 20/21 (willow)	5 (Miscanthus) 100/21 (willow)
	Soil preparation	Includes all tillage activities.		
	Liming	Process as for annuals. Frequency assumed: once per 20 years.	1 (Miscanthus)	5 (Miscanthus)
	Sowing (planting)	As for annuals. Performed only once over the crop life cycle (20 years for miscanthus, 21 years for willow).	1 (Miscanthus) 20/21 (willow)	5 (Miscanthus) 100/21 (willow)
	Plant protection	As for annuals, but here, different amount are applied for the given years.	Miscanthus: 1 (application year 1, 2, 3) Willow: 20/21 (application year 1, 2, 3, 6, 12, 18)	Miscanthus: 5 (same pattern as for 20 years) Willow: 100/21 (same pattern as for 20 years
	Fertilisation	For miscanthus, different amounts are applied in years 1, 2, 3, and then the same amount is applied for years 4-20. One process is made for years 4-20, one for year 2 and one for year 3. No application on year 1. For willow, fertilisation is first performed the year after planting (year 3), each harvest year except for the last one, and each first post-harvest year.	Miscanthus: 19 (but different amount applied on year 2 and 3) Willow: 13*(20/21)	Miscanthus: 95 (same pattern as for 20 years) Willow: 13*(100/21)
	Irrigation	No irrigation for willow and miscanthus.	-	-
	Harvest	For miscanthus, 18 harvests; for willow, 6 harvests.	Miscanthus: 18 Willow: 7*(20/21)	Miscanthus: 90 Willow: 7*(100/21)
Ryegrass (lolium perenne)	Liming	As for miscanthus/willow	1 (2 rotations)	5 (10 rotations)
	Sowing	As for annuals, but only once every 10 years	2	10
	Others	All other operations as for annuals	20	100

3. Use of electricity

Some of the processes in this life cycle inventory require electricity input (e.g. pumping in the irrigation system).

As consequential LCA uses marginal data, the electricity considered is the marginal electricity, i.e. the electricity from the technology (and source) that would react to the demand of one more unit of electricity.

Conformingly with Weidema (2003) and Ekvall and Weidema (2004), one key step in determining the marginal supplier is the identification of the market trend for the process or activity of interest: Under a rising market trend, the marginal supplier is the most competitive one; under a decreasing market trend, the marginal supplier is the least competitive, i.e. the one that is taken out of production.

In this project, the concept of complex marginal technologies introduced by Mathiesen et al. (2009) is acknowledged, i.e. that the marginal technology shift from one hour to another depending on the variations in both heat and power demand. This involves that the annual marginal is a set of different technologies.

According to the authors, this set of affected technologies should be identified from a comprehensive energy system analysis that takes into account seasonal and diurnal fluctuations as well as the integration of fluctuating resources into the energy system such as wind power.

Lund et al. (2010) did, through the use of the EnergyPlan deterministic model (described in Lund, 2010), calculate such a composite electricity marginal for Denmark, based on a hour-by-hour electricity demand. The complex electricity marginal selected in this study is adapted from the simulation performed by Lund et al. (2010). This consists of 1 % wind, 51 % coal (at power plant and CHP) and 43 % natural gas (at power plant and CHP). The remaining 5 % consist of excess electricity production (e.g. because of high wind conditions) that is then used for replacing heat production in district heating.

The complex marginal presented in the simulations by Lund et al. (2010), for coal and natural gas, does not consist of production at power plant only but also at small and large combined heat and power plant (CHP). This means that the system is reacting for the heat production since both heat and power are produced at CHP plants. This reaction has been calculated in the simulations by Lund et al. (2010), which also includes the credit obtained by the use of excess electricity.

In this study, the high voltage electricity production, i.e. out from the energy plant, is based on Lund et al. (2010) (table 3, BAU + PP-Ngas) and uses the processes from the Ecoinvent database (v2.0). However, for the electricity produced in combined heat and power, the process is modelled as for electricity produced in a power plant only, because there are no appropriate cogeneration processes in the Ecoinvent database (they are all allocated and it is without the scope of this study to re-build such process). The heat that is reacting is however included, based on Lund et al. (2010), and similarly it is accounted for as heat producing unit only when CHP units are concerned.

Table 6 presents the high electricity voltage process used for this study.

Table 6. High voltage Danish marginal electricity process, at power plant[1]

Output	**Amount**	**Comment**
Electricity, high voltage, Danish marginal, at power plant	1 kWh	
Inputs	**Amount**	**Comment**
Electricity, at wind power plant/RER U	0.01 kWh	Based on Lund et al. (2010) see text. This Ecoinvent process for wind is documented in Burger and Bauer (2007).
Electricity, hard coal, at power plant/NORDEL U	0.51 kWh	Based on Lund et al. (2010) see text. This amount includes the production from power plant (0.49 kWh) and from large CHP plant (0.02 kWh). This Ecoinvent process for coal at power plant is documented in Dones et al. (2007).
Electricity, natural gas, at power plant/NORDEL U	0.43 kWh	Based on Lund et al. (2010) see text. This amount includes the production from power plant (0.18 kWh), from large CHP plant (0.09 kWh) and from small CHP plant (0.16 kWh). This Ecoinvent process for natural gas at power plant is documented in Faist-Emmenegger et al. (2007).
Heat, at hard coal industrial furnace 1-10MW/RER U	-0.03 kWh	Based on Lund et al. (2010), see text. This amount includes the production from large-CHP coal (0.13 kWh) and from coal boiler (-0.16 kWh). This Ecoinvent process for heat from coal is documented in Dones et al. (2007).
Heat, natural gas, at boiler condensing modulating >100 kWh/RER U	0.08 kWh	Based on Lund et al. (2010), see text. This amount includes the production from small-CHP natural gas (0.20 kWh) and from natural gas boiler (-0.12 kWh). This Ecoinvent process for heat from natural gas is documented in Faist-Emmenegger et al. (2007).

[1] The excess electricity used in an electric boiler and the resulting heat from it is not presented in this table as it cancels out.

This high voltage electricity then goes through the transmission network (medium voltage electricity), and the process used to model this is based on the Ecoinvent process “Electricity, medium voltage, production Nordel, at grid/NORDEL U”. The process used for this study is in fact exactly the same, except that the high voltage electricity used is the one presented in table 6 above. This is presented in Table 7.

Table 7. Medium voltage Danish marginal electricity process, at transmission network

Output	**Amount**	**Comment**
Electricity, medium voltage, Danish marginal	1 kWh	
Inputs	**Amount**	**Comment**
Electricity, high voltage, Danish marginal, at power plant	1.0093 kWh	As defined in Table 6.
Sulphur hexafluoride, liquid, at plant/RER U	3.7262 x 10^{-8} kg	
Transmission network, electricity, medium voltage/CH/I U	3.24 x 10^{-8} km	
Emissions to air		
Heat, waste	0.018338 MJ	
Sulphur hexafluoride	3.7262 x 10^{-8} kg	
Emission to soil		
Heat, waste	0.015004 MJ	

The electricity used at the consumer level (at the farm, in the case of this study) is the low voltage electricity at the distribution network. Similarly to the procedure used for medium voltage, the low voltage marginal is built based on the Ecoinvent process “Electricity, low voltage, production Nordel, at grid/NORDEL U”. This is presented in Table 8.

Table 8. Low voltage Danish marginal electricity process, at distribution network (at consumer)

Output	**Amount**	**Comment**
Electricity, low voltage, Danish marginal	1 kWh	
Inputs	**Amount**	**Comment**
Electricity, medium voltage, Danish marginal	1.0947 kWh	As defined in Table 7.
Sulphur hexafluoride, liquid, at plant/RER U	2.1854 x 10^{-9} kg	
Transmission network, electricity, low voltage/CH/I U	2.94 x 10^{-7} km	
Emissions to air		
Heat, waste	0.067695 MJ	
Sulphur hexafluoride	2.1854 x 10^{-9} kg	
Emission to soil		
Heat, waste	0.20308 MJ	

For the 2050 scenario, a sensitivity analysis is carried out for an energy marginal being 100 % renewable. This is presented in the 2050 scenario section.

4. Transport distance between farm and field

The transport distance considered between the farm (i.e. where the machinery, slurry and other inputs are stored, as well as the crops products) and the field is estimated as 1 km, based on the Ecoinvent database. Loaded inputs, like slurry, mineral fertilisers or pesticides that needs to be transported to the field are accounted for through their respective processes (e.g. slurry spreading process, fertilising process and application of pesticides), assuming this 1 km distance.

The process “transport, tractor and trailer” from the Ecoinvent database **is used for every operation where a load needs to be transported between the field and the farm**. This applies for the harvested grain and the harvested straw. The Ecoinvent process “transport, tractor and trailer” takes into account that the loaded tractor is loaded at full capacity only in one direction and comes back empty. The process is expressed in tkm, i.e. one tonne of good transported over 1 km. Table 9 presents the tonnes of fresh product to be transported for each product to transport. A diesel consumption of 0.0436 kg per tkm is considered.

Table 9. Tonnes of fresh product to be transported, for each product to be transported

Product to transport	Tonnes of fresh product/ha*y (to transport over 1 km)	Comment
Spring barley, JB3	5	See table 35 for fresh yield.
Spring barley, JB6	5.7	See table 35 for fresh yield.
Winter wheat, JB3	6.6	See table 35 for fresh yield.
Winter wheat, JB6	8.0	See table 35 for fresh yield.
Sugar beet	56.6	See table 35 for fresh yield.
Rye grass, JB3	55.42	See table 35. 8600 FE/ha*1.16 kg DM/FE * kg fresh weight/0.18 kg DM * t/1000 kg. DM in crop from Møller et al. (2000).
Rye grass, JB6	48.98	7600 FE/ha*1.16 kg DM/FE * kg fresh weight/0.18 kg DM * t/1000 kg. DM in crop from Møller et al. (2000).
Willow, JB3, wet	21.2	Assuming 0.50 t dry weight/ t fresh weight, based on Heller et al. (2003); Jensen et al. (2009); Ledin (1996) and Mleczek et al. (2010).
Willow, JB3, dry	14.2	Assuming 0.50 t dry weight/ t fresh weight, as for willow, JB3, wet.
Willow, JB6, wet	25.44	Assuming 0.50 t dry weight/ t fresh weight, as for willow, JB3, wet.
Willow, JB6, dry	21.62	Assuming 0.50 t dry weight/ t fresh weight, as for willow, JB3, wet.
Miscanthus, autumn, wet, 4-20	34.66	Assuming 0.44 t dry weight/ t fresh weight, based on Kristensen (2003).
Miscanthus, autumn, dry, JB3, 4-20	29.45	Assuming 0.44 t dry weight/ t fresh weight.

Miscanthus, autumn, dry, JB6, 4-20	34.66	Assuming 0.44 t dry weight/ t fresh weight.
Miscanthus, spring, wet, JB3, 4-20	11.76	Assuming 0.85 t dry weight/ t fresh weight, based on Kristensen (2003)
Miscanthus, spring, dry, JB3, 4-20	10.00	Assuming 0.85 t dry weight/ t fresh weight.
Miscanthus, spring, JB6, 4-20	11.06	Assuming 0.904 t dry weight/ t fresh weight.
Miscanthus, autumn, wet, y3	12.48	Only 60 % harvest. Assuming 0.44 t dry weight/ t fresh weight.
Miscanthus, autumn, dry, JB3, y3	10.61	Only 60 % harvest. Assuming 0.44 t dry weight/ t fresh weight.
Miscanthus, autumn, dry, JB6, y3	12.48	Only 60 % harvest. Assuming 0.44 t dry weight/ t fresh weight.
Miscanthus, spring, wet, JB3, y3	4.23	Only 60 % harvest. Assuming 0.85 t dry weight/ t fresh weight.
Miscanthus, spring, wet, JB6, y3	3.98	Only 60 % harvest. Assuming 0.904 t dry weight/ t fresh weight.
Miscanthus, spring, dry, JB3, y3	3.60	Only 60 % harvest. Assuming 0.85 t dry weight/ t fresh weight.
Miscanthus, spring, dry, JB6, y3	3.98	Only 60 % harvest. Assuming 0.904 t dry weight/ t fresh weight.
Spring barley straw, JB3	2.75	See table 35. Considering 0.85 t dry weight/ t fresh weight, from Møller et al. (2000).
Spring barley straw, JB6	3.14	See table 35. Considering 0.85 t dry weight/ t fresh weight, from Møller et al. (2000).
Winter wheat straw, JB3	3.64	See table 35. Considering 0.85 t dry weight/ t fresh weight, from Møller et al. (2000).
Winter wheat straw, JB6	4.4	See table 35. Considering 0.85 t dry weight/ t fresh weight, from Møller et al. (2000).
Sugar beet top	13.5	See table 35. Considering 0.12 t dry weight/ t fresh weight, from Møller et al. (2000).

5. Propagation (seeds, cuttings or rhizomes production)

Crops from agricultural production need to be propagated, e.g. through seeds (all annual crops and permanent rye grass), cuttings (willow) or rhizomes (miscanthus). This stage is not systematically included in LCA and LCI, and when it is, it is rarely transparent and detailed.

As a first step, the amount of seed, rhizome or cutting needed per 1 ha of land cultivated with each of the selected crop must be determined. This was done mostly based on the Ecoinvent database as well as on some literature data, as shown in table 10.

Table 10. Amount of seed, cutting or rhizome needed for each crop, for main scenarios

Crop	Seed, cutting or rhizome needed	Reference	Comment
Spring barley	0.014484 kg seed per kg (wet) primary yield (72.42 kg seed ha^{-1} on JB3 and 82.64 kg seed ha^{-1} on JB6 ; see Note 1)[1]	Nemecek and Kägi (2007)	Process "barley grains IP, at farm/CH U"
Catch crop	As for ryegrass		
Winter wheat	0.02591 kg seed per kg (wet) primary yield (171.00 kg seed ha^{-1} on JB3 and 207.28 kg seed ha^{-1} on JB6; see Note 2)[1]	Nemecek and Kägi (2007)	Process "wheat grains IP, at farm/CH U"
Miscanthus	20 000 rhizomes ha^{-1}. This corresponds to 0.1 ha rhizomes per ha miscanthus, since 1 ha supplied rhizomes to plant 10 ha at 20000 rhizomes/ha (Styles and Jones, 2007)	Styles et al. (2008); Atkinson (2009); Styles and Jones (2007)	Planted the second year
Willow	15 000 cuttings ha^{-1}. 15 000 cuttings are needed for this, meaning 1 ha "willow for cuttings production" per ha willow.	Personal communication with Jens B. Kjeldsen, (DJF). To be seen as a maximal value.	Planted the second year
Sugar beet	2.9405 x 10^{-5} kg seed per kg (wet) primary yield (1.66 kg seed ha^{-1} on JB3 and JB6; see Note 3)[1]	Nemecek and Kägi (2007)	Process "sugar beets IP, at farm/CH U".
Silage maize	0.00043933 kg per kg (wet) primary yield (17.08 kg seed ha^{-1} on JB3 and 16.91 kg seed ha^{-1} on JB6; see Note 4)[1]	Nemecek and Kägi (2007)	Process "silage maize IP, at farm/CH U".
Ryegrass	0.00098765 kg seed per kg (wet) primary yield (54.76 kg seed ha^{-1} on JB3 and 48.39 kg seed ha^{-1} on JB6; see Note 5)[1]	Nemecek and Kägi (2007)	Process "Grass from meadow intensive IP, at field/CH U"

[1] All data for DM content used in note 1 to note 5 are from Møller et al. (2000) and yields (kg DM/ha) are from table 46.

Note 1: Spring barley on:
JB3: 0.014484 kg seed/kg (wet) primary yield * kg primary yield/0.85 kg DM * 4.25 * 10^3 kg DM/ha = 72.42 kg seed/ha;
JB6: 0.014484 kg seed/kg (wet) primary yield * kg primary yield/0.85 kg DM * 4.85 * 10^3 kg DM/ha = 82.64 kg seed/ha;

Note 2: Winter wheat on:
JB3: 0.02591 kg seed/ kg (wet) primary yield * kg primary yield/0.85 kg DM * 5.61 * 10^3 kg DM/ha = 171.00 kg seed/ha;
JB6: 0.02591 kg seed/ kg (wet) primary yield * kg primary yield/0.85 kg DM * 6.80 * 10^3 kg DM/ha = 207.28 kg seed/ha;

Note 3: Sugar beet on:
JB3 and JB6: 2.9405 x 10^{-5} kg seed/kg (wet) primary yield * kg primary yield/0.22 kg DM * 12.45 * 10^3 kg DM/ha = 1.66 kg seed/ha;

Note 4: Silage maize on:
JB3: 0.00043933 kg seed/ kg (wet) primary yield * kg primary yield/0.31 kg DM * 12.05 * 10^3 kg DM/ha = 17.08 kg seed/ha;
JB6: 0.00043933 kg seed/ kg (wet) primary yield * kg primary yield/0.31 kg DM * 11.93 * 10^3 kg DM/ha = 16.91 kg seed/ha;

Note 5: Ryegrass on:
JB3: 0.00098765 kg seed/ kg (wet) primary yield * kg primary yield/0.18 kg DM * 9.98 * 10^3 kg DM/ha = 54.76 kg seed/ha;
JB6: 0.00098765 kg seed/ kg (wet) primary yield * kg primary yield/0.18 kg DM * 8.82 * 10^3 kg DM/ha = 48.39 kg seed/ha;

As a second step, the life cycle inventory for producing the seed must be established. For all seeds from cereals (barley and wheat), the same inventory data as used for the production of the grain can be used (Nemecek and Kägi, 2007), to which a transport and seed processing process (drying, cleaning) is added. This procedure is also used for maize, sugarbeet and ryegrass. For barley, wheat and maize, a 1:1 relation can be used, i.e. 1 kg grain from the main crop is needed to produce 1 kg seed. This can be translated in terms of ha needed of the main crop (per kg of seed) based on the corresponding yields (for maize, the conversion is done considering 12.05 * 10^3 kg DM/ha * kg primary yield/0.31kg DM = 38870.97 kg/ha for maize on JB3 and 11.93 * 10^3 kg DM/ha * kg primary yield/0.31kg DM = 38483.87 kg/ha for maize on JB6).

Two different transport distances are considered: from the seed producing farm to the processing centre and from the processing centre/regional storehouse and from there to the farm where the seeds will be sown. This consists of 30 km by lorry for the former and the latter (Ecoinvent process “Transport, lorry >32t, EURO3/RER U”, Spielmann et al., 2007; table 5-124, p.96).

As a first proxy, the drying process is taken as in the Ecoinvent database (process “grain drying, high temperature/CH U”, Nemecek and Kägi (2007)). The drying energy required can be estimated based on psychometric chart knowing the initial and final humidity of the grains. The seed processing is, in the ecoinvent database, translated in terms of electricity consumption. As for the drying, the same values as used in the Ecoinvent database are used as a first proxy. In both cases, the electricity used is the marginal electricity for Denmark.

For sugarbeet, based on Nemecek and Kägi (2007), the process for seed should be adjusted as compared to the production of the main crop to take into account, among others, the difference in yield. For sugarbeet seed, a yield of 20 hkg/ha is considered (Plantedirektorate, 2009). The yield for the main crop is, for both JB3 and JB6, 566 hkg/ha. Therefore, a quantity of 28.3 kg (56600/2000 = 28.3) sugar beet was taken as an input per kg seed produced (instead of 1:1 as for cereals). This results in 5 x 10^{-4} ha of sugar beet needed per kg of seed (28.3/566 x 10^2).

For ryegrass seed, a yield of 12 hkg/ha is considered (Plantedirektorate, 2009). The yield of the main crop is, for JB3 9.98 Mg DM/ha, and the DM content is 18.0 % (Møller, 2000: value for durable grass). This means a wet yield of about 55444 kg/ha for ryegrass main crop on JB3 (and 49000 kg/ha on JB6). Therefore, for JB3, a quantity of 46.2 kg (55444/1200 = 46.2) ryegrass was taken as an input per kg seed produced. Using ryegrass

DM yield for JB6 (8.82 Mg DM/ha), a quantity of 40.83 kg ryegrass is needed as an input per kg seed produced. This can be translated to 8.33 x 10^{-4} ha main crop needed per kg seed (JB3 and JB6).

For miscanthus, the procedure differs, as cultivation of miscanthus for rhizomes is performed differently than cultivation of miscanthus for stem (Atkinson, 2009; Bullard and Metcalfe, 2001). First, a 3 year cycle is assumed for production of rhizomes. This is identical as shown in table 4, but in year 3, instead of harvesting (a part of) the stems, the rhizomes are harvested. In this process, rhizomes are lifted (in order to loosen the rhizomes mass), harvested and separated from soil (Atkinson, 2009). Atkinson (2009) suggests that field lifting of rhizomes is achieved using conventional rotary cultivator. This is also what Bullard and Metcalfe (2001) assumed. Rhizomes are then harvested and a potato planter is used to separate rhizomes from the soil, based on Atkinson (2009) as well as Bullard and Metcalfe (2001). Energy requirement for this specific process can be estimated as the same for standard potato grading operations (Bullard and Metcalfe, 2001).

The process for 1 ha rhizome production could therefore roughly be constituted of “miscanthus production year 1, 1 ha”, “miscanthus production year 2, 1 ha”, “miscanthus production year 3, 1 ha, without stem harvest”, “harvesting, by complete harvester, potatoes, 1 ha” (taken as a proxy for the rhizome harvesting), “potato planter, 1 ha”, and “tillage, rotary cultivator, 1 ha”. Diesel consumption is adjusted in function of the soil type as in Dalgaard et al. (2001).

Rhizomes are then transported considering the transportation processes described above.

In a nutshell, for 1 ha rhizome, the following inputs are assumed:

- Herbicide application: (5.13 kg/ha gluphosat (twice this dose), 3.4 kg/ha dinitrianiline compounds, 0.763 kg/ha phenoxy-compounds, 2.2 kg/ha nemzoic compounds, 0.02 kg/ha [sulfonyl]urea-compounds, 0.015 kg “pesticide unspecified”) (same as received for miscanthus in year 1, year 2 and year 3)
- Mineral fertilizer: 15 plus 30 kg/ha N, 25.4 plus 16.4 kg triple superphosphate (as P_2O_5) and 70.8 kg plus 50.9 kg/ha K_2O (same as for miscanthus, year 2 plus year 3)
- Slurry fertilisers: same as miscanthus, y 2 plus miscanthus, y 3
- Planting of rhizomes, application of herbicides (x2), application of mineral fertilisers (x2), application of slurry(x2)
- Field processes for year 2 and year 3
- Lifting rhizomes (rotary cultivator)
- Harvesting rhizomes (potato planting)
- Transport of harvested rhizomes from field to farm, for 1 ton rhizomes

Moreover, it is considered that 1 ha motherfield can deliver rhizomes for planting 5 ha (at 20000 rhizomes/ha), based on a personal communication with Uffe Jørgensen, DJF.

For willow, 300 000 cutting/ha are assumed. Field for cutting production are harvested annually. One ha cutting comprises all the processes needed until the first harvest of willow (year 6). Transport of the cuttings to the farm is included.

The methodology described above assumes that seeds are produced in Denmark, which may not be true in practice, especially for e.g. maize. Best practice would require to build the inventory based on the origin of the marginal seeds.

Table 11 summarizes the life cycle inventory data to be used for seeds.

Table 11. Life cycle inventory for seed

Output data	Unit	Input data ha of main crop	Other inputs	Comment
Barley seed	1 kg seed	JB3: 2.00×10^{-4} JB6: 1.75×10^{-4}	Transport Seed processing	Based on Ecoinvent process “Barley seed IP, at regional storehouse/CH U”
Wheat seed	1 kg seed	JB3: 1.52×10^{-4} JB6: 1.25×10^{-4}	Transport Seed processing	Based on Ecoinvent process “Wheat seed IP, at regional storehouse/CH U”
Sugar beet seed	1 kg seed	JB3 and JB6: 5.00×10^{-4}	Transport Seed processing	Based on Ecoinvent process “Sugar beet seed IP, at regional storehouse/CH U”, adjusted for yield, see text.
Silage maize seed	1 kg seed	JB3: 2.57×10^{-5} JB6: 2.60×10^{-5}	Transport Seed processing	Based on Ecoinvent process “Maize seed IP, at regional storehouse/CH U”
Ryegrass seed	1 kg seed	JB3 and JB6: 8.33×10^{-4}	Transport Seed processing	Based on Ecoinvent process “Grass seed IP, at regional storehouse/CH U”, adjusted for yield, see text.

6. Tillage

6.1 General description

Soil tillage refers to the mechanical operations performed to the soil in order to improve its physical conditions and favour the establishment of the crop to be sown on that soil. Tillage aims, among others, to prepare seedbeds, control weeds, bury residues, loosen and mix the soil (so it improves its aeration and water infiltration) and cause fast breakdown of organic matter (so it increases the release of minerals for plant nutrition) (Kristian Aase, 2007). According to Nichols (2007), effective tillage eliminates competitive vegetation (e.g. weeds) and stimulates favourable soil microbiological activities.

Tillage operations differ based on the soil type and the crop. Ploughing may (or may not when conservation tillage is practiced) be used to deeply stir up the soil. Harrowing can then be performed to break up clods and lumps of soil and provide a finer finish, which can be followed by rolling to compact the loosened soil. Harrow can also be used to cover the seed after sowing.

Table 12 presents the different tillage operations needed for all selected crops on sandy soil (JB3), and table 13 presents the tillage operations needed for each crops on sandy loam (JB6). Information in table 12 and 13 is based on a personal communication with Jens Bonderup Kjeldsen, DJF, Åhrus University.

Table 12. Tillage operations needed for all selected crops and their frequency of occurrence, on sandy soil (JB3). A blank cell means that the operation is not performed for that crop[a]

	Spring barley	Spring barley & Catch crop	Winter wheat	Willow	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass
Ploughing (21 cm), spring	1/y	1/y		1/LC	1/LC	1/LC	1/y	1/y	1/LC
Ploughing (21 cm), autumn			1/y						
Harrowing, **by spring tine harrow**	1/1y	1/y	1/y	1/LC	1/LC	1/LC	1/y	1/y	1/LC
Seedbed harrowing, light	1/y	1/y	1/y	1/LC	1/LC	1/LC	1/y	1/y	1/LC
Rolling	1/y	1/y	1/y	1/LC	1/LC	1/LC	1/y	1/y	1/LC
Stubble harrowing	1/y		1/y				1/y	1/y	

[a] LC: Life cycle of the crop. In this study: 21 years for willow, 20 years for Miscanthus and 2 years for rye grass.

Table 13. Tillage operations needed for all selected crops and their frequency of occurrence, on sandy loam soil (JB6). A blank cell means that the operation is not performed for that crop[a]

	Spring barley	Spring barley & Catch crop	Winter wheat	Willow	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass
Ploughing (21 cm), autumn	1/y	1/y	1/y	1/LC	1/LC	1/LC	1/y	1/y	1/LC
Harrowing, **by rotary harrow**	1/y	1/y	1/y	1/LC	1/LC	1/LC	1/y	1/y	1/LC
Seedbed harrowing, heavy	1/y	1/y	1/y	1/LC	1/LC	1/LC	1/y	1/y	1/LC
Rolling	1/y	1/y	1/y	1/LC	1/LC	1/LC	1/y	1/y	1/LC
Stubble harrowing[b]	1/y		1/y				1/y	1/y	

[a] LC: Life cycle of the crop. In this study: 21 years for willow, 20 years for Miscanthus and 2 years for rye grass.

[b] When straw is incorporated only.

6.2 Material consumption data and fuel use for tillage operations

The data for material consumption related to the different tillage operations were taken from the Ecoinvent database, but the diesel consumption was adjusted based on the norm values presented by Dalgaard et al. (2001). As suggested by Dalgaard et al. (2001), the norm values are corrected for soil type; by a factor of 1.0 for sandy loam and 0.9 for sandy soil. The data from the Ecoinvent database include the machinery production, and all processes are described in Nemecek and Kägi (2007). Table 14 presents, for each tillage process, the Ecoinvent process used as well as the diesel consumption considered, for both sandy and sandy loam soils. The Ecoinvent database considers a specific weight of diesel of 0.84 kg per liter (Nemecek and Kägi, 2007, p.59), so this value is used for conversions in l per ha.

Table 14. Processes used and adjusted diesel consumption for material consumption of all tillage operations

Tillage operation	Ecoinvent process used	Diesel consumption	
		Sandy (JB3)	Sandy loam (JB6)
Ploughing (21 cm), spring	Tillage, ploughing/CH U	18 l ha^{-1}	20 l ha^{-1}
Ploughing (21 cm), autumn	Tillage, ploughing/CH U	20.7 l ha^{-1}	23 l ha^{-1}
Harrowing, by spring tine harrow	Tillage, harrowing, by spring tine harrow/CH U	4.76 l ha^{-1}[a]	5.29 l ha^{-1}[a]
Harrowing, by rotary harrow	Tillage, harrowing, by rotary harrow/CH U	12.32 l ha^{-1}[a]	13.69 l ha^{-1}[a]
Seedbed harrowing, light	Tillage, harrowing, by spring tine harrow/CH U	3.6 l ha^{-1}	4 l ha^{-1}
Seedbed harrowing, heavy	Tillage, harrowing, by rotary harrow/CH U	5.4 l ha^{-1}	6 l ha^{-1}
Rolling	Tillage, rolling/CH U	1.8 l ha^{-1}	2.0 l ha^{-1}
Stubble harrowing[b]	Mulching, CH/U	6.3 l ha^{-1}	7.0 l ha^{-1}

[a] From Ecoinvent database, including an adjustment for sandy soils.

[b] Only when straw is incorporated.

The process used from the Ecoinvent database estimate many of the emissions to air based on the diesel consumed. These were corrected accordingly. The detail of these corrections is presented in section 7, for the case of lime application.

7. Liming

Lime is used on agricultural soils in order to maintain a soil pH ensuring optimal crop nitrogen uptake. Lime is therefore used for soils with low pH, so it is not a crop-related input but rather a site-related input. Different type of lime may be used, but the most used in Denmark is calcium carbonate ($CaCO_3$) (Gyldenkærne et al., 2005). In order to be market as “agricultural lime”, the $CaCO_3$ content of the lime must be at least 70 % of the lime (dankalk, year unknown). According to Dankalk (dankalk, year unknown), the primary material for the production of agricultural lime in Denmark is whether white chalk from North Jutland or calcined limestone. For such application of lime obtained directly from the ground, Nemecek and Kägi (2007) recommend to use the inventory data from the process **“limestone, milled, packed, at plant CH”** from Althaus et al. (2007). Lime could also emerge as a by-product of the manufacture of other products, e.g. sugar. Yet, this type of lime would not react to a change in demand for the crop considered in this study, and therefore cannot be the marginal. In this study, the process “limestone, milled, packed, at plant CH” from Althaus et al. (2007) will be used.

As lime application results in CO_2 emissions in the field (IPCC, 2006), the amount of lime applied for each crop types must be determined. These CO_2 emissions are considered under field processes.

In this project, it is considered that lime is applied to annual crops every 5 years and for perennials, it is assumed that lime is applied every 20 years.

The amount of lime applied per hectare for a 5 years period was estimated from the data in the latest Danish Inventory Report for the IPCC (Nielsen et al., 2009). Based on this, the amount of lime used for the last 5 years of data (2003 to 2007) is 2 237 000 ton of pure $CaCO_3$ (table 7.26 from Nielsen et al., 2009). (Data in pure $CaCO_3$ avoid the need to differ between lime and dolomite). The amount of agricultural area for this same period is, on average, 2 676 703 ha (table 7.26 from Nielsen et al., 2009). Using these figures, a rough estimate can be made for a 5-years lime consumption of 0.8357 ton per hectare. This amount of lime is assumed to be the same for each crop. This is of course a rather rough estimate, but no better data were available. Table 15 summarizes the data about lime to be used in this project.

Table 15. Amount of lime applied on the field for each crops.

Crops	Frequency of application	Amount of $CaCO_3$ per application	Amount for a 20 yr horizon	Amount for a 100 yr horizon (per ha)
Annuals (spring barley, winter wheat, silage maize)	Once every 5 years	0.8357 ton per hectare	3.3428 ton per hectare (4 applications)	16.714 ton per hectare (20 applications)
Perennials (miscanthus, willow, ryegrass)	Once every 20 years	0.8357 ton per hectare	0.8357 ton per hectare (1 application)	4.1785 ton per hectare (5 applications)

Hedegaard Jensen et al. (2007) as well as Thyø and Wenzel (2007) used, for whole crop maize, an input of 200 kg lime per hectare per year, based on a personal communication with Klaus Felby (so this is equivalent to 1 ton for 5 years). According to JYSK (2010), application of lime normally takes place every 3 to 6 years and between 2 and 4 ton of lime per hectare is applied during an application. The amounts considered in this project are a bit lower than this, but corresponds to the previsions from Birkmose (2005) (as reported by Gyldenkærne et al., 2007). In fact, these authors report future use of 0.5 million ton $CaCO_3$ per year in Denmark (2 500 000 ton per 5 years; an amount of 2 237 000 ton per 5 years was used in this project). Similarly, Dankalk (Dankalk, year unknown) reports an amount of 0.5 to 1 ton of lime per hectare to use on soil JB1 to JB6. These values correspond to those used in the present study.

It is considered that lime is applied with the same spreader as mineral fertiliser, i.e. using the Ecoinvent process "Fertilising, by broadcaster, CH/U". This process is adjusted to consider the specific diesel consumption for lime spreading. In this study, the value use is based on Dalgaard et al. (2001): 1.5 L diesel/ha*y (value uncorrected for soil type. This means the diesel consumption is 1.5 L diesel/ha*y for soil JB6 (correction factor of 1 for sandy loam) and 1.35 L diesel/ha*y for soil JB3 (correction factor of 0.9 for sandy soils). The process used from the Ecoinvent database estimate many of the emissions to air based on the diesel consumed. These were corrected accordingly. Table 16 presents the process considered for lime application in this study as compared to the one from Ecoinvent database, for liming 1 ha of land. The consumption and fabrication of lime is considered through another process "limestone, milled, packed, at plant CH", as described above.

Table 16. Adaptation of the Ecoinvent process “Fertilising, by broadcaster, CH/U” for this study, for liming 1 ha

	Original value, from Nemecek and Kägi (2007)	This study		Comment
		JB3	JB6	
Inputs				
Tractor production	0.687 kg	0.687 kg	0.687 kg	
Agricultural machinery, general production	0.241 kg	0.241 kg	0.241 kg	
Diesel, at regional storage	5.29 kg	1.134 kg	1.26 kg	Assuming a density of 0.84 kg/L (Nemecek and Kägi, 2007, p. 59)
Shed	0.00171 m^2	0.00171 m^2	0.00171 m^2	
Emissions to air[a]				
NMVOC	0.0143 kg	0.0143 kg	0.0143 kg	Not a function of the diesel consumption (Nemecek and Kägi, 2007)
NO_X	0.231 kg	0.231 kg	0.231 kg	Not a function of the diesel consumption (Nemecek and Kägi, 2007)
CO, fossil	0.021 kg	0.021 kg	0.021 kg	Not a function of the diesel consumption (Nemecek and Kägi, 2007)
CO_2, fossil	16.5 kg	4.18 kg	3.93 kg	Considering 3.12 x 10^{3} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
SO_2	0.00533 kg	0.00135 kg	0.00127 kg	Considering 1.01 g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
CH_4, fossil	0.000683 kg	0.000173 kg	0.000163 kg	Considering 1.29 x 10^{-1} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
Benzene	3.86 x 10^{-5} kg	9.78 x 10^{-6} kg	9.20 x 10^{-6} kg	Considering 7.30 x 10^{-3} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
$PM_{2.5}$	0.0208 kg	0.0208 kg	0.0208 kg	Not a function of the diesel consumption (Nemecek and Kägi, 2007)
Cd	5.29 x 10^{-8} kg	1.34 x 10^{-8} kg	1.26 x 10^{-8} kg	Considering 1.00 x 10^{-5} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
Cr	2.65 x 10^{-7} kg	6.70 x 10^{-8} kg	6.30 x 10^{-8} kg	Considering 5.00 x 10^{-5} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
Cu	9.06 x 10^{-6} kg	2.28 x 10^{-6} kg	2.14 x 10^{-6} kg	Considering 1.70 x 10^{-3} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
N_2O	0.000635 kg	0.000161 kg	0.000151 kg	Considering 1.20 x 10^{-1} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
Ni	3.7 x 10^{-7} kg	9.38 x 10^{-8} kg	8.82 x 10^{-8} kg	Considering 7.00 x 10^{-5} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
Zn	5.29 x 10^{-6} kg	1.34 x 10^{-6}	1.26 x 10^{-6}	Considering 1.00 x 10^{-3} g/kg diesel

		kg	kg	consumption (Nemecek and Kägi, 2007) (table 7.1)
Benzo(a)pyrene	1.59 x 10^{-7} kg	4.02 x 10^{-8} kg	3.78 x 10^{-8} kg	Considering 3.00 x 10^{-5} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
PAH	1.74 x 10^{-5} kg	4.41 x 10^{-6} kg	4.15 x 10^{-6} kg	Considering the emissions factors of the 6 PAH presented in (Nemecek and Kägi, 2007) (table 7.1)
NH_3	0.000106 kg	2.68 x 10^{-5} kg	2.52 x 10^{-5} kg	Considering 2.00 x 10^{-2} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
Se	5.29 x 10^{-8} kg	1.34 x 10^{-8} kg	1.26 x 10^{-8} kg	Considering 1.00 x 10^{-5} g/kg diesel consumption (Nemecek and Kägi, 2007) (table 7.1)
Emissions to soil				
Zn	0.000897 kg	0.000897 kg	0.000897 kg	Not a function of the diesel consumption (Nemecek and Kägi, 2007)
Pb	1.49 x 10^{-6} kg	1.49 x 10^{-6} kg	1.49 x 10^{-6} kg	Not a function of the diesel consumption (Nemecek and Kägi, 2007)
Cd	3.4 x 10^{-7} kg	3.4 x 10^{-7} kg	3.4 x 10^{-7} kg	Not a function of the diesel consumption (Nemecek and Kägi, 2007)

[a] The emission to air “Heat, waste” is not considered.

8. Sowing

Sowing is performed every year for annual crops, and once over the life cycle for perennial crops (willow, miscanthus, ryegrass). The process used for sowing is the ecoinvent process “Sowing/CH U” (for all crops except willow and miscanthus), adjusted with the diesel consumption presented in Dalgaard et al. (2001), i.e. 2.7 L/ha (JB3) and 3.0 L/ha (JB6). The emissions that are function of the amount of diesel burned are also adjusted accordingly.

For miscanthus, planting may be done using a manure spreader followed by cultivation and rolling but this is not likely to represent future practices as it results in rather unpredictable plant spacing and establishment rate (DEFRA, 2007; Heaton et al., 2004). A potato planter can also be adapted and used to plant the rhizomes, but the optimal option consists to use a specialized Miscanthus planter (Heaton et al., 2004).

For willow, planting may be performed by a step planter.

For this study, the most important parameter to consider regarding sowing operations is the associated consumption of diesel related to the planting. Therefore, for these two crops, the Ecoinvent process “Planting, CH/U” has been used, which involve a diesel consumption of 20 L/ha. This consumption has been adjusted, for willow, based on Heller et al. (2003), whom used an empirical formula to estimate the diesel consumption, having as inputs the maximal available PTO power (which they estimated at 78 kW) and the total power required for the operation (which they estimated at 52 kW). Based on this, and an operating rate of 2.5 h/ha (Heller et al., 2003) the diesel consumed for planting willow is estimated at 56.6 L/ha. As a proxy, this value will also be used for miscanthus. Because these values are significantly higher than those of the Ecoinvent process, a sensitivity analysis will be carried out with a fuel use of 20 L/ha. In both cases, values are adjusted in function of the soil type, based on Dalgaard et al. (2001).

9. Plant protection

For each crop, application of pesticides products (herbicides, insecticides and fongicides) is an integral part of plant protection operations. Table 17 presents the pesticides types and the amount of each to be applied annually for each crop types. For ryegrass, values are integrated over the lifecycle and expressed annually. Sugarbeet data are from the “Dansk Landbrugs Grovvareselskab” (DLG, 2009). This crop requires important chemical control, as compare to other annuals crops.

For each pesticides types, it is considered that the same amount is applied on both soil types. The inventory data for the production of these pesticides are taken from the Ecoinvent database (Nemecek and Kägi, 2007). The data from Nemecek and Kägi (2007) are, however, based on Green (1987), which is rather old data. These data only consider energy inputs. According to the authors, these data are nevertheless reliable, and can be apply for the European context (the data from Green were derived for US plants which patent expired, but they are the results of simulation models, not direct merasurement), through they warn that they should not be used for anything else than for agricultural-related LCA.

The authors argue that given the importance of patents in the pesticides industry, it is very hard to get recent data. The authors also highlight that the impact of pesticides is generally small in agricultural LCA, being generally below 5 %, but emphasize that the toxicity can be significant.

In Nemecek and Kägi (2007), each pesticides are classified in class, and the classes corresponding to the pesticides used in this study are also presented in table 17. Conformingly to the methodology suggested in Nemecek and Kägi (2007), each pesticides not listed in the categories made by the authors (Nemecek and Kägi, 2007, table 10.3) are assigned to the general category “pesticides, at regional storehouse”. Correspondence between trade name and compound were obtained through the FOOTPRINT In this study, European data are used (RER), but adjusted with the marginal electricity defined in section 3. This is justified by the fact that there are pesticides producing companies in Denmark (e.g. Cheminova A/S).

Table 17. Application of pesticides for each selected crops, for both soil types. All values in kg ha^{-1} y^{-1}.

Pesticide name	Pesticide class (Nemecek and Kägi, 2007), obtained from University of Hertfordshire (2010)	Type[a]	Spring barley	Spring barley & Catch crop	Winter wheat	Maize silage	Sugar beet[b]	Rye grass
Fluoroxypir	Phenoxy compounds	H			0.00350	0.0360		0.080
Foramsulfuron	Pesticide, unspecified	H				0.0300		
Pendimethalin	Dinitroaniline compounds	H				0.5000		
Idosulfuron	[sulfonyl]urea compounds[c]	H				0.0133		
Bentazon	Benzo[thia]diazole compounds	H				0.2160		
Clopyralid	Benzoic compounds	H						0.040
MCPA	MCPA	H						0.400
Tribenuron-methyl	Triazine compounds	H	0.00375	0.00375				
Ioxynil	Nitrile compounds	H	0.05000	0.05000				
Pyreclostrobin	Pyretroid compounds[c]	F	0.06250	0.06250	0.02400			
Diflufenican	Diphenylether compounds	H			0.02000			
Bromoxynil	Nitrile compounds	H	0.05000	0.05000	0.02400			
Glyphosate	Glyphosate	H			0.72000			
Lamda-cyhalothrin	Pyretroid compounds	I	0.00375	0.00375	0.00375			
Prosulfocarb	[thio]carbamate compounds	H			0.80000			
Boscalid	Pesticide, unspecified	F			0.17475			
Florasulam	Pesticide, unspecified	H			0.04000			
Tebuconazole	Cyclic N compounds	F			0.06250			0.125
Epoxiconazole	Cyclic N compounds	F			0.14400			
Metamitron	Triazine compounds	H					2.45	
Phenmedipham	[thio]carbamate compounds	H					2.91	
Ethofumesate	Pesticide, unspecified	H					0.091	
Penetrating oil (Penol 33 E)	Pesticide, unspecified	oil					0.90	

[a] H: herbicide; F: fungicide; I: insecticide. [b] Conversions in kg/ha were performed based on the following densities: Metamitron: 1.225 g/ml; Phenmedipham: 0.97 g/ml; Ethofumesate: 1.3 g/ml and Penol 33E: 0.9 g/ml. [c] Deduced, as this compound does not figure among the substances specified by Nemecek and Kägi (2007).

Miscanthus, in the establishment phase, is particularly vulnerable to competition with weeds. The year before planting (year 1), a systemic herbicide is therefore applied to prevent important yield decrease due to competition with weeds. A dose of 3 L/ha is considered, based on a personal communication with Jens Bonderup Kjeldsen, DJF, Arhus University (Kjeldsen, 2010). After planting (year 2), a pre-emergence weed killer (pendimethalin, 4 L/ha) is applied. During the emergence (year 2), specific herbicides may be used depending on the weed present. In this study, based on a personal communication with Jens Bonderup Kjeldsen, DJF, Åhrus University (Kjeldsen, 2010) and a fact sheet from Irish research (Finnan and Caslin, 2008), it is considered that fluroxypyr (0.7 L/ha) clopyralid (1.25 L/ha), Metsulfuron-methyl (20 g/ha) and Thifensulfurol-methyl (15 g/ha) are applied. The third year, glyphosate is applied again, late April or early May where grass weeds are present (3 L/ha). After that, it is considered that the crop will surpass weed growth and therefore chemical control is no longer required (Finnan and Caslin, 2008). Nevertheless, a treatment every 4th year after the first harvest is considered (glyphosat pre emergence, 3L/ha: year 8, year 12 and year 16), in order to clean up for potential problematic weed species. This is based on a personal communication with national experts (Jørgensen, 2010). Chemical weed treatments for miscanthus, over its life cycle, is summarised in table 18.

Table 18. Pesticides applied to miscanthus (autumn and spring harvest) over the 20 year life cycle

Pesticide	Type[a]	Pesticide class (Nemecek and Kägi, 2007)	Amount over lifecycle (kg/ha)	Comment
Glyphosat	H	Glyphosat	25.65	Before planting (year 1) and the 3rd year. Also on year 8, 12 and 16. Amount of 3L/ha per application. Density of 1.71 g/ml used for conversion.
Pendimethalin	H	Dinitroaniline compounds	3.4	Applied on year 2. Density of 0.85 g/ml used for conversion.
Fluroxypyr	H	Phenoxy compounds	0.763	Applied on year 2. Density of 1.09 g/ml used for conversion.
Clopyralid	H	Benzoic compounds	2.20	Applied on year 2. Density of 1.76 g/ml used for conversion.
Metsulfuron-methyl	H	[sulfonyl]urea compounds	0.02	Applied on year 2.
Thifensulforol-methyl	H	Pesticides, unspecified	0.015	Applied on year 2.

[a] H: herbicide; F: fungicide; I: insecticide.

As miscanthus, willow is particularly vulnerable to competition with weed during the establishment. Once the plantation is established, a high amount of weed is tolerated. The year before planting (year 1), a systemic herbicide is applied to control perennial weeds. A dose of 3 L/ha is considered, based on a personal communication with Jens Bonderup Kjeldsen, DJF, Arhus University (Kjeldsen, 2010). Shortly after planting (year 2), pendimethalin (4 L/ha) is applied to ensure a good, fine seedbed. During the establishment (year 3), various herbicides may be applied, depending on the amount of weed. In this study, the following are considered: fluazifop-p-butyl (2 L/ha) and clopyralid (1.25 L/ha) (based on a personal communication with Jens Bonderup Kjeldsen, DJF, Åhrus University) (Kjeldsen, 2010), and a factsheet for chemical weed control of willow in Ireland, (Finnan and Caslin, 2008)). After the first harvest (year 6), glyphosat is applied to ensure the plantation is kept weed free (3 L/ha). This is then performed every other harvest (harvest then occur every 3 years, meaning next applications will take place on year 12 and 18). Once canopy closure occurs (a few months after the harvest), the coppice controls its own weeds due to reduced light levels reaching the ground surface (Finnan and Caslin, 2008). At maturity, the underlying vegetation does not cause any detrimental effects to the plantation and may even contribute to prevent pest species as it provides an habitat for predators of some pests. Therefore, no pesticides are applied during this period. Chemical plant protection is to some extent a dynamic activity, and more or less applications may occur depending on the actual conditions on the field for a particular year. It is nevertheless judged that the doses used in this study are representative of a how a "typical" Danish willow plantation would be managed. The overall pesticide application for willow lifecycle is summarised in table 19.

Table 19. Pesticides applied to willow over its 21 years lifecycle

Pesticide	Type[a]	Pesticide class (Nemecek and Kägi, 2007)	Amount over lifecycle (kg/ha)	Comment
Glyphosat	H	Glyphosat	20.52	4 times 3 L/ha:(year 1, 6, 12 and 18). Density of 1.71 g/ml used for conversion.
Pendimethalin	H	Dinitroaniline compounds	3.4	Applied on year 2. Density of 0.85 g/ml used for conversion.
Fluazifop-p-butyl	H	Phenoxy compounds	2.44	Applied on year 3. Density of 1.22 g/ml used for conversion.
Clopyralid	H	Benzoic compounds	2.20	Applied on year 3. Density of 1.76 g/ml used for conversion.

[a] H: herbicide; F: fungicide; I: insecticide.

Application of pesticides is carried out by a field sprayer with an 800 L carrying capacity, based on Nemecek and Kägi (2007) (process "Application of plant protection products, by field spreader/CH U"). This process is adjusted for diesel consumption based on norm data presented by Dalgaard et al. (2001), i.e. a consumption of 1.35 L/ha is considered on JB3 and of 1.5 L/ha on JB6. The emissions from diesel burning have been adjusted consequently, as detailed in the case of lime spreading (section 7).

In order to estimate the amount of pesticides drift to air and surface waters, the Danish PestLCI model (Birkved and Hauschild, 2006) was used. This model allows for distinction between pesticide type, crop type and climate, among others.

Pesticides drift contributes, in environmental assessment, to toxicity. This will be calculated by the use of USETOX model (Rosenbaum et al., 2008).

10. Fertilization

10.1 General description

The fertilisation operations are performed in conformity with Danish regulations. In Denmark, the farmers' use of N fertilisers is restricted by Danish law (Gødskningsbekendtgørelsen, 2008; Gødskningsloven, 2006). It means that the amount of N fertiliser farmers are allowed to bring out has an upper ceiling, both as mineral fertiliser and animal slurry.

As a high animal density country, an important proportion of Danish agricultural soils are fertilized with organic fertilisers. In the Danish national inventory report to the UNFCCC, Nielsen et al. (2009) (table 6.31) present the total amount of nitrogen applied to soils in Denmark, from 1990 to 2007, as well as the origin of this nitrogen (synthetic fertiliser, animal waste, crop residue, etc.). These statistics show that the ratio "animal waste applied": "synthetic fertiliser" has progressively increased from 1:2 in 1990 to reach a ratio of approximately 1:1 in 2004, 2005, 2006 and 2007. Based on this, it is assumed in this study that the nitrogen demand of the crops is fulfilled by 50 % of organic fertiliser and 50 % of mineral fertiliser. For willow, however, this is handled differently, since slurry spreading is only practicable on harvest years. Therefore, out of 13 fertilisations, 4 will be 100 % slurry and the 9 others 100 % mineral fertilisers (table 4).

The present section presents the origin, amount and mass balances of the different fertilizers to be used in this study. The determination of marginal mineral fertiliser is also discussed. The life cycle data related to fertilization input, i.e. the calculations of the emissions (ex.: ammonia) are included in the section "growing cycle".

10.2 Synthetic fertilizer

10.2.1 General

The inorganic fertiliser to be used in this study must be the marginal one, as marginal data are used in consequential LCA. This represents the data from the marginal supply, i.e. the one responding to a minute change in demand on the market in question. In a life cycle assessment of Danish pork production, Dalgaard (2007) highlights synthetic fertilizer among the most important input to fattening pig farm.

This means that the consequences of turning additional hectare of land to bioenergy production in Denmark should be anticipated and modeled. Which N, P and K fertilisers on the market are likely to react, which producing technologies and where in the world?

The trend in mineral fertilizer consumption, as presented by Statistics Denmark (Statistics Denmark, 2010), is presented in figure 2.

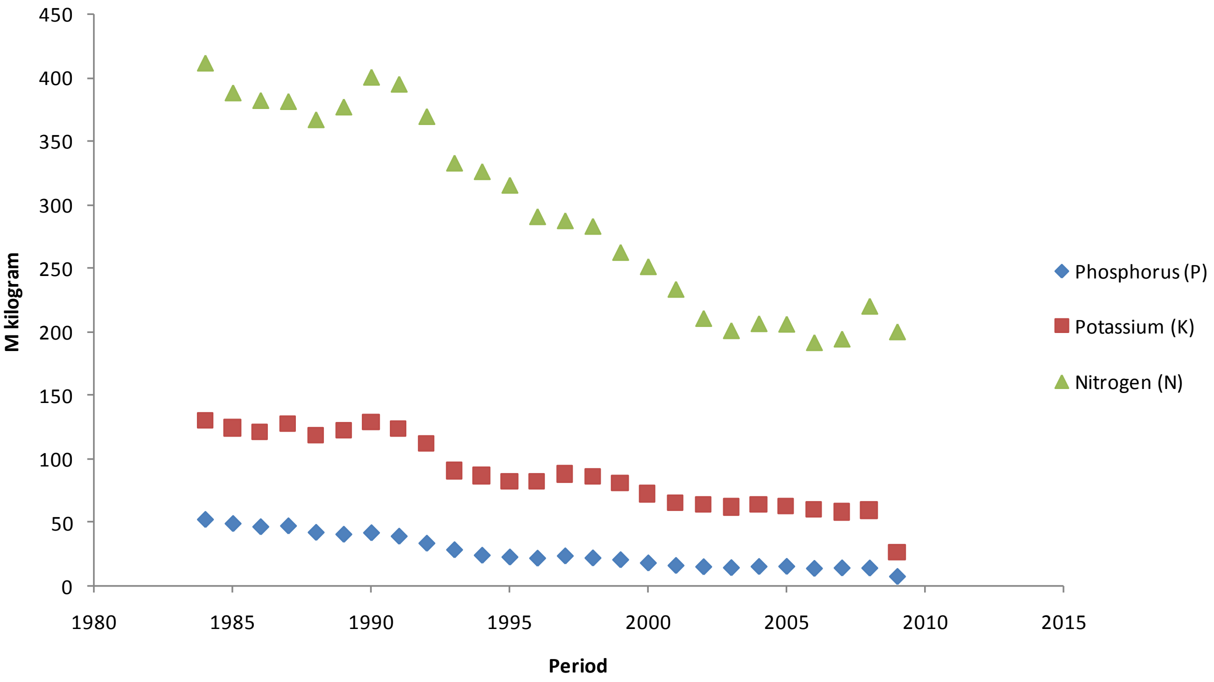

Figure 2. Trend in total supply of mineral fertilizers in Danish farms from 1984 to 2009

10.2.2 Nitrogen

Consumption of nitrogen mineral fertilizer has, in Denmark as well as in the EU, experienced a significant decrease over the last 20 years (FAO stat, 2010; EFMA, 2009; Euro stat, 2010; Denmark Statistics, 2010). This is, among other, the result of enhanced environmental regulations. According to EFMA (2009), N use efficiency has increased by 45 % since 1985. Worldwide, however, the trend for most commercial N fertilizers during these years is a net increase (IFA, 2010; FAO stat, 2010).

In order to identify the marginal N in consequential LCA, the market scope must be identified; i.e. would a change in demand for commercial N affect the Danish market, the European market, or the global market? Then, what is the trend of this market (declining or rising)?

Recent consequential LCA (Nielsen et al., 2005; Dalgaard et al., 2008; Nielsen et al., 2008 as well as Schmidt, 2007) identified calcium ammonium nitrate produced in Eastern Europe plants to be the less competitive supplier of synthetic N. Three of these studies (Nielsen et al., 2005; Dalgaard et al., 2008 and Nielsen et al., 2008) based their market analysis on the European market, and claimed that the least competitive fertilizer is the one affected, based on a decreased in consumption in the European market due to environmental restrictions. The data they used are from Patyk and Reinhardt (1997), claiming that these are assumed to represent the less competitive technologies.

In contrary, Schmidt (2007) argues that the geographical market for fertilizer is not limited to Europe, based on the import share of the supply to EU25 in 2005, which is over 20 % for ammonia, ammonia nitrate and calcium ammonia nitrate. Therefore, Schmidt (2007) proposed to identify the marginal N based on the global market. In spite of this, Schmidt (2007) nevertheless considers data from the European market to determine the marginal N, ending up assuming that calcium ammonium nitrate, as the most commonly used N fertilizer in Europe, is the marginal N fertilizer.

The basis for identifying the marginal N lies, for all these studies, on historical data. Yet, the LCA aims to assess the consequences (occurring in the future) of the implementation of given scenarios, so forecasts based on state-of-the-art models shall be prioritized over simple extrapolation of historical data.

Recent forecasts indicate increases of N use for both the world and Western Europe. This is due, among others, to economic growth and increased demand for food and energy crops (Tenkorang and Lowenberg-DeBoer, 2009; EFMA, 2009).

On a short term perspective (2009-2013), FAO (2009) forecast an annual increase rate of 1.8 % for the consumption of commercial N fertilizer in Western and Central Europe. Worldwide, the annual increase forecasted is 2.2 %. FAO (2009) however warns that these values should be seen in the light of the 2008 economical crisis, highlighting that this involves that the calculations are performed relative to a rather low baseline. To illustrate this, FAO (2009) also performed the forecasts using 2007 as a baseline year (in both cases, a recovery beginning in 2009/2010 is assumed). The forecasts (2007-2013) indicate an annual increase rate for world N consumption of 1.7 %; but for Western and Central Europe, a slight decrease (-0.7 %) is however forecasted when 2007 is used as a baseline. Medium-term forecasts (2009-2019) are presented in EFMA (2009b) for Europe (EU-27), indicating an increase in N consumption of 4.1 % (and 3 % when forecasts are made for 2007-2019). EFMA (2009) actually highlights Denmark as a country where consumption of N is forecast to rise, as a result of expected development of energy crops. The longer term forecasts (up to 2030) made by Tenkorang and Lowenberg-DeBoer (2009) indicate a substantial global increase in all regions. Projections for EU indicate a commercial N consumption of 10.4, 14.9 and 15.3 M megatonnes for 2005, 2015 and 2030, respectively. For the world, their forecasts indicate a commercial N consumption of 90.7, 115.4 and 137.4 M megatonnes (for 2005, 2015 and 2030, respectively).

Based on this, it is concluded that a rising trend for N fertilizer should be taken into account in determining the marginal. A rising market trend involves, based on the principles presented by Weidema (2003), that the most competitive supplier is the one affected by a change of demand. It is however acknowledge that, for N fertilisers, the trend may not only be market driven and influenced by a number of factors like agri-environmental measures or other policy intervention types (e.g. CAP measures in EU countries), which are common in the agricultural sector.

Assuming that consumption is an indication of the competitiveness of a given fertilizer (the rationale being that, based on a market logic, it is the most competitive product that is the most consumed), urea can clearly be identified as the marginal N on the global market. In fact, it is by far the most consumed N fertilizer (EFMA, 2009; IFA, 2010; FAO stat, 2010). Based on the data 2006/2007, urea represented 55 % of world capacity of N fertilizers (total 132.1 M tonnes of N), followed by ammonium nitrate with 13 % of the world capacity. This world capacity was mostly based in the Asia/Oceania region, with 59 %, followed by Western and Central Europe (13 %).[1]

On the perspective of the European market, data from FAO stat (FAO stat, 2010) indicates, for "European Union", that the most consumed N fertilizers for 1997 to 2002 are ammonium nitrate and calcium ammonium nitrate. EFMA (2009c) indicates, for EU-27 (for 2006-2007) that calcium ammonium nitrate is the most consumed fertilizer (24 %), followed by ammonium nitrate (19 %) and urea (18 %), which represents a relatively balanced range of the N fertilisers available. In Denmark, latest compilation from Plantedirektorate (Plantedirektorate, 2007) indicates "N fertilizer with sulphur" as the most consumed fertilizer in Denmark from 1999 to 2005. However, data from Nielsen (2009), which presents the consumption of synthetic N in Denmark for 2007, does not present any data for "N fertilizer with sulphur". In the inventory report of Nielsen et al. (2009), the most consumed N fertilizer is "Calcium ammonium nitrate and other nitrate types". Urea is not as much used in Western Europe as compare to the rest of the world due to efforts towards ammonia emissions reductions, which favoured a shift towards calcium ammonium nitrate and ammonium nitrate.

Based on this, two N fertilizers may be distinguished as the potential marginal, depending on the market considered: urea (global market) and calcium ammonium nitrate (European market). For the European market, however, this could shift due to current EU targets (EMFA, 2009). In fact, because of the competition with the global market, EMFA (2009) states that fertilizers manufacturer in the EU are unlikely to be able to pass on

---

[1] http://www.efma.org/documents/file/statistics/capacity.pdf

additional environmental costs. As a result, EMFA (2009) highlights that the efficient European plants may lose their production capacity at the benefit of less efficient plants not subjected to environmental regulations. These would then likely be producers of urea.

In order to understand if the choice of the marginal N fertilizer is likely to be of importance or not for the LCA, a LCA screening of the N fertilizers in the Ecoinvent database (Nemecek and Kägi, 2007) (N fertilizer at regional storehouse) was performed. Based on this, and an impact assessment performed according to the EDIP 2003 method, it appears that there are significant differences in the environmental impacts related to the fabrication of the different fertilizers. The tendency that can be highlighted from this screening is that calcium ammonium nitrate (and ammonium nitrate) are affecting the different environmental impacts categories much more than urea, except for the category "ozone depletion" where it is the opposite. Figure 3 presents the results obtained for the impact category "global warming, horizon of 100 years" as an illustration of this.

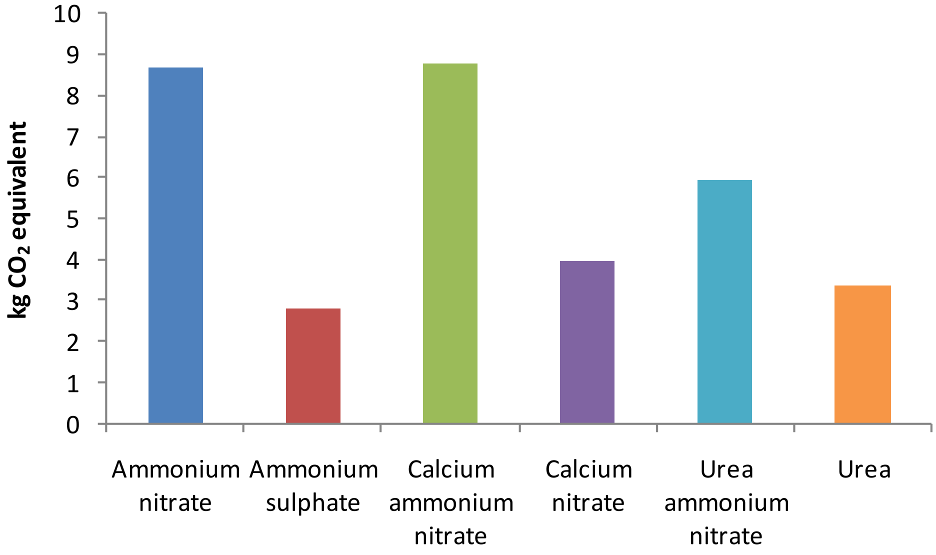

Figure 3. Characterization results of the LCA screening of selected N fertilizers for global warming (100 years)

The screening in Figure 2 is for the production of the fertilizers. When applying these fertilizers to field, however, urea becomes a greater concern, especially for ammonia emissions (and indirect N_2O emissions). This is especially critical for soil with pH > 7 (Harrison and Webb, 2001). As mentioned earlier, ammonia concerns related to urea represents one of the fundamental drivers in the shift from urea towards calcium ammonium nitrate in Western Europe.

Urea has a much higher NH_3 emission factor (0.13 kg NH_3-N per kg N applied) than calcium ammonium nitrate (0.01 kg NH_3-N per kg N applied), based on data from Nielsen et al. (2009). In fact, two moles of ammonia have the potential to be formed per mole of urea, in the presence of urease enzyme (Mobley and Hausinger, 1989). A way to prevent this consists to use urease inhibitors. Ammonia contributes, among other, to acidification and eutrophication of waters. Part of this ammonia contributes to "indirect" N_2O emissions (0.01 kg N_2O-N are emitted per kg of (NH_3-N + NO_x-N) volatilized, based on IPCC guidelines (IPCC, 2006)). Yet, the impact “global warming” is very sensitive to N_2O, given its relatively high global warming potential compared to others greenhouse gas involved in agricultural LCA systems.

EFMA (2009) presents the carbon footprint comparison between urea and calcium ammonium nitrate. Their results indicate that overall, urea has a greater carbon footprint (approximately 11 kg CO_2 equivalent per kg N versus 8 kg CO_2 equivalent per kg N for calcium ammonium nitrate). However, the methodology and assumptions behind these results are not presented, except that the calcium ammonium nitrate was produced in a plant with abatement technologies for N_2O. EFMA (2009) highlights that if abatement technologies are adopted for N_2O, the N_2O emissions from the production of nitric acid (an input for calcium ammonium nitrate production) are between 1.85 to 2.5 kg N_2O per ton of nitric acid.

On the other hand, Harrison and Webb (2001) highlights that the greater susceptibility of nitrate (NO_3^-) based fertilizers to denitrification may lead to increased N_2O emissions (as compare to when urea is used). This is particularly the case under wet conditions (e.g. spring or wet summer) and warm conditions; applications should thus be avoided in these periods. For the Danish context (legislation and climate), applications of fertilisers do take place in spring and this could hardly be changed, meaning that the gain in NH_3 with urea may be overcome by the emissions of N_2O. The extensive review carried out by Harrison and Webb (2001) nevertheless concludes that replacing urea by ammonium nitrate does have the potential to reduce NH_3 emissions without increasing N_2O emissions, though these are very much dependent upon season and weather.

Based on this screening and the difference between NH_3 emission factors of these two fertilizers, it can be concluded that the choice of the marginal N does make a difference in the LCA, so it appears relevant to include both urea and calcium ammonium nitrate in the analysis.

Moreover, it should be highlighted that both urea and calcium ammonium nitrate are derived from the same substance, ammonia, which is the richest source of N for any of the synthetic N fertilisers available (Longacre et al., 2010). Table 20 presents, based on Longacre et al. (2010), some of the most used N fertilisers in the light of the substances from which they are synthesised. Nitric acid (HNO_3), which source components are N from air and water, is also an important source material in the synthesis of ammonium nitrate and its derivates (like calcium ammonium nitrate).

Table 20. Classification of selected N commercial fertilizers versus their origin (ammonia, nitric acid, or other)

Fertilizers derived from ammonia and nitric acid	Fertilizers derived from ammonia	Others

Ammonium nitrate (AN):
• Synthesized through acid-base reaction of nitric acid and ammonia in aqueous solution.
• AN is a component part of other N fertilizers:
  • **Ammonium sulphate-nitrate**
  • **Calcium ammonium nitrate**
	Urea:
	Ammonia and CO_2 are reacted under high pressure (1.2 to 2.8 MPa) and high temperature (175 to 210 °C). The partial dehydration of ammonium carbamate formed in the reactor produces urea as well as water.
		Sodium nitrate:
		• Natural sources from Chilean deposit (caliche)[a]

	Ammonium sulphate: • Produced mostly through reaction between ammonia and sulphuric acid.	**Calcium cyanamide (CaN_2):** • Made from limestone ($CaCO_3$) and coke.
	Ammonium chloride	

[a] Synthetic production involving nitric acid or ammonia, according to the process.

A proportion of 97 % of nitrogen fertilisers is derived from ammonia (EFMA, 2004). Ammonia is produced synthetically through the so-called "Haber-Bosch process", a high pressure catalytic process using, as a N source, the N from air.

The natural gas is generally the most competitive source for H (EFMA, 2009). While the N from air is not constrained in supply (N represents 78 % of the air composition), the supply in natural gas is subjected to constraints. Moreover, according to EFMA (2009), natural gas represents between 50 to 70 % of the total feedstock cost, meaning that the cost of natural gas is an important parameter in the price of N fertilizers.

In the light of this, it appears that the ultimate product affected by a change of demand in N fertilisers (under a rising trend) is the supply for H to synthesize the ammonia necessary to produce all fertilisers. The production of this H inevitably involves interactions with the energy market (whether the hydrogen is from fossil resources or from electrolysis, which requires an input of electricity). Yet, the link between agricultural and natural gas markets has rarely been assessed in explicit terms (Whistance and Thompson, 2010).

In summary, raising the demand for synthetic N, which is forecasted on the long-run, involves rising the demand for ammonia, which involves an increased demand for H supply, for which the most competitive source appears to be natural gas. According to the International Energy Agency (IEA, 2007), gas resources are more than sufficient to fulfill projected increases in demand to 2030, based on proven reserves of 180 trillion cubic meter at the end of 2005. Based on a 2% annual production growth rate, reserves would last about 40 years, and based on 2007 production rate, reserves would be equivalent to 64 years of supply (IEA, 2007). IEA (2007) however mention that duration of supply is likely to be greater, as proven reserves have grown by more than 80 % over the past two decades.

For the life cycle assessment, this means that natural gas may be treated as a constrained resource or not, depending on the time scope considered. If natural gas is a considered a constrained resource, it means that prioritization has to be made over its various uses. If its use for the fertilising industry is prioritized, then this natural gas is not available for other competing uses, for instance CHP production, meaning that a demand for others C source material in CHP production is created, e.g. coal, or eventually biomass in the case of a 100 % renewable energy system. In this specific case (displaced natural gas towards the fertilisers industry giving rise to an increase in biomass-for-energy), this is likely to involve a demand for additional fertiliser (for producing this biomass-for-energy), besides from leading to arable land expansion. Such a scenario appears rather unsustainable. This also applies in the case of hydrogen being produced by biomass, which is of growing interest (e.g. Kalinci et al., 2009; Balat and Kirtay, 2010).

On the other hand, if natural gas is not considered as a constrained resource, then the cause-effect relation is straight-forward: a rising demand for fertilizer involves a rising demand for natural gas. This in turns may interact in the energy market by a change in price that could have repercussions in substituted energy products (e.g. coal). However, the price elasticity of demand for natural gas is close to zero (Whistance and Thompson, 2010), meaning that natural gas demand is rather inelastic, so changes in price induce only small adjustments to the quantity demanded.

In this case, it would be reasonable to assume that a potential increase (or decrease) in the natural gas price due to a higher demand induced by the fertilizer industry will not affect the amount of natural gas demanded in the energy market.

In the present case, natural gas is not regarded as constrained resource, so no interactions with C source material for CHP production or with expansion of arable land are considered.

EFMA (2010) presents the capacity indices of major N fertilizers in EU-25 from 1990 to 2007. From this, it can be observed that the capacity of NPK fertilizers is significantly lower than for straight N fertilizers.[2] Moreover, based on EFMA (2004), 78 % of the nitrogen is applied through straight fertilisers in Western Europe countries, the remaining being applied in multinutrient compound fertilisers. Therefore, straight fertilisers are used in this study. This also simplifies the inventory building.

The data for both urea and calcium ammonium nitrate production are taken from the Ecoinvent processes "Calcium ammonium nitrate, as N, at regional storehouse/RER U" and "Urea, as N, at regional storehouse/RER U". These represent European data. However, the marginal producing technology for urea is not likely to be European. In fact, EFMA (2004) specifies that new capacities (for ammonia, from which 97 % of the N fertilisers are derived) are developed in high-demand developing countries (South Asia and China), where the social and environmental legislation is less constraining than in other countries and where cheap supply of natural gas is available. However, no data are available for these, so European data used as a best proxy.

10.2.3 Phosphorus

Forecasts for P demand are similar to those of nitrogen. Short-term projections for P_2O_5 consumption in "West and Central Europe" (FAO, 2009) indicate stability (consumption 3 M tonnes in 2008 and in 2013). The longer

---

[2] http://www.efma.org/documents/file/statistics/Cap.dev.EU25..pdf

term forecasts (up to 2030) made by Tenkorang and Lowenberg-DeBoer (2009) however indicate a consumption increase in all regions considered in the model, except for the region “rest of Europe” (Eastern Europe and former soviet union countries). Tenkorang and Lowenberg-DeBoer (2009) projections for EU indicate a commercial P consumption of 3.1, 4.3 and 5.2 M megatonnes for 2005, 2015 and 2030, respectively. For the world, their forecasts indicate a commercial P consumption of 36.6, 43.8 and 52.9 M megatonnes (for 2005, 2015 and 2030, respectively). These forecasts, however, may be underestimated as they do not include the recent increases in biofuel demand nor an economic growth that continues in developing countries (particularly China and India). For EU-15, however, phosphorus consumption is forecasted to decline by 13.6 % on the short-term horizon (2008-2018) (EFMA, 2009).

Drastic decreases in P (or K) fertilisation, as opposed to N, does not have immediate negative consequences for yield (FAO, 2009). This means that P and K fertilisers demand are likely to be affected much more than N by changes in price for agricultural commodities, as this occurred in 2008. Moreover, repeated application of phosphorus that took place on most European soils have increased the readily available soil reserves of phosphorus, meaning that phosphorus demand from the European market would be likely to decrease drastically in case of economical crisis.

FAO (2009) reports that close to 40 new monoammonium phosphate, diammonium phosphate and triple superphosphate units shall be constructed between 2008-2013 in 10 different countries, and nearly half of it should be in China. Other facilities are also planned in Africa, West Asia, East Asia and Latin America. Most of these 40 new units should be diammonium phosphate units. Based on statistics from the International fertiliser Association, diammonium phosphate is, in both “Western Europe” and the world, is the P fertiliser with the greatest apparent consumption for the period 1999-2008 (IFA, 2010) (compared to monoammonium phosphate and triple superphosphate). Based on this, diammonium phosphate is considered to be the marginal P fertiliser in this study.

For Denmark, however, integrated PK fertilisers are by far the most used P fertiliser source (FAOstat, 2010; Plantedirektorate, 2010) (0-4-21 with Mg and Cu). Nemecek and Kägi (2007) mentions that multinutrient fertilisers can be approximated by combining their respective inventories. Unfortunately, there is no inventory for such integrated PK fertilisers in the Ecoinvent database (but only for integrated NP fertilisers).

Most P fertilisers (integrated NPK, single and triple superphosphate as well as mono- and diammonium phosphates) are made from phosphoric acid, which is in turn made from phosphate rock and sulphuric acid. Given that the phosphate rock is a limited and non substitutable resource essential for all known life forms, one interest regarding the use of P fertilisers in this LCA lies in reflecting the impact of changes regarding use of land in Denmark (towards more bioenergy) on the depletion of P reserves. According to Jonhston and Steén (2000), estimates of current reserves that can be exploited vary from 100 years to 250 years, but this forecast can be as long as 600 to 1000 years if known potential reserves are taken into account. Roberts and Stewart (2002) present world reserve estimate of 88 years as well as an estimate of 343 years for reserve base (i.e. the share of current reserves plus known potential reserves that meets specific minimum physical and chemical criteria for exploitation).

Phosphate rock reserves are controlled by 3 main countries, namely Morocco, China and the US (Cordell et al., 2009). However, Altaus et al. (2007) distinguish between only 2 types of phosphate rock mining: as done in the US (wet, 29 % P_2O_5 in crude ore) and as done in Morocco (dry, 33 % P_2O_5 in crude ore). According to the authors, these two phosphate rock mining processes represent a share of about 40 to 50 % of the world production of phosphate rock. In this study, the phosphate rock mining process used is the one from Morocco, since it is likely to be the most competitive, besides being the place where the largest economically extractable reserves are located.

Not using multinutrient fertilisers for P involves that the P fertiliser used shall be single or triple superphosphate. In this study, triple superphosphate is used as the marginal fertiliser. There is huge uncertainty on that. As for nitrogen, the choice of a particular fertiliser has implications. In fact, a screening in SimaPro (v.7.1) comparing single and triple superphosphate was performed and it showed that, for most environmental impact categories of the EDIP impact assessment method, the production of single superphosphate yields more environmental impacts than for triple superphosphate (this also applies when comparing with other P fertilisers).

10.2.4 Potassium

Long term projections for K fertilisers consumption by Tenkorang and Lowenberg-DeBoer (2009) also indicate an increase trend, for EU and world wide. This corresponds to a consumption of 3.2, 5.0 and 6.0 M megatonnes in 2005, 2015 and 2030, respectively, for the EU. For the world, the forecasts show a consumption of 26.6, 28.5 and 32.8 M megatonnes for 2005, 2015 and 2030, respectively.

In 2009, the demand for potash dropped to its lowest level since the past 30 years (Heffer and Prud'homme, 2009). However, strong demand prospects in the medium term have prompted many prospective producers to invest in potash projects and global potash capacity is forecasted to increase from 40 M tonnes K_2O in 2008 to 54 M tonnes K_2O in 2013 (FAO, 2009).

Potassium, like phosphorus, is mined from natural deposits. However, economically extractable reserves of potassium are forecasted to last much longer, some 350 years based on the lower estimates of global reserves and actual rate of consumption (Jonhston, 2003). Roberts and Stewart (2002) report a world reserve of 325 years and a reserve base of 658 years. Jonhston (2003) highlights that if accounting for current estimation of total resources (i.e. potential reserves), K_2O may last many millennia. Based on this, scarcity does not appear to be an issue for potassium, even though it also comes from finite reserves.

Varieties of potassium fertilisers include potassium chloride, potassium sulphate and potassium nitrate. However, potassium chloride (KCl) accounts for about 95 % of all potassium fertilisers used in agriculture, being the cheapest per tonne (Jonhston, 2003). Potassium chloride is therefore considered as the marginal K fertiliser, i.e. the one most likely to be affected by a change in demand, and is therefore the one used in this study.

Mined potash salts are separated in order to produced KCl. There are three main processes used to carry out this separation: thermal dissolution, flotation and electrostatic separation (Nemecek and Kägi, 2007). The choice of the method is function of the raw salt as well as of the final product requirements, and sometime consists of a mix of different technologies (Kali, 2010). However, according to Jonhson (2003), the most commonly used method for carrying out this separation is thermal dissolution. In this process, the salt is added to a hot sodium chloride saturated solution (solvent), where only potassium chloride dissolve while other salts (among which NaCl) can be removed by filtration. The solution is then passed into vacuum coolers where the KCl crystallises, so the KCl can then be filtered and dried (Jonhston, 2003).

In this project, the environmental impacts due to the production of KCl are modelled using the Ecoinvent process “Potassium chloride, as K_2O, at regional storehouse/RER U”. This is mainly based on data from Germany, which is the largest supplier of potassium fertiliser in Western Europe (Nemecek and Kägi, 2007). The process includes a mix of the three main used technologies for concentration of the salt.

10.2.5 Application of mineral fertilisers

The application of mineral fertilisers are included by the Ecoinvent process ”Fertilising, by broadcaster”. Emissions from the diesel consumption by the tractor are adjusted based on the norm values presented by Dalgaard et al. (2001), which corresponds to 1.8 L/ha on JB3 and 2 L/ha on JB6. The emissions caused by burning diesel are adjusted in consequence.

10.3 Organic fertilizer (animal manure)

In Denmark, the largest share of N in animal manure is handled in the form of slurry (Mikkelsen et al., 2006; figure 8). However, for the organic fertilizer, increasing the demand for any of the selected crop would not impact on the slurry production as such. This is simply because no one will “produce” more simply because the demand for fertilisers is rising, slurry being a by-product of another activity, namely meat production.

The most competitive slurry would therefore simply be the one that is more likely to be available in the area where the crops needing fertilisation are. This depends of the husbandry production of this area.

Nielsen et al. (2009) present, for the different IPCC livestock categories, the N excreted per animal type as well as the total number of animals in Denmark. Based on this, the N excreted per year for the different IPCC livestock categories can be calculated, for 1990 to 2007. Figure 4 illustrates the importance of the livestock categories “swine” and “dairy cattle” as a source of N fertilizer as compared to the other livestock categories. This of course does not represent the actual amount of N available for fertilization as the losses are not taken into account, but present an overview of the available N from the different IPCC livestock categories. Though the organic N from “swine” appears predominant over the one from “dairy cattle”, it is considered in the present project that 50 % of the slurry is from “swine” and 50 % from “dairy cattle”. This is because the type of organic fertilizer to be applied for a given crop farm is much dependant on the location of this farm, so the slurry type to be applied will depend of the husbandry farm-type in this location.

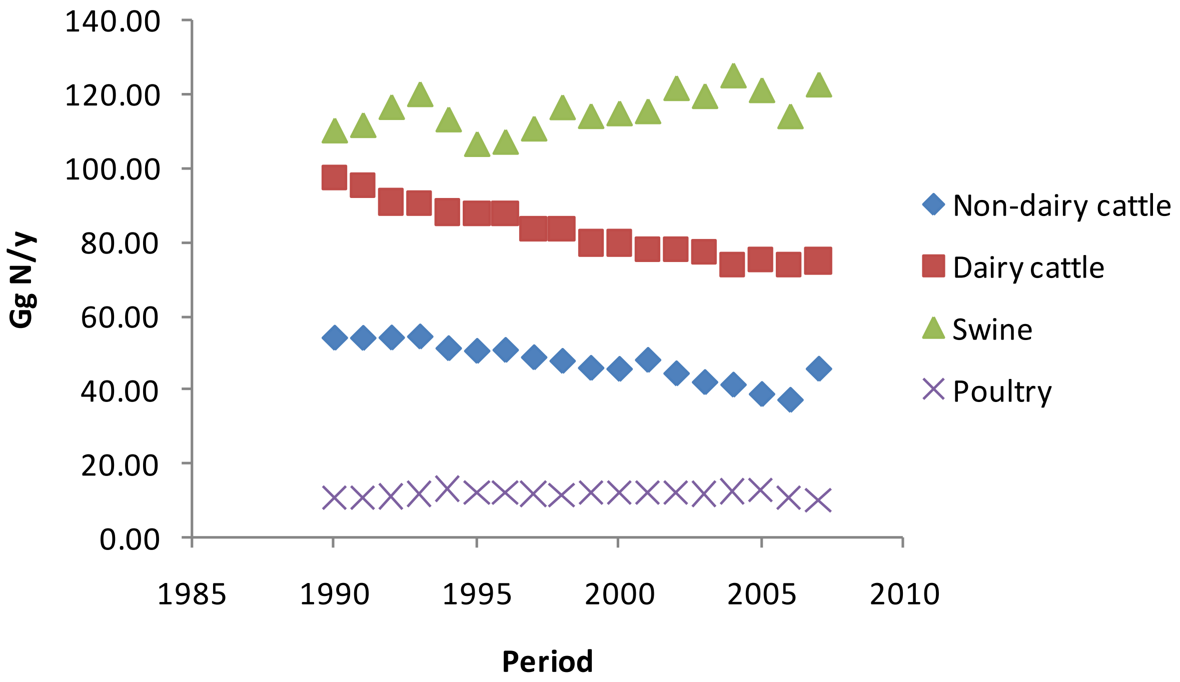

Figure 4. N excreted per year for the different IPCC livestock categories, based on data from Nielsen et al. (2009)

For IPCC livestock category “swine”, it is chosen to use slurry from fattening pigs housed in a fully slatted floor pig facility. According to Dalgaard (2007) the majority of farms in Denmark have exclusively fattening pigs. For IPCC livestock category “dairy cattle”, the slurry composition for this study is based on a cubicle housing system with slatted floor (1.2 m channel).

For both fattening pig and dairy cow, the slurry composition was determined based on the exact same methodology and assumptions as presented in Wesnæs et al. (2009) (section A.1.2 to A.1.4 of Annex A). In their study, Wesnæs et al. (2009) established a reference slurry composition for both fattening pig and dairy cow slurry in order to carry out a life cycle assessment of slurry management technologies in Denmark. The methodology presented in Wesnæs et al. (2009) take for basis the Danish normative system for assessing manure composition, for which Poulsen et al. (2001) established the technical background report. Updates of this report are published every year by Danmaks Jordbrugs Forskning (DJF) (“normtal” data). As in Wesnæs et al. (2009), the values for DM (ex-storage), N, P and K (ex-animal) used are based on the DJF “normtal” data. In the present case, however, the latest updated values will be used, i.e. those in Poulsen (2009) (Wesnæs et al. (2009) used the 2008 data). This is why the N, P and K values differ slightly as those presented by Wesnæs et al. (2009). However, since the DM (ex-storage) has the same value in “normtal” 2008 and 2009, all other values are the same (since these values are all dependent upon DM). These values assumed that the slurry is stored in a concrete tank (for pig, cut straw is added as a floating layer; for cows, it is assumed that a natural crust is forming). Concerns related to the use of the “normtal” data are expressed in Wesnæs et al. (2009), since these data do not consider water addition in the housing system, which results in higher ex-storage concentrations than those found in practice as the slurry is not diluted. These data are nevertheless used as they are considered as the “Danish standard data” for the majority of Danish studies about slurry (Wesnæs et al., 2009).

As discussed in Wesnæs et al. (2009), the slurry composition is the very basis for assessing the nutrient flow from the slurry in the environment. Yet, the slurry composition may be highly variable from one farm to another, depending, among others, on the diet, the slurry management, the housing system, the in-house environmental conditions, the storage time, etc. Through the slurry composition used in this project is based on best available Danish data, it does not pretend to represent the “average Danish slurry” for both fattening pigs and dairy cows, so any use of the data presented in this project must be done in the light of this consideration.

Tables 21 and 22 present the slurry composition used for this project, for fattening pigs and dairy cows, respectively. The values of interest for this project are the values ex-storage (i.e. before application), but the values for slurry ex-housing and ex-animal are given for information. The number of digits should not be seen as an indication of precision of the values; many digits were conserved as rounding data at this stage is likely to result in inconsistencies in the different mass balances to be carried out in later stages.

Table 21. Composition of the pig slurry to be used as an organic fertilizer in the present slurry

	Slurry ex-animal	Slurry ex-housing	Slurry ex-storage	Source and assumptions
Total mass (ton)	1	1	1	
Total N (kg)	6.565	5.449	4.765	N ex-animal from Poulsen (2009) (3.02 kg / 0.46 ton). Values ex-housing and ex-storage obtained from mass balances. Losses considered (during housing and during storage): NH_3, N_2O, N_2, NO. See table 23 for details about N losses. Ex-storage values adjusted considering water addition of 86 kg during the storage.
P (kg)	1.087	1.087	1.001	P ex-animal from Poulsen (2009) (0.50 kg / 0.46 ton). No losses considered. Ex-storage values adjusted considering water addition of 86 kg during the storage.
K (kg)	2.848	2.848	2.622	K ex-animal from Poulsen (2009) (1.31 kg / 0.46 ton). No losses considered. Ex-storage values adjusted considering water addition of 86 kg during the storage.
DM (kg)	77.481	69.733	61.000	DM ex-storage from Poulsen (2009). Losses during storage: 5 % of the ex-housing values. Losses during housing: 10 % of the ex-animal value. Water addition of 86 kg during storage is taken into account.
Ash (kg)	13.249	13.249	12.200	Ash ex-storage = 20 % of DM ex-storage. No losses considered. Water addition of 86 kg during storage is taken into account.
VS (kg)	64.232	56.483	48.800	VS ex-storage = 80 % of DM ex-storage. Losses considered during storage and housing (absolute values) are the same as for DM (all DM loss was VS). Water addition of 86 kg during storage is taken into account.
C (kg)	37.113	33.402	29.219	C ex-storage = 47.9 % of DM ex-storage, based on ratio C:DM obtained by Knudsen and Birkmose (2005). Losses assumed to follow the same pattern as DM: losses during storage of 5 % of the ex-housing value and losses during housing of 10 % of the ex-animal value. Water addition of 86 kg during storage is taken into account.
Cu (g)	30.009	30.009	27.633	Cu ex-storage = 0.0453 % of DM ex-storage, based on ratio Cu:DM obtained by Knudsen and Birkmose (2005). No losses considered. Water addition of 86 kg during storage is taken into account.
Zn (g)	89.432	89.432	82.350	Zn ex-storage = 0.135 % of DM ex-storage, based on ratio Zn:DM obtained by Knudsen and Birkmose (2005). No losses considered. Water addition of 86 kg during storage is taken into account.
Density (kg/m^3)	1053	1053	1053	From literature references for slurry density (Sherlock et al., 2002; Sanchez and Gonzalez, 2004). To be seen as an indicative value rather than as an exact value.
pH			7.8	Based on Sommer and Husted (1995).

Table 22. Composition of the dairy cow slurry to be used as an organic fertilizer in the present study

	Slurry ex-animal	Slurry ex-housing	Slurry ex-storage	Source and assumptions
Total mass (ton)	1	1	1	
Total N (kg)	6.892	6.363	5.807	N ex-animal from Poulsen (2009) (140.6 kg / 20.4 ton). Values ex-housing and ex-storage obtained from mass balances. Losses considered (during housing and during storage): NH_3, N_2O, N_2, NO. Addition of N through straw added in the stable accounted for. See table 23 for details about N balance. Ex-storage values adjusted considering water addition of 44 kg during the storage.
P (kg)	1.020	1.032	0.989	P ex-animal from Poulsen (2009) (20.8 kg / 20.4 ton). Addition of P through straw added in the stable accounted for (see table 24). No losses considered. Ex-storage values adjusted considering water addition of 44 kg during the storage.
K (kg)	5.819	6.088	5.831	K ex-animal from Poulsen (2009) (118.7 kg / 20.4 ton). Addition of K through straw added in the stable accounted for (see table 24). No losses considered. Ex-storage values adjusted considering water addition of 44 kg during the storage
DM (kg)	125.768	113.192	103.000	DM ex-storage from Poulsen (2009). Losses during storage: 5 % of the ex-housing values. Losses during housing: 10 % of the ex-animal value. Water addition of 44 kg during storage is taken into account.
Ash (kg)	21.506	21.506	20.600	Ash ex-storage = 20 % of DM ex-storage. No losses considered. Water addition of 44 kg during storage is taken into account.
VS (kg)	104.262	91.685	82.400	VS ex-storage = 80 % of DM ex-storage. Losses considered during storage and housing (absolute values) are the same as for DM (all DM loss was VS). Water addition of 44 kg during storage is taken into account.
C (kg)	55.212	49.691	45.217	C ex-storage = 43.9 % of DM ex-storage, based on ratio C:DM obtained by Knudsen and Birkmose (2005). Losses assumed to follow the same pattern as DM: losses during storage of 5 % of the ex-housing value and losses during housing of 10 % of the ex-animal value. Water addition of 44 kg during storage is taken into account.
Cu (g)	12.151	12.151	11.639	Cu ex-storage = 0.0113 % of DM ex-storage, based on ratio Cu:DM obtained by Knudsen and Birkmose (2005). No losses considered. Water addition of 44 kg during storage is taken into account.
Zn (g)	23.334	23.334	22.351	Zn ex-storage = 0.0217 % of DM ex-storage, based on ratio Zn:DM obtained by Knudsen and Birkmose (2005). No losses considered. Water addition of 44 kg during storage is taken into account.
Density (kg/m^3)	1053	1053	1053	From literature references for slurry density (Sherlock et al., 2002; Sanchez and Gonzalez, 2004). To be seen as an indicative value rather than as an exact value.
pH			7.8	Based on Sommer and Husted (1995).

Table 23. Assumptions for N losses in the establishment of slurry composition

Losses	Pig slurry	Dairy cow slurry
Losses in-house (kg)		
NH_3-N	16 % of N ex-animal (Poulsen et al., 2001)	8 % of N ex-animal (Poulsen et al., 2001)
N_2O-N	0.002 kg N_2O-N per kg N ex-animal (IPCC, 2006)	0.002 kg N_2O-N per kg N ex-animal (IPCC, 2006)
N_2-N	Assumption that N_2-N = N_2O-N * 3 (based on data from Dämmgen and Hutchings, 2008)	Assumption that N_2-N = N_2O-N * 3 (based on data from Dämmgen and Hutchings, 2008)
NO-N	Assumption that N_2-N = N_2O-N * 1 (based on data from Dämmgen and Hutchings, 2008)	Assumption that N_2-N = N_2O-N * 1 (based on data from Dämmgen and Hutchings, 2008)
Losses during storage (kg)		
NH_3-N	2 % of N ex-housing (Poulsen et al., 2001), the N ex-housing being estimated according to Poulsen et al. (2001), i.e. : N ex-animal – NH_3-N losses in-house (and not accounting for other losses).	2 % of N ex-housing (Poulsen et al., 2001), the N ex-housing being estimated according to Poulsen et al. (2001), i.e. : N ex-animal – NH_3-N losses in-house (and not accounting for other losses) + N from straw addition.
N_2O-N	0.005 kg N_2O-N per kg N ex-animal (IPCC, 2006)	0.005 kg N_2O-N per kg N ex-animal (IPCC, 2006)
N_2-N	Assumption that N_2-N = N_2O-N * 3 (based on data from Dämmgen and Hutchings, 2008)	Assumption that N_2-N = N_2O-N * 3 (based on data from Dämmgen and Hutchings, 2008)
NO-N	Assumption that N_2-N = N_2O-N * 1 (based on data from Dämmgen and Hutchings, 2008)	Assumption that N_2-N = N_2O-N * 1 (based on data from Dämmgen and Hutchings, 2008)

Table 24. Assumptions for N, P and K balance through straw addition in the stable, for dairy cows.

Parameter	Value
kg straw / animal * day	1.2 (Poulsen et al., 2001)
Straw DM (%)	85 (Poulsen et al., 2001)
kg N / kg DM	0.005 (Poulsen et al., 2001)
kg P / kg DM	0.00068 (Poulsen et al., 2001)
kg K / kg DM	0.01475 (Poulsen et al., 2001)
kg slurry / animal	20 400 (Poulsen, 2009)
Addition of N, P and K related to straw addition	0.0913 kg N; 0.0124 kg P; 0.269 kg K (calculated based on the above parameters)

10.3.1 Application of slurry

Slurry spreading is performed by trail hose application tanker. This process is modelled by the Ecoinvent process “Slurry spreading, by vacuum tanker”. The process includes the diesel for slurry application, construction of the tractor, the slurry tanker and a shed, all divided by their estimated life time and slurry amount in this period. Emissions from the diesel consumption by the tractor are adjusted based on the norm values presented by Dalgaard et al. (2001), which corresponds to 0.54 L/t slurry on JB3 and 0.60 L/t slurry on JB6 (this includes loading). The emissions caused by burning diesel are adjusted in consequence.

10.4 Annual fertilisation for each crop selected

10.4.1 Needs in N, P and K for all crops

The annual fertilisation needs for each of the selected crop is based on the fertilisation guidelines issued by the Danish Ministry of Food, Agriculture and Fisheries (Ministry of Food, Agriculture and Fisheries, 2009), except for Miscanthus. These are what the farmers use to make their fertilisation plan.

Table 25 presents the needs in N, P and K for each of the selected crop, on both a sandy soil (JB3) and a sandy loam soil (JB6).

Table 25. Fertilisation needs for each selected crop, in kg/ha

(Kg/ha)	JB3 (sand)			JB6 (sandy loam)		
	N	P	K	N	P	K
Spring barley	126	22	45	114	22	45
Spring barley & Catch crop[a]	109	22	45	97	22	45
Winter wheat	166	22	66	161	22	66
Willow	120	15	50	120	15	50
Miscanthus (autumn)[b,c]	90	15	75	90	15	75
Miscanthus (spring) [c]	60	15	75	60	15	75
Maize silage	162	44	135	139	44	135
Sugar beet	123	43	150	102	43	150
Rye grass	342	36	239	325	36	239

[a] Catch crops are assumed to reduce the N norm by 17 kg N/ha.

[b]For N, values come from Olesen et al. (2001).

[c]For N, these are the values for year 4 to 20. No N is applied in year 1, 30 kg/ha is applied on year 2 and 60 kg/ha is applied on year 3, for both spring and autumn harvest.

The nutrients needs presented in table 26 are fulfilled by 50 % synthetic fertiliser and 50 % organic fertiliser, as detailed earlier. The organic fertiliser consists of 50 % fattening pig slurry and 50 % dairy cow slurry, and the slurry composition considered are those presented in table 21 and 22 (slurry ex-storage).

10.4.2 Fertilisation balance for N

The fertilisation balance is presented, for each crops grown in JB3, in Table 26, detailing the origin of each nutrient. Table 27 presents the same balance for crops cultivated on JB6. For willow, there is 2 types of applications, i.e. 100 % mineral N and 100 % animal manure N.

Table 26. Amount and origin of N fertilizer added, for each of the selected crop on soil JB3 (sandy soil)

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % mineral)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Willow (100 % animal manure)	Miscanthus (both), year 2	Miscanthus (both), year 3
Total N needs[a]	126	109	166	120	90	60	162	123	342	120	30	60
Amount from mineral N	126 Kg N/ha *50% from mineral = 63.0 kg/ha	109 Kg N/ha *50% from mineral = 54.5 kg/ha	166 Kg N/ha *50% from mineral = 83.0 kg/ha	120 Kg N/ha *100% from mineral = 120.0 kg/ha	90 Kg N/ha *50% from mineral = 45.0 kg /ha	60 Kg N/ha *50% from mineral = 30.0 kg /ha	162 Kg N/ha *50% from mineral = 81.0 kg/ha	123 Kg N/ha *50% from mineral = 61.5 kg/ha	342 Kg N/ha *50% from mineral = 171.0 kg/ha	120 Kg N/ha *0% from mineral = 0 kg/ha	30 Kg N/ha *50% from mineral = 15.0 kg /ha	60 Kg N/ha *50% from mineral = 30.0 kg /ha
Amount from pig slurry[b]	(126 Kg N/ha *50% from slurry *50% from pig) /0.75 = 42.0 kg/ha	(109 Kg N/ha *50% from slurry *50% from pig) /0.75 = 36.3 kg/ha	(166 Kg N/ha *50% from slurry *50% from pig) /0.75 = 55.3 kg/ha	120 Kg N/ha *0% from slurry = 0 kg/ha	(90 Kg N/ha *50% from slurry *50% from pig) /0.75 = 30.0 kg/ha	(60 Kg N/ha *50% from slurry *50% from pig) /0.75 = 20.0 kg/ha	(162 Kg N/ha *50% from slurry *50% from pig) /0.75 = 54.0 kg/ha	(123 Kg N/ha *50% from slurry *50% from pig) /0.75 = 41.0 kg/ha	(162 Kg N/ha *50% from slurry *50% from pig) /0.75 = 114.0 kg/ha	(120 Kg N/ha *100% from slurry *50% from pig) /0.75 = 80.0 kg/ha	(30 Kg N/ha *50% from slurry *50% from pig) /0.75 = 10.0 kg/ha	(60 Kg N/ha *50% from slurry *50% from pig) /0.75 = 20.0 kg/ha
Amount from cow slurry[c]	(126 Kg N/ha *50% from slurry *50% from cow) /0.70 = 45.0 kg/ha	(109 Kg N/ha *50% from slurry *50% from cow) /0.70 = 38.9 kg/ha	(166 Kg N/ha *50% from slurry *50% from cow) /0.70 = 59.3 kg/ha	(120 Kg N/ha *0% from slurry = 0 kg/ha	(90 Kg N/ha *50% from slurry *50% from cow) /0.70 = 32.1 kg/ha	(60 Kg N/ha *50% from slurry *50% from cow) /0.70 = 21.4 kg/ha	(162 Kg N/ha *50% from slurry *50% from cow) /0.70 = 57.9 kg/ha	(123 Kg N/ha *50% from slurry *50% from cow) /0.70 = 43.9 kg/ha	(162 Kg N/ha *50% from slurry *50% from cow) /0.70 = 122.1 kg/ha	(120 Kg N/ha *100% from slurry *50% from cow) /0.70 = 85.7 kg/ha	(30 Kg N/ha *50% from slurry *50% from cow) /0.70 = 10.7 kg/ha	(60 Kg N/ha *50% from slurry *50% from cow) /0.70 = 21.4 kg/ha

[a] From table 25.

[b] Considering an efficiency of 75 % for fattening pig slurry, i.e. if 1 kg of slurry-N is applied, only 0.75 kg will be available for plants uptake.

[c] Considering an efficiency of 70 % for dairy cow slurry, i.e. if 1 kg of slurry-N is applied, only 0.70 kg will be available for plants uptake.

Table 27. **Amount and origin of N fertilizer added, for each of the selected crop on soil JB6 (sandy loam)**

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % mineral)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Willow (100 % animal manure)	Miscanthus (both), year 2	Miscanthus (both), year 3
Total N needs[a]	114	97	161	120	90	60	139	102	325	120	30	60
Amount from mineral N	114 kg N/ha *50% from mineral = 57.0 kg/ha	97 kg N/ha *50% from mineral = 48.5 kg/ha	161 kg N/ha *50% from mineral = 80.5 kg/ha	120 Kg N/ha *100% from mineral = 120.0 kg/ha	90 kg N/ha *50% from mineral = 45.0 kg/ha	60 kg N/ha *50% from mineral = 30.0 kg/ha	139 kg N/ha *50% from mineral = 69.5 kg/ha	102 kg N/ha *50% from mineral = 51.0 kg/ha	325 kg N/ha *50% from mineral = 162.5 kg/ha	120 Kg N/ha *0% from mineral = 0 kg/ha	30 Kg N/ha *50% from mineral = 15.0 kg /ha	60 kg N/ha *50% from mineral = 30.0 kg/ha
Amount from pig slurry[b]	(114 kg N/ha *50% from slurry *50% from pig) /0.75 = 38.0 kg/ha	(97 kg N/ha *50% from slurry *50% from pig) /0.75 = 32.3 kg/ha	(161 kg N/ha *50% from slurry *50% from pig) /0.75 = 53.7 kg/ha	120 Kg N/ha *0% from slurry = 0 kg/ha	(90 kg N/ha *50% from slurry *50% from pig) /0.75 = 30.0 kg/ha	(60 kg N/ha *50% from slurry *50% from pig) /0.75 = 20.0 kg/ha	(139 kg N/ha *50% from slurry *50% from pig) /0.75 = 46.3 kg/ha	(102 kg N/ha *50% from slurry *50% from pig) /0.75 = 34.0 kg/ha	(325 kg N/ha *50% from slurry *50% from pig) /0.75 = 108.3 kg/ha	(120 Kg N/ha *100% from slurry *50% from pig) /0.75 = 80.0 kg/ha	(30 Kg N/ha *50% from slurry *50% from pig) /0.75 = 10.0 kg/ha	(60 kg N/ha *50% from slurry *50% from pig) /0.75 = 20.0 kg/ha
Amount from cow slurry[c]	(114 kg N/ha *50% from slurry *50% from cow) /0.70 = 40.7 kg/ha	(97 kg N/ha *50% from slurry *50% from cow) /0.70 = 34.6 kg/ha	(161 kg N/ha *50% from slurry *50% from cow) /0.70 = 57.5 kg/ha	(120 Kg N/ha *0% from slurry = 0 kg/ha	(90 kg N/ha *50% from slurry *50% from cow) /0.70 = 32.1 kg/ha	(60 kg N/ha *50% from slurry *50% from cow) /0.70 = 21.4 kg/ha	(139 kg N/ha *50% from slurry *50% from cow) /0.70 = 49.6 kg/ha	(102 kg N/ha *50% from slurry *50% from cow) /0.70 = 36.4 kg/ha	(325 kg N/ha *50% from slurry *50% from cow) /0.70 = 116.1 kg/ha	(120 Kg N/ha *100% from slurry *50% from cow) /0.70 = 85.7 kg/ha	(30 Kg N/ha *50% from slurry *50% from cow) /0.70 = 10.7 kg/ha	(60 kg N/ha *50% from slurry *50% from cow) /0.70 = 21.4 kg/ha

[a] From table 25.

[b] Considering an efficiency of 75 % for fattening pig slurry, i.e. if 1 kg of slurry-N is applied, only 0.75 kg will be available for plants uptake.

[c] Considering an efficiency of 70 % for dairy cow slurry, i.e. if 1 kg of slurry-N is applied, only 0.70 kg will be available for plants uptake.

10.4.3 Determination of the amount of pig and cow slurry added

The amount of pig and cow slurry added on each soil type can be calculated at this stage. For pig slurry, this can be done, crop by crop, by dividing the amount of added N from pig slurry by the amount of N contained in the pig slurry. As an example for spring barley on JB3, this is calculated as: 42.0 kg N added from pig slurry per ha / 4.765 k N per ton pig slurry (ex-storage) = 8.81 ton pig slurry per ha. The same procedure is applied with cow slurry. Table 28 presents, for each crop and each soil type, the annual amount of pig and cow slurry to be applied, per hectare.

Table 28. Amount of pig and cow slurry used for each crop type, on both soil JB3 and soil JB6

	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Miscanthus (both), year 2	Miscanthus (both), year 3
JB3											
Amount of slurry from fattening pigs (ex-storage slurry) (ton/ha)	8.81	7.63	11.61	16.79	6.30	4.20	11.33	8.60	23.92	2.10	4.20
Amount of slurry from dairy cows (ex-storage slurry) (ton/ha)	7.75	6.70	10.21	14.76	5.54	3.69	9.96	7.56	21.03	1.85	3.69
JB6											
Amount of slurry from fattening pigs (ex-storage slurry) (ton/ha)	7.97	6.79	11.26	16.79	6.30	4.20	9.72	7.14	22.74	2.10	4.20
Amount of slurry from dairy cows (ex-storage slurry) (ton/ha)	7.01	5.97	9.90	14.76	5.54	3.69	8.55	6.27	19.99	1.85	3.69

10.4.4 Fertilisation balance for P

For each crops, most of the fertilization needs will be fulfilled by the added slurry. However, when the balance is not fulfilled, it is considered that the farmer will seek for optimal yield, thus applying as much fertilizer as the law allow him/her to do so. Therefore, it is considered that the gap between the P needed by each crops (based on the law) and the P received from manure is fulfilled by the marginal synthetic fertilizer. Table 29 and 30 present, for JB3 and JB6 respectively, the balance for P fertilization, showing the amount of P added with the slurry and the amount of synthetic P to be added. When there is a surplus, no synthetic fertilizer is added.

Table 29. Amount and origin of P fertilizer added, for each of the selected crop on soil JB3 (sandy soil)

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Miscanthus (both), year 2	Miscanthus (both), year 3
Total P needs[a]	22	22	22	15	15	15	44	43	36	15	15
Amount from pig slurry[b]	8.81 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 8.82 kg /ha	7.63 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 7.63 kg /ha	11.61 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 11.62 kg /ha	16.79 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 16.81 kg /ha	6.30 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 6.30 kg /ha	4.20 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 4.20 kg /ha	11.33 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 11.34 kg /ha	8.60 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 8.61 kg /ha	23.92 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 23.95 kg /ha	2.10 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 2.10 kg /ha	4.20 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 4.20 kg /ha
Amount from cow slurry[c]	7.75 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 7.66 kg /ha	6.70 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 6.63 kg /ha	10.21 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 10.10 kg /ha	14.76 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 14.60 kg /ha	5.54 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 5.47 kg /ha	3.69 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 3.65 kg /ha	9.96 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 9.85 kg /ha	7.56 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 7.48 kg /ha	21.03 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 20.80 kg /ha	1.85 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 1.82 kg /ha	3.69 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 3.65 kg /ha
Balance to be fulfilled by mineral fertilisers[d]	22 -8.82 - 7.66 = 5.51 kg /ha	22 -7.63 - 6.63 = 7.74 kg /ha	22 -11.62 - 10.10 = 0.28 kg /ha	15 -16.81 - 14.60 = -16.40 kg /ha	15 -6.30 - 5.47 = 3.22 kg /ha	15 -4.20 - 3.65 = 7.15 kg /ha	44 -11.34 - 9.85 = 22.80 kg /ha	43 -8.61 - 7.48 = 26.91 kg /ha	36 -23.95 - 20.80 = -8.75 kg /ha	15 -2.10 - 1.82 = 11.07 kg /ha	15 -4.20 - 3.65 = 7.15 kg /ha

[a] From table 25.

[b] For each crop, the amount of pig slurry per hectare was determined in table 28.

[c] For each crop, the amount of cow slurry per hectare was determined in table 28.

[d] The negative sign indicates that this amount is a surplus, meaning that more P than needed is applied. This involves that no synthetic P is added.

Table 30. Amount and origin of P fertilizer added, for each of the selected crop on soil JB6 (sandy loam)

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Miscanthus (both), year 2	Miscanthus (both), year 3
Total P needs[a]	22	22	22	15	15	15	44	43	36	15	15
Amount from pig slurry[b]	7.97 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 7.98 kg /ha	6.79 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 6.79 kg /ha	11.26 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 11.27 kg /ha	16.79 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 16.81 kg /ha	6.30 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 6.30 kg /ha	4.20 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 4.20 kg /ha	9.72 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 9.73 kg /ha	7.14 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 7.14 kg /ha	22.74 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 22.76 kg /ha	2.10 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 2.10 kg /ha	4.20 ton pig slurry/ha * 1.001 kg P/ton pig slurry = 4.20 kg /ha
Amount from cow slurry[c]	7.01 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 6.93 kg /ha	5.97 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 5.90 kg /ha	9.90 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 9.79 kg /ha	14.76 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 14.60 kg /ha	5.54 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 5.47 kg /ha	3.69 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 3.65 kg /ha	8.55 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 8.45 kg /ha	6.27 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 6.20 kg /ha	19.99 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 19.77 kg /ha	1.85 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 1.82 kg /ha	3.69 ton cow slurry/ha * 0.989 kg P/ton cow slurry = 3.65 kg /ha
Balance to be fulfilled by mineral fertilisers[d]	22 -7.98 - 6.93 = 7.08 kg /ha	22 -6.79 - 5.90 = 9.31 kg /ha	22 -11.27 -9.79 = 0.93 kg /ha	15 -16.81 -14.60 = -16.40 kg /ha	15 -6.30 - 5.47 = 3.22 kg /ha	15 -4.20 - 3.65 = 7.15 kg /ha	44 -9.73 - 8.45 = 25.81 kg /ha	43 -7.14 - 6.20 = 29.65 kg /ha	36 -22.76 -19.77 = -6.53 kg /ha	15 -2.10 - 1.82 = 11.07 kg /ha	15 -4.20 - 3.65 = 7.15 kg /ha

[a] From table 25.

[b] For each crop, the amount of pig slurry per hectare was determined in table 28.

[c] For each crop, the amount of cow slurry per hectare was determined in table 28.

[d] The negative sign indicates that this amount is a surplus, meaning that more P than needed is applied. This involves that no synthetic P is added.

10.4.5 Fertilisation balance for K

As for P, it is considered that the gap between the K needed by each crops (based on the law) and the K received from manure is fulfilled by the marginal synthetic fertilizer. Tables 31 and 32 present, for JB3 and JB6 respectively, the balance for K fertilization, showing the amount of K added with the slurry and the amount of synthetic K to be added. When there is a surplus, no synthetic fertilizer is added.

Table 31. Amount and origin of K fertilizer added, for each of the selected crop on soil JB3 (sandy soil)

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Miscanthus (both), year 2	Miscanthus (both), year 3
Total K needs[a]	45	45	66	50	75	75	135	150	239	75	75
Amount from pig slurry[b]	8.81 ton pig slurry/ha * 2.622 kg K/ton pig slurry = 23.11 kg /ha	7.63 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 19.99 kg /ha	11.61 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 30.45 kg /ha	16.79 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 44.02 kg /ha	6.30 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 16.51 kg /ha	4.20 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 11.01 kg /ha	11.33 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 29.71 kg /ha	8.60 ton pig slurry/ha * 2.622 kg K2.622 kg K /ton pig slurry = 22.56 kg /ha	23.92 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 62.73 kg /ha	2.10 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 5.50 kg /ha	4.20 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 11.01 kg /ha
Amount from cow slurry[c]	7.75 ton cow slurry/ha * 5.831 kg K/ton cow slurry = 45.19 kg /ha	6.70 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 39.09 kg /ha	10.21 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 59.53 kg /ha	14.76 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 86.07 kg /ha	5.54 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 32.28 kg /ha	3.69 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 21.52 kg /ha	9.96 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 58.10 kg /ha	7.56 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 44.11 kg /ha	21.03 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 122.65 kg /ha	1.85 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 10.76 kg /ha	3.69 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 21.52 kg /ha
Balance to be fulfilled by synthetic fertilisers[d]	45 -23.11- 45.19 = -23.30 kg/ha	45 -19.99 -39.09 = -14.08 kg/ha	66 -30.45 -59.53 = -23.98 kg/ha	50 -44.02 -86.07 = -80.09 kg/ha	75 -16.51 - 32.28 = 26.22 kg/ha	75 -11.01 - 21.52 = 42.48 kg/ha	135 - 29.71 - 58.10 = 47.19 kg/ha	150 -22.56 -44.11 = 83.33 kg/ha	239 - 62.73 - 122.65 = 53.62 kg/ha	75 -11.01 - 21.52 = 58.74 kg/ha	75 -11.01 - 21.52 = 42.48 kg/ha

[a] From table 25.

[b] For each crop, the amount of pig slurry per hectare was determined in table 28.

[c] For each crop, the amount of cow slurry per hectare was determined in table 28.

[d] The negative sign indicates that this amount is a surplus, meaning that more K than needed is applied. This involves that no synthetic K is added.

Table 32. Amount and origin of K fertilizer added, for each of the selected crop on soil JB6 (sandy loam)

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Miscanthus (both), year 2	Miscanthus (both), year 3
Total K needs[a]	45	45	66	50	75	75	135	150	239	75	75
Amount from pig slurry[b]	7.97 ton pig slurry/ha * 2.622 kg K/ton pig slurry = 20.91 kg /ha	6.79 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 17.79 kg /ha	11.26 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 29.53 kg /ha	16.79 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 44.02 kg /ha	6.30 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 16.51 kg /ha	4.20 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 11.01 kg /ha	9.72 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 25.50 kg /ha	7.14 ton pig slurry/ha * 2.622 kg K2.622 kg K /ton pig slurry = 18.71 kg /ha	22.74 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 59.61 kg /ha	2.10 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 5.50 kg /ha	4.20 ton pig slurry/ha * 2.622 kg K /ton pig slurry = 11.01 kg /ha
Amount from cow slurry[c]	7.01 ton cow slurry/ha * 5.831 kg K/ton cow slurry = 40.88 kg /ha	5.97 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 34.79 kg /ha	9.90 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 57.74 kg /ha	14.76 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 86.07 kg /ha	5.54 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 32.28 kg /ha	3.69 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 21.52 kg /ha	8.55 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 49.85 kg /ha	6.27 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 36.58 kg /ha	19.99 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 116.55 kg /ha	1.85 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 10.76 kg /ha	3.69 ton cow slurry/ha * 5.831 kg K /ton cow slurry = 21.52 kg /ha
Balance to be fulfilled by synthetic fertilisers[d]	45 -20.91- 40.88 = -16.79 kg/ha	45 -17.79 -34.79 = -7.58 kg/ha	66 -29.53 -57.74 = -21.27 kg/ha	50 -44.02 -86.07 = -80.09 kg/ha	75 -16.51 - 32.28 = 26.22 kg/ha	75 -11.01 - 21.52 = 42.48 kg/ha	135 - 25.50 - 49.85 = 59.66 kg/ha	150 -18.71 -36.58 = 94.71 kg/ha	239 - 59.61 - 116.55 = 62.84 kg/ha	75 -11.01 - 21.52 = 58.74 kg/ha	75 -11.01 - 21.52 = 42.48 kg/ha

[a] From table 25.

[b] For each crop, the amount of pig slurry per hectare was determined in table 28.

[c] For each crop, the amount of cow slurry per hectare was determined in table 28.

[d] The negative sign indicates that this amount is a surplus, meaning that more K than needed is applied. This involves that no synthetic K is added.

10.4.6 Overall nutrients input for fertilization

Table 33 shows, for each crop cultivated on 1 ha of JB3, an overview of all the nutrients added during fertilization. Since calculations were performed with a software keeping all decimals, the occurrence of rounding inconsistencies is possible.

Table 33. Overview of added fertilizers and nutrients on JB3, for all crops, per fertilizer type, for a fertilizing event. All values expressed for 1 ha.

	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Willow (100 % mineral)	Miscan-thus (both), year 2	Miscan-thus (both), year 3
Pig Slurry												
Total mass of slurry (ton)	8.81	7.63	11.61	16.79	6.3	4.2	11.33	8.6	23.92	0	2.10	4.20
N (kg)	42.0	36.3	55.3	80.0	30.0	20.0	54.0	41.0	114.0		10.0	20.0
P (kg)	8.82	7.63	11.62	16.81	6.30	4.20	11.34	8.61	23.95		2.10	4.20
K (kg)	23.11	19.99	30.45	44.02	16.51	11.01	29.71	22.56	62.73		5.50	11.01
C (kg)	257.54	222.80	339.30	490.56	183.96	122.64	331.13	251.41	699.05		61.32	122.64
Cu (kg)	0.2436	0.2107	0.3209	0.4639	0.1740	0.1160	0.3132	0.2378	0.6611		0.0580	0.1160
Zn (kg)	0.7259	0.6279	0.9563	1.3826	0.5185	0.3456	0.9332	0.7086	1.9702		0.1728	0.3456
Cow Slurry												
Total mass of slurry (ton)	7.75	6.7	10.21	14.76	5.54	3.69	9.96	7.56	21.03	0	1.85	3.69
N (kg)	45	38.9	59.3	85.71	32.1	21.4	57.9	43.9	122.1		10.7	21.4
P (kg)	7.66	6.63	10.10	14.60	5.47	3.65	9.85	7.48	20.80		1.82	3.65
K (kg)	45.19	39.09	59.53	86.07	32.28	21.52	58.10	44.11	122.65		10.76	21.52
C (kg)	350.40	303.12	461.64	667.43	250.28	166.86	450.51	342.06	951.08		83.43	166.86
Cu (kg)	0.0902	0.0780	0.1188	0.1718	0.0644	0.0429	0.1160	0.0880	0.2448		0.0215	0.0429
Zn (kg)	0.1732	0.1498	0.2282	0.3299	0.1237	0.0825	0.2227	0.1691	0.4701		0.0412	0.0825
Mineral N												
N (kg)	63	54.5	83	60	45.0	30.0	81.0	61.5	171.0	120.0	15.0	30.0
Mineral P												
P (kg)	5.51	7.74	0.28	0	3.22	7.15	22.80	26.91	0	15.0	11.07	7.15
Mineral K												
K (kg)	0	0	0	0	26.22	42.48	47.19	83.33	53.62	50.0	58.74	42.28
Total nutrients added												
N (kg)	150.0	129.7	197.6	165.7	107.1	71.4	192.9	146.4	407.1	120.0	35.7	71.4
P (kg)	22.0	22.0	22.0	31.40	15.0	15.0	44.0	43.0	44.75	15.0	15.0	15.0
K (kg)	68.30	59.08	89.98	130.09	75.0	75.0	135.00	150.00	239.00	50.0	75.0	75.0
C (kg)	607.94	525.92	800.94	1157.99	434.24	289.50	781.64	593.47	1650.13	0.0	144.75	289.50
Cu (kg)	0.3338	0.2887	0.4397	0.6357	0.2384	0.1589	0.4291	0.3258	0.9059	0.0	0.0795	0.1589
Zn (kg)	0.8991	0.7778	1.1845	1.7125	0.6422	0.4281	1.1559	0.8777	2.4403	0.0	0.2141	0.4281

Similarly, table 34 shows, for each crop cultivated on 1 ha of JB6, an overview of all the nutrients added during fertilization. Since calculations were performed with a software keeping all decimals, the occurrence of rounding inconsistencies is possible.

Table 34. Overview of added fertilizers and nutrients on JB6, for all crops, per fertilizer type, for a fertilizing event. All values expressed for 1 ha.

	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Miscanthus (autumn)	Miscanthus (spring)	Maize silage	Sugar beet	Rye grass	Willow (100 % mineral)	Miscan-thus (both), year 2	Miscan-thus (both), year 3
Pig Slurry												
Total mass of slurry (ton)	7.97	6.79	11.26	16.79	6.30	4.20	9.72	7.14	22.74	0	2.10	4.20
N (kg)	38.00	32.33	53.67	80.00	30.00	20.00	46.33	34.00	108.33		10.0	20.0
P (kg)	7.98	6.79	11.27	16.81	6.30	4.20	9.73	7.14	22.76		2.10	4.20
K (kg)	20.91	17.79	29.53	44.02	16.51	11.01	25.50	18.71	59.61		5.50	11.01
C (kg)	233.02	198.27	329.08	490.56	183.96	122.64	284.12	208.49	664.30		61.32	122.64
Cu (kg)	0.2204	0.1875	0.3112	0.4639	0.1740	0.1160	0.2687	0.1972	0.6282		0.0580	0.1160
Zn (kg)	0.6567	0.5588	0.9275	1.3826	0.5185	0.3456	0.8007	0.5876	1.8722		0.1728	0.3456
Cow Slurry												
Total mass of slurry (ton)	7.01	5.97	9.90	14.76	5.54	3.69	8.55	6.27	19.99	0	1.85	3.69
N (kg)	40.71	34.64	57.50	85.71	32.14	21.43	49.64	36.43	116.07		10.7	21.4
P (kg)	6.93	5.90	9.79	14.60	5.47	3.65	8.45	6.20	19.77		1.82	3.65
K (kg)	40.88	34.79	57.74	86.07	32.28	21.52	49.85	36.58	116.55		10.76	21.52
C (kg)	317.03	269.75	447.73	667.43	250.28	166.86	386.55	283.66	903.81		83.43	166.86
Cu (kg)	0.0816	0.0694	0.1152	0.1718	0.0644	0.0429	0.0995	0.0730	0.2326		0.0215	0.0429
Zn (kg)	0.1567	0.1333	0.2213	0.3299	0.1237	0.0825	0.1911	0.1402	0.4468		0.0412	0.0825
Mineral N												
N (kg)	57.0	48.5	80.5	0	45.0	30.0	69.5	51.0	162.5	120.0	15.0	30.0
Mineral P												
P (kg)	7.08	9.31	0.93	0	3.22	7.15	25.81	29.65	0	15.0	11.07	7.15
Mineral K												
K (kg)	0	0	0	0	26.22	42.48	59.66	94.71	62.84	50.0	58.74	42.28
Total nutrients added												
N (kg)	135.71	115.48	191.67	225.71	107.14	71.43	165.48	121.43	386.90	120.0	35.7	71.4
P (kg)	22.00	22.00	22.00	31.40	15.00	15.00	44.00	43.00	42.53	15.0	15.0	15.0
K (kg)	61.79	52.58	87.27	130.09	75.00	75.00	135.00	150.00	239.00	50.0	75.0	75.0
C (kg)	550.04	468.02	776.82	1157.99	434.24	289.50	670.67	492.14	1568.11	0.0	144.75	289.50
Cu (kg)	0.3020	0.2569	0.4265	0.64	0.2384	0.1589	0.3682	0.2702	0.8609	0.0	0.0795	0.1589
Zn (kg)	0.8134	0.6921	1.1488	1.71	0.6422	0.4281	0.9918	0.7278	2.3190	0.0	0.2141	0.4281

11. Irrigation

For all crops involving irrigation (crops on JB3 soil, except for willow and miscanthus; there is generally no irrigation for JB6 soils in Denmark), irrigation has been considered through the Ecoinvent process "Irrigating/ha/CH U", described in Nemecek and Kägi (2007). Adjustments regarding the electricity source were made, through, as the process is run in Denmark.

This process considers that irrigation is performed with a mobile sprinkler system, with the irrigation water coming from surface water, with an annual water sprayed of 1200 m^3 per ha (4 times 300 m^3 water). This includes the fix installed pump (30m^3/h, 7-8 bar with a 22 kW engine), the polyethylene main water pipe, the excavation (for the main pipe) as well as the tractor needed to install the equipment on the field. Also included are the hydrant (valve assembly unit), the mobile turbine-driven irrigation automaton and the PVC water hose to link the automaton to the hydrant. The energy use is also included, considering 880 kWh/ha (22 kW * 1200 m^3/ha * h/30 m^3 = 880 kWh/ha). Since lifetime of the different equipment components were considered in the process of expressing this process per hectare, no additional adjustments are necessary to consider the crop lifetime.

12. Growing cycle

12.1 General description

This process was created in order to reflect the inputs and outputs flows related to the crop system itself. Inputs flows of C and N include the organic and inorganic fertilizer inputs, the inputs from liming, the inputs from non-harvested biomass (harvestable and non-harvestable residues), the inputs from root residues and root derived organic compounds released during growth (C only). Outputs flows of C and N include the C and N harvested (main crop and harvested residues), the losses through air (as a function of the inputs), the leaching losses (N), the losses of soil C as well as the portion of N mineralized as a result of soil C losses. The latter is in turn a source for indirect N_2O emissions.

Nitrate leaching is calculated by the empirical model N-LES_4. Atmospheric N deposition is considered as an input for this model. Reliable data for atmospheric N deposition in Denmark are available from the National Environmental Research Institute (NERI). However, atmospheric N deposition is not considered as an input in the estimation of N-emissions flows to air. This is done in order to avoid double counting. In fact, all indirect N_2O emissions are based on N flows (resulting from the studied crop system) that are eventually re-deposited. Additional N inputs from atmospheric deposition would then contribute to double counting.

Non C and N inputs flows included here are only those related to manure and lime. Pesticides products, emissions due to fuel use or to consumption of infrastructure (ex.: tractors, irrigation equipment, spreader) are not included here, as accounted for in earlier sections.

One limitation of the model is the consideration of C and N inputs from weed residues. These were regarded as highly variable and rather site specific, so it was judge that the precision gained by the inclusion of this information in the balances was overcome by the uncertainty attached to it. Therefore, C and N flows from weed are not included.

12.2 Repartition of DM from crop products

12.2.1 General description

In this study, the DM from direct crop products is separated in three main categories: primary yields, secondary yield and non-harvestable DM being an input to soil. Part of this non-harvestable DM is above ground (e.g. stubble, leaves, branches and twigs for woody crops, etc.) and part of it is below ground (root residues).

It is necessary to partition the DM in these three categories as the methodology used for estimation of C and N entering the soil system is expressed as a fraction of this DM.

Flows of C and N from rhizodeposits, i.e. releases of root derived organic compounds of low and high molecular weight (amino acids, organic acids, mono- and polysaccharides), are not estimated as a function of DM, so they are not presented in this section.

Figure 5 illustrates the DM repartition considered

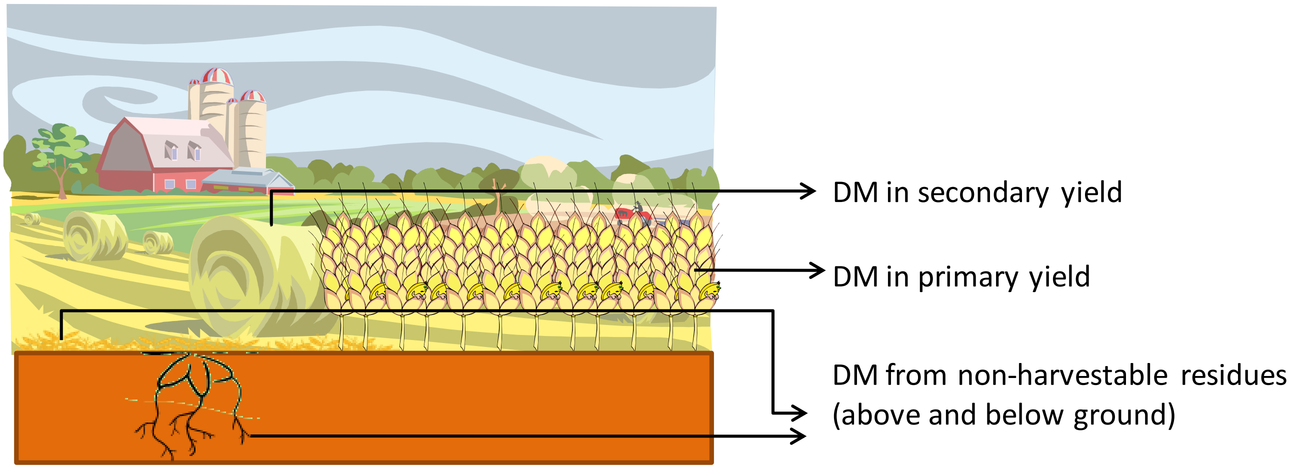

Figure 5. Illustration of the DM reparation considered

12.2.2 Primary yields

Flows of C and N are dependent upon various factors related to crop and soil. This includes, among others, primary crop yield. Primary crop yield refers to the yield of the main product, i.e. the product for which the cultivation is performed.

For all crops (except miscanthus and willow), values for primary yield are taken from the Norm data (Plantedirektoratet, 2009), so it is consistent with the N inputs from fertilization presented earlier. Since the Norm Data does not distinguish for the climate type, the yields are assumed to be the same under both climate types considered (wet and dry).

For willow, yield was adapted from Lærke (2010):

- In Lærke (2010), an average yield of 12.5 ton DM per hectare can be estimated from all data presented in figure 1, for the hybrid "Bjørn". Yield for willow cultivated on JB3, under wet climate was estimated to be 85 % of this average yield. This assumes that commercial yield would be reduced of 15 % when compared to research yield, due to unproductive turning areas at field margins as well as to harvest losses.
- Yield for willow cultivated on JB3, under dry climate, is estimated to be 67 % of the yield under wet climate, for the same soil type. This is based on Mortesen et al. (1998) as well as on unpublished data showing the sensitivity of willow yield to different drought conditions.
- Yield for willow cultivated on JB6, under wet climate, is assumed to be the same as the yield on JB3 (wet climate) plus an increase corresponding to what would the increase of yield would be if irrigation is performed (on a JB3 soil, under wet climate). Based on unpublished data from DJF, such irrigation would increase the yield by 20 %. Therefore, the yield assumed for willow on JB6 (wet climate), corresponds to the yield on JB3 (wet climate) plus 20 %.
- Yield for willow cultivated on JB6, under dry climate, is assumed to be 85 % of the yield obtained under dry climate.

Yield data for miscanthus (spring and autumn harvest) are adapted from Olesen et al. (2001):

- For year 4 to 20:
    - Soil JB3, wet climate: the yield is estimated as the average of the values for soils JB1 and JB4 presented in Olesen et al. (2001) (values for year 4-20). This corresponds to 15.25 t DM/ha*y for autumn harvest miscanthus and to 10 t DM/ha*y for spring harvest miscanthus.

    - Soil JB3, dry climate: the yield is estimated as 85 % of the above calculated value. This assumes that there is a 15 % yield decrease for miscanthus under the "dry climate". This is lower than for willow because miscanthus uses less water than willow. This gives a yield of 12.96 t DM/ha*y for autumn harvest miscanthus and of 8.5 t DM/ha*y for spring harvest miscanthus.

    - Soil JB6, for both climates: the yield is set identical to the yield on soil JB3 - wet climate. For wet climate, there is no increase as compared to JB3 as the effect of "extra water availability" on JB6 is assumed compensated by the fact that miscanthus benefits from a warmer soil on JB3. For dry climate, the yield is also set the same as for JB3 - wet climate as miscanthus probably seldom lack water on a dry sandy loam.

- For year 1: No yield, as this is prior to plantation.
- Year 2 and 3: same procedure as for year 4-20. The values obtained with this procedure correspond to the total primary yield. However, for year 2, this yield is not harvested, and for year 3, only 60 % of this yield is harvested.

The primary yields (in Mg DM/ha) for spring barley (with and without catch crop), winter wheat, silage maize, sugar beet and rye grass are presented in table 35. On this table, it should be noticed that yields for JB3 are for irrigated crops, except for willow (this is also the case for miscanthus, which is not presented in table 35). It should also be noted that only willow (and miscanthus, which is not presented in table 35) have a different primary yield for wet and dry climate.

Table 36 presents primary yields for miscanthus (spring and autumn harvest) for dry and wet climate (for miscanthus, it is considered that the soil type, i.e. sandy versus sandy loam, does not affect the yield).

Table 35. **Primary yield and DM data considered for spring barley, winter wheat, maize silage, sugar beet, rye grass and willow cultivated on JB3 and JB6. Primary yield is considered identical for dry and wet climate except for willow.**

	Spring barley	Spring barley & Catch crop	Winter wheat	Maize silage	Sugar beet	Rye grass	Willow (wet climate)	Willow (dry climate)
Soil JB3 (sand)								
Primary yield (hkg/ha)[a]	50	50	66	10300[c]	566	8600[c]		
DM in crop (% of the total mass) [b]	85	85	85	1.17[d]	22	1.16[d]		
Primary yield (Mg DM/ha)	***4.25***	***4.25***	***5.61***	***12.05***	***12.45***	***9.98***	***10.60***[e]	***7.10***[f]
Soil JB6 (sandy loam)								
Primary yield (hkg/ha)	57	57	80	10200[c]	566	7600[c]		
DM in crop (% of the total mass)	85	85	85	1.17[d]	22	1.16[d]		
Primary yield (Mg DM/ha)	***4.85***	***4.85***	***6.80***	***11.93***	***12.45***	***8.82***	***12.72***[g]	***10.81***[h]

[a] All yields presented in this row for JB3 are for irrigated crops.

[b] Values presented in this row are all from Møller et al. (2000).

[c] Here, the yield is expressed in feed unit (FE) per hectare, based on the original data presented in Plantedirektoratet (2009).

[d] This is the amount of DM per feed unit, in kg DM per FE. For silage maize, the values presented correspond to a silage maize with a “medium” content of digestible carbohydrates, based on Møller et al. (2000). For ryegrass, the values presented are for durable grass (varigt enggræs).

[e] In Lærke (2010), an average yield of 12.5 ton DM per hectare can be estimated from all data presented in figure 1, for the hybrid “Bjørn”. Yield for willow cultivated on JB3, under wet climate, is here estimated to be 85 % of this average yield. This assumes that commercial yield would be reduced of 15 % when compared to research yield, due to unproductive turning areas at field margins as well as to harvest losses.

[f] Yield for willow cultivated on JB3, under dry climate, is estimated to be 67 % of the yield under wet climate, for the same soil type. This is based on Mortesen et al. (1998) as well as on unpublished data showing the sensitivity of willow yield to different drought conditions.

[g] Yield for willow cultivated on JB6, under wet climate, is assumed to be the same as the yield on JB3, under wet climate plus irrigation. Based on unpublished data from DJF, it is assumed that irrigation, under a wet climate, would increase yield by 20 %.

[h] Yield for willow cultivated on JB6, under dry climate, is assumed to be 85 % of the yield obtained under dry climate.

Table 36. Primary yield for miscanthus, autumn and spring harvest, under wet and dry climate

	Miscanthus (autumn harvest)		Miscanthus (spring harvest)	
Soil type	**JB3**	**JB6**	**JB3**	**JB6**
Wet climate				
Primary yield, year 1 (Mg DM/ha*y)	0[a]	0[a]	0[a]	0[a]
Primary yield, year 2 (Mg DM/ha*y)[b]	5.5[c]	5.5[d]	4[c]	4[d]
Primary yield, year 3 (Mg DM/ha*y)	9.15[c]	9.15[d]	6.0[c]	6.0[d]
Primary yield, year 4 to 20 (Mg DM/ha*y)	15.25[c]	15.25[d]	10.0[c]	10.0[d]
Dry climate				
Primary yield (Mg DM/ha)	0[a]	0[a]	0[a]	0[a]
Primary yield, year 2 (Mg DM/ha*y)[b]	4.68[e]	5.5[d]	3.4[e]	4[d]
Primary yield, year 3 (Mg DM/ha*y)[f]	7.78[e]	9.15[d]	5.1[e]	6.0[d]
Primary yield, year 4 to 20 (Mg DM/ha*y)	12.96[e]	15.25[d]	8.5[e]	10.0[d]

[a] Prior to planting.

[b] This primary yield is not harvested in year 2.

[c] Average of values presented in Olesen et al. (2001) for year 2 for soil JB1 and JB4.

[d] Yield on soil JB6, for both climates, is set identical to the yield on soil JB3 - wet climate.

[e] These values assume that there is a 15 % yield decrease for miscanthus under the dry climate, compared to the wet climate.

[f] Only 60 % of this primary yield is harvested on year 3.

12.2.3 Secondary yields

Secondary yields apply for all crops where a “secondary” product can be harvested, that is to say spring barley and winter wheat (through straw) as well as sugar beet (through beet tops). It consists of the harvestable fraction of crop residues and consequently does not include fractions that are non-harvestable (e.g. part of the straw that cannot be harvested due to machinery-related constraints). The harvestable fraction of residues may, in practice, be only partly harvested, or even not harvested at all. In this project, it is the two extreme cases that are considered, i.e. 0 and 100 % harvested (i.e. 100% of what can physically be harvested).

For spring barley, winter wheat and sugar beets the secondary yields are estimated from the available data in Statistics Denmark (Statistics Denmark, 2010: tables HALM, HALM1 and HST6). For these crops, for years 1997 to 2008 (spring barley and winter wheat) and years 1990 to 2004 (sugar beets), yield data for both the primary and secondary yields are available.

For spring barley, the ratio secondary yield on primary yield is 60 % from 1997 to 2008, and 55 % from 2003 to 2008. Similarly, for winter wheat, this ratio is 63 % from 1997 to 2002, and 55 % from 2003 to 2008. For this project, it was decided to use the average from 2003 to 2008, i.e. 55 % for both spring barley and winter wheat. These values for the secondary to primary yield ratio (55 %

for both spring barley and winter wheat) are in fact corresponding to the exact figures presented in Gyldenkærne et al. (2007).

For sugar beet, the 14-years data available show a tendency of the yield for beet top to decrease (and the yield for sugar beet to increase). In fact, while the beet top yield was 24.3 Mg DM per hectare in 1990, it was 18 Mg DM per hectare in 2001 and it dropped to 8.6 Mg DM per hectare in 2002. The average ratio beet top to sugar beet for year 2002, 2003 and 2004 (the 3 last years of data) is 13 %, which is the value used for this project. Gyldenkærne et al. (2007) assumed no harvest for the sugar beet tops. However, they assumed a ratio of 0.34 for fodder beat. The value of 13 % may be an underestimation of the actual amount of beet tops returned to soil. A sensitivity analysis with a value of 34 % was performed to estimate the importance of this assumption.

No secondary harvests are assumed for silage maize, willow, miscanthus and rye grass. As the catch crop is not harvested, it does not contribute to secondary yield and therefore the ratio secondary to primary yield is the same as for spring barley without catch crop.

Table 37. Values used to estimate secondary yields as a function of primary yield

Crop	Ratio secondary yield to primary yield used	Remark
Spring barley	0.55	Estimation based on values for 2003 to 2008 from Statistics Denmark.
Winter wheat	0.55	Estimation based on values for 2003 to 2008 from Statistics Denmark.
Sugar beet	0.13	Estimation based on values for 2002, 2003 and 2004 from Statistics Denmark.
Permanent ryegrass	0	No harvest of secondary product assumed for this crop
Miscanthus (autumn and spring harvest)	0	No harvest of secondary product assumed for this crop
Willow	0	No harvest of secondary product assumed for this crop
Silage maize	0	No harvest of secondary product assumed for this crop

From the information presented in table 37, the secondary yields (in Mg DM/ha) can therefore be calculated. This is presented in table 38.

Table 38. Estimation of secondary yields (Mg DM/ha) for all selected crops

Crop	Primary yield (Mg DM/ha) (from table 35 and 36) (A)		Ratio secondary yield to primary yield used (table 37) (B)	Secondary yield (Mg DM/ha) (A * B)	
Soil type	JB3	JB6		JB3	JB6
Spring barley	4.25	4.85	0.55	2.34	2.67
Spring barley and catch crop[a]	4.25	4.85	0.55	2.34	2.67
Winter wheat	5.61	6.80	0.55	3.09	3.74
Sugar beet	12.45	12.45	0.13	1.62	1.62
Permanent ryegrass	31.39	27.74	0	0	0
Miscanthus (autumn harvest), year 4-20	15.25 (wet) 12.96 (dry)	15.25 (wet) 15.25 (dry)	0	0	0
Miscanthus (Spring harvest), year 4-20	10.0 (wet) 8.5 (dry)	10.0 (wet) 10.0 (dry)	0	0	0
Willow	10.60 (wet) 7.10 (dry)	12.72 (wet) 10.81 (dry)	0	0	0
Silage maize	12.05	11.93	0	0	0

[a] Same as for spring barley, because catch crop is not harvested.

12.2.4 Non-harvestable residues (above ground and below ground)

A complete balance for assessment of C and N flows involves that the amount of residues to soil from all selected crop must be determined, for both above ground and below ground residues.

The non-harvestable above ground residues may be estimated from the harvest index, the DM in primary yield and the DM in secondary yield. The harvest index represents the primary yield share of total above ground biomass (harvestable plus non-harvestable) at harvest, with both primary yield and total yield are expressed in terms of DM. Knowing the primary as well as the secondary yields (in terms of DM), the non-harvestable DM from above ground residues can be estimated from the harvest index.

The below ground biomass can be estimated similarly, by the use of the ratio below ground biomass on total net biomass production (i.e. primary yield, secondary yield and all non-harvestable residues). This ratio, as well as the harvest indexes, are taken from Gyldenkærne et al. (2007) and are presented in table 39 for all annual crops, except for the catch crop, as the amount of dry matter returned to soil is directly known.

Table 39. Harvest index and ratio below ground biomass on total net biomass for all annual crops

Crop	Ratio DM in primary yield on DM in total above ground biomass (harvest index)	Ratio DM in below ground biomass on DM in total net biomass produced
Spring barley	0.45	0.17
Winter wheat	0.39	0.25
Sugar beet	0.70	0.12
Silage maize	0.85	0.15

The above values are not available for perennial crops. Therefore, the proportion of DM in above and below ground biomass was estimated differently for these crops.

For perennial ryegrass, an overall C input to soil of 5.6 t C/ha*y is considered, as estimated by Petersen (2010). This estimation is based on Soussana et al. (2004) as well as Kuzyakov and Domanski (2000). This can be further separated into above and below ground biomass through the assumption that this C input is distributed according to a ratio 2:1 between the below ground and the above ground biomass, based on Petersen (2010) as well as IPCC (2006: footnote l of table 11.2). Accordingly, the above ground non-harvestable biomass contributes to an input of 1.87 t C/ha*y and the below ground biomass to an input of 3.73 t C/ha*y. Assuming, based on Petersen (2010), a C content of 0.45 t C per ton DM for all crop parts, these values can be translated in terms of DM input just like annuals crops, which gives: 4.15 t DM/ha*y for above ground biomass and 8.30 t DM/ha*y for below ground biomass, for a total input of 12.45 t DM/ha. This estimate is in the range of values presented by Christensen et al. (2009) for grass leys established over 2 to 6 years (9.9 to 14.6 t DM/ha).

For miscanthus, data for residual above ground biomass are, as for primary yield, mostly based on Olesen et al. (2001), as these values are based on Danish experiments. Accordingly:

- Year 1: the above ground biomass for year 1 is 0 as this is before the plantation.
- Year 2:
    - For JB3, wet climate: the average of the values presented by Olensen et al. (2001) for soil JB1 and JB4 for year 2 is considered, i.e. 2.04 Mg DM/ha*y for autumn harvest and 3.54 Mg DM/ha*y for spring harvest.
    - For JB3, dry climate: the above ground residual biomass yield was assumed to decrease of 15 % compared the value calculated for JB3, wet climate, as this

    assumption was made when establishing the primary yield. This gives an above ground residual biomass of 1.73 Mg DM/ha*y for autumn harvest and 3.01 Mg DM/ha*y for spring harvest.
  - For JB6, both climates: same values as for JB3, wet climate assumed, conformingly to the assumptions made for primary yield.
- Year 3: Same procedure as for year 2. This gives:
  - For JB3, wet climate: 3.51 Mg DM/ha*y for autumn harvest and 5.76 Mg DM/ha*y for spring harvest.
  - For JB3, dry climate: 2.98 Mg DM/ha*y for autumn harvest and 4.90 Mg DM/ha*y for spring harvest.
  - For JB6, both climate: 3.51 Mg DM/ha*y for autumn harvest and 5.76 Mg DM/ha*y for spring harvest.
- Year 4 to 20: Same procedure as for year 2 and 3. This gives:
  - For JB3, wet climate: 5.63 Mg DM/ha*y for autumn harvest and 10.88 Mg DM/ha*y for spring harvest.
  - For JB3, dry climate: 4.79 Mg DM/ha*y for autumn harvest and 9.25 Mg DM/ha*y for spring harvest.
  - For JB6, both climates: 5.63 Mg DM/ha*y for autumn harvest and 10.88 Mg DM/ha*y for spring harvest.

The below ground biomass was estimated as 16 % of the total above ground biomass (residues plus harvest), conformingly with Olesen et al. (2001). For years with no or partial harvest, this takes into account the entire primary yield.

Table 40 summarizes all data about residual above and below ground biomass for miscanthus.

Table 40. Summary of above and below ground residual biomass amount for miscanthus

Miscanthus type	Soil type	Climate type	Year in crop life cycle	Biomass amount (Mg DM/ha*y)	
				Above ground	Below ground
Autumn harvest	JB3, JB6	wet, dry	1	0	0
Autumn harvest	JB3	wet	2	2.04	1.21
Autumn harvest	JB3	wet	3	3.51	2.03
Autumn harvest	JB3	wet	4-20	5.63	3.34
Autumn harvest	JB3	dry	2	1.73	1.03
Autumn harvest	JB3	dry	3	2.98	1.72
Autumn harvest	JB3	dry	4-20	4.79	2.84
Autumn harvest	JB6	wet, dry	2	2.04	1.21
Autumn harvest	JB6	wet, dry	3	3.51	2.03
Autumn harvest	JB6	wet, dry	4-20	5.63	3.34
Spring harvest	JB3, JB6	wet, dry	1	0	0
Spring harvest	JB3	wet	2	3.54	1.21
Spring harvest	JB3	wet	3	5.76	1.88
Spring harvest	JB3	wet	4-20	10.88	3.34
Spring harvest	JB3	dry	2	3.01	1.03
Spring harvest	JB3	dry	3	4.90	1.60
Spring harvest	JB3	dry	4-20	9.25	2.84
Spring harvest	JB6	wet, dry	2	3.54	1.21
Spring harvest	JB6	wet, dry	3	5.76	1.88
Spring harvest	JB6	wet, dry	4-20	10.88	3.34

For willow, the DM from non-harvested above ground biomass (NH*AG*) is estimated as the DM from leaves (*L*) plus the DM from woody material (*WM*) lost from the trees (e.g. branches and twigs). This is illustrated in equation (1):

$$NHAG = L + WM \qquad \text{(Equation 1)}$$

For the woody biomass DM, it is anticipated that the loss during harvest corresponds to 7.5 % of the total production. The total production is estimated by dividing the primary yield by 92.5 %, i.e. assuming that the anticipated primary yield is only 92.5 % of the full potential yield, because of losses (based on a communication with Jørgensen, 2010). This could have been divided by 0.85 instead, then accounting for the turning areas, but this is not done here because it is the ambition of the present database to be as disaggregated as possible. The DM from woody material is therefore estimated as in equation (2):

$$WM = 0.075 \times \frac{PY}{0.925} \qquad \text{(Equation 2)}$$

Where PY is the primary yield (in terms of DM per ha).

The DM from leaf is estimated based on the model developed by Lindroth and Båth (1999). Based on Lindroth and Båth (1999), it is assumed that 20 % of the total biomass production (TBP) is going to leaves (f_L), and 25 % to roots (f_R). Lindroth and Båth (1999), in their equation (2), express the total biomass production as:

$$TBP = \frac{PY}{(1-f_L-f_R)} \qquad \text{(Equation 3)}$$

This equation is used to estimate the amount of DM from the leaves, but it needs to be improved. In fact, this equation does not include the DM from woody material. To include the woody material biomass, and taking into account the value for f_L (0.2) and f_R (0.25), equation (3) may be rewritten as:

$$TBP = \frac{PY+WM}{0.55} \qquad \text{(Equation 4)}$$

Based on the definition and value of f_L, equation (1) may be rewritten as:

$$NHAG = 0.20\,TBP + WM \qquad \text{(Equation 5)}$$

Combining equations (5) with equation (2) and equation (4) allows calculating the non-harvestable above ground biomass from the primary yield only:

$$NHAG = \left(0.075 \times \frac{PY}{0.925}\right) + \frac{0.20}{0.55}\left[PY + \left(0.075 \times \frac{PY}{0.925}\right)\right] \qquad \text{(Equation 6)}$$

The below ground biomass (BG) is calculated based on the definition and value of f_R (i.e. the fraction of total biomass production going to roots; 25 % based on Lindroth and Båth, 1999) as well as on equation (4) and (2). This is presented in equation (7):

$$BG = \frac{0.25}{0.55}\left[PY + \left(0.075 \times \frac{PY}{0.85}\right)\right] \qquad \text{(Equation 7)}$$

Based on equations 6 and 7, the DM in non-harvestable above ground biomass as well as in below ground biomass for willow is presented in table 41.

Table 41. DM in non harvestable above ground biomass and below ground biomass for willow, for soil JB3 and JB6, under wet and dry climates

Crop	Soil type	Climate	Non harvestable above ground biomass (Mg DM/ha)	Below ground biomass (Mg DM/ha)
Willow	JB3	Wet	5.03	5.21
Willow	JB3	Dry	3.37	3.49
Willow	JB6	Wet	6.03	6.25
Willow	JB6	Dry	5.13	5.31

For catch crop DM input to soil, an amount of 0.40 Mg DM/ha is considered. This is shown in table 42. This includes the whole DM input from the catch crop (i.e. the catch crop itself as well as all above and below ground residues, rhizodeposits excluded). A DM input of 0.40 Mg DM/ha is slightly lower than the values presented by Askegaard and Eriksen (2008). In fact, Askegaard and Eriksen (2008) measured 0.8 and 1.1 Mg DM/ha (year 1 and year 2) for a ryegrass catch crop and 1.8 Mg DM/ha (both year 1 and year 2) for a clover catch crop. In both cases, the main crop was spring barley.

The value used in Petersen (2010) is even higher, i.e. an average input to soil of 1 t C/ha*y for catch crops (corresponding to 2.22 Mg DM/ha*y, assuming 0.45 t C/t DM).

In this project, the type of catch crop (e.g. perennial ryegrass, Italian ryegrass, clover, etc.) is not specified as the idea is only to reflect the inclusion of a catch crop on the overall C and N balance on a perspective of life cycle perspective where it is sought to reflect land use changes consequences as a result of using biomass for energy. In other words, the idea is not to investigate a particular catch crop but rather an average overall effect of including a catch crop with spring barley.

Table 42. Input to soil from the catch crop, for both dry and wet climate, on JB3 and JB6

	Input to soil (Mg DM/ha)
Catch crop	0.40

12.2.5 Overview of DM repartition for all selected crops

Table 43 summarizes the DM repartition in all selected crops, cultivated on JB3 and JB6 and for both climate (dry and wet).

Table 43. Repartition of the DM for all selected crops cultivated on JB3 and JB6 under wet and dry climates, under the baseline scenario, WITH harvest of secondary yield. All data in Mg DM per hectare per year.

Yield (Mg DM/ha)	Climate	Spring barley	Spring barley & Catch crop	Winter wheat	Willow	Miscanthus (autumn) Year 4-20[a]	Miscanthus (spring) Year 4-20[a]	Maize silage	Sugar beet	Rye grass
Soil JB3 (sand)										
Primary yield (Mg DM/ha)	Wet	4.25	4.25	5.61	10.60	15.25	10.0	12.05	12.45	9.98
	Dry	4.25	4.25	5.61	7.10	12.96	8.50	12.05	12.45	9.98
Secondary yield (Mg DM/ha)	Wet	2.34	2.34	3.09	0	0	0	0	1.62	0
	Dry	2.34	2.34	3.09	0	0	0	0	1.62	0
Non-harvestable residues (above ground)[b] (Mg DM/ha)	Wet	2.86	2.86[c]	5.69	5.03	5.63	10.88	2.13	3.72	4.15
	Dry	2.86	2.86[c]	5.69	3.37	4.79	9.25	2.13	3.72	4.15
Below ground residues (Mg DM/ha)	Wet	1.93	1.93[c]	4.79	5.21	3.34	3.34	2.50	2.43	8.30
	Dry	1.93	1.93[c]	4.79	3.49	2.84	2.84	2.50	2.43	8.30
Soil JB6 (sandy loam)										
Primary yield (Mg DM/ha)	Wet	4.85	4.85	6.80	12.72	15.25	10.0	11.93	12.45	8.82
	Dry	4.85	4.85	6.80	10.81	15.25	10.0	11.93	12.45	8.82
Secondary yield (Mg DM/ha)	Wet	2.67	2.67	3.74	0	0	0	0	1.62	0
	Dry	2.67	2.67	3.74	0	0	0	0	1.62	0
Non-harvestable residues (above ground) (Mg DM/ha)	Wet	3.26	3.26[b]	6.90	6.03	5.63	10.88	2.11	3.72	4.15
	Dry	3.26	3.26[b]	6.90	5.13	5.63	10.88	2.11	3.72	4.15
Below ground residues (Mg DM/ha)	Wet	2.21	2.21[c]	5.81	6.25	3.34	3.34	2.48	2.43	8.30
	Dry	2.21	2.21[c]	5.81	5.31	3.34	3.34	2.48	2.43	8.30

[a] See table 36 for values corresponding to year 1, 2 and 3.

[b] For annuals, it is calculated as: (primary yield/harvest index) – primary yield – secondary yield. Example for winter wheat on JB3, wet climate: [5.61 Mg DM primary yield/ha * (DM total above ground/0.39 DM in primary yield)] - 5.61 Mg DM/ha – 3.09 Mg DM/ha = 5.69 Mg DM/ha*y of non-harvestable above ground biomass.

[c] This does not include the contribution for the catch crop, as the catch crop contribution is given as a whole (above and below ground), corresponding to an addition of 0.4 Mg DM/ha.

Table 44. Repartition of the DM for all selected crops cultivated on JB3 and JB6 under wet and dry climates, under the baseline scenario, WITHOUT harvest of secondary yield (secondary yield is incorporated). All data in Mg DM per hectare per year.

Yield (Mg DM/ha)	Climate	Spring barley	Spring barley & Catch crop	Winter wheat	Sugar beet
		Soil JB3 (sand)			
Primary yield	Wet	4.25	4.25	5.61	12.45
(Mg DM/ha)	Dry	4.25	4.25	5.61	12.45
Secondary yield (harvested)	Wet	0	0	0	0
(Mg DM/ha)	Dry	0	0	0	0
Above ground residues[a,b]	Wet	5.19	5.19[c]	8.77	5.34
(Mg DM/ha)	Dry	5.19	5.19[c]	8.77	5.34
Below ground residues	Wet	1.93	1.93[c]	4.79	2.43
(Mg DM/ha)	Dry	1.93	1.93[c]	4.79	2.43
		Soil JB6 (sandy loam)			
Primary yield	Wet	4.85	4.85	6.80	12.45
(Mg DM/ha)	Dry	4.85	4.85	6.80	12.45
Secondary yield (harvested)	Wet	0	0	0	0
(Mg DM/ha)	Dry	0	0	0	0
Above ground residues[a,b]	Wet	5.93	5.93[b]	10.64	5.34
(Mg DM/ha)	Dry	5.93	5.93[b]	10.64	5.34
Below ground residues	Wet	2.21	2.21[c]	5.81	2.43
(Mg DM/ha)	Dry	2.21	2.21[c]	5.81	2.43

[a] As the secondary yield is not harvested, it becomes part of the above-ground residues.

[b] Calculated as: (primary yield/harvest index) – primary yield – secondary yield. Example for winter wheat on JB3, wet climate: [5.61 Mg DM primary yield/ha * (DM total above ground/0.39 DM in primary yield)] - 5.61 Mg DM/ha – 0 Mg DM/ha = 8.77 Mg DM/ha*y of above ground biomass.

[c] This does not include the contribution for the catch crop, as the catch crop contribution is given as a whole (above and below ground), corresponding to an addition of 0.4 Mg DM/ha.

12.3 Content of N and C in the DM of residues

The interest in determining the DM repartition from the biomass (primary yield, secondary yield, above ground residues, below ground residues) lies in estimating the flows of C and N according to the different scenarios.

For C, this is rather straightforward, as it is assumed, based on Petersen (2010), that the C content of the DM corresponds to 0.45 t C/t DM for all crop parts. In the case of below ground residues, this also includes C input from rhizodeposition.

For N, IPCC (2006) provides default factor for the N content in below and above ground residues, expressed in kg N/kg DM (table 11.2, IPCC, 2006). For ryegrass and all selected annual crops, however, Nielsen et al. (2009) also provide figures for the N content in above ground crop residues, directly expressed in kg N/ha*y. Data in Nielsen et al. (2009) do not account for secondary yield (i.e. when straw is incorporated), except in the case of beet tops. These data are used as judged more representative for Denmark than IPCC values (IPCC, 2006). However, there is no data in Nielsen et al. (2009) for N content of above ground residues (excluding tops) from sugar beet. Therefore, a value of 0.026 kg N/kg DM has been considered.

For scenarios involving straw incorporation, the N content from the straw was considered. This was estimated using the content of raw protein in straw from the values presented in Møller et al. (2000). To obtain the N content of straw (in kg N/kg DM), the standard value of 6.25 of the so-called “nitrogen conversion factor” was used (i.e. raw protein = 6.25 * N), which assumed that the average N content of protein is about 16 % (FAO, 2003).

In the case of N from below ground residues, no specific Danish data were found, so the IPCC data (IPCC, 2006) were used as a best proxy.

For willow, the N content of above and below ground residues is considered as 0.005 kg N/kg DM, based on Eckerssten et al. (2006). The N content of above ground residues is taken at 0.006 kg N/kg DM for autumn harvested miscanthus and at 0.01 kg N/kg DM for spring harvested miscanthus, based on Jørgensen (1997). This applies for all life cycle “stages” of miscanthus (i.e. year 1, year 2, year 3 and year 4-20). The N content of below ground residues is taken at 0.005 kg N/kg DM for both autumn and spring harvested miscanthus.

For the catch crop, an overall input of 0.034 kg N/kg DM is considered.

Table 45 summarises the different values considered as regarding N and C content in the crop residues.

Table 45. N and C content of residues

	Spring barley, JB3	Spring barley, JB6	Catch crop	Winter wheat, JB3	Winter wheat, JB6	Silage maize, JB3	Silage maize, JB6	Willow	Miscanthus (autumn)	Miscanthus (spring)	Sugar beet	Rye grass, JB3	Rye grass, JB6
N content of residues													
Above ground biomass [a] (kg N/ha)	10.4	10.4	-	17.0	17.0	6.3[c]	6.3[c]	-	-	-	-	26.2[d]	26.2[d]
Above ground biomass (kg N/kg DM)	0.004[b]	0.003[b]	-	0.003[b]	0.002[b]	0.003[b]	0.003[b]	0.005[e]	0.006[f]	0.010[f]	0.026[g]	0.006[b]	0.006[b]
Sugar beet top (kg N/kg DM)	-	-	-	-	-	-	-	-	-	-	0.035[b]	-	-
Straw [h] (kg N/kg DM)	14.96	17.07	-	16.29	19.75	-	-	-	-	-	-	-	-
Catch crop (kg N/kg DM)	-	-	0.034[i]	-	-	-	-	-	-	-	-	-	-
Below ground biomass [j] (kg N/kg DM)	0.014	0.014	-	0.009	0.009	0.007	0.007	0.005	0.005	0.005	0.014	0.012	0.012
C content of residues[k]													
Above ground biomass (kg C/kg DM)	0.45	0.45	-	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sugar beet top (kg C/kg DM)	-	-	-	-	-	-	-	-	-	-	0.45	-	-
Straw (kg C/kg DM)	0.45	0.45	-	0.45	0.45	-	-	-	-	-	-	-	-
Catch crop (kg C/kg DM)	-	-	0.45	-	-	-	-	-	-	-	-	-	-
Below ground biomass, including rhizodeposition (kg C/kg DM)	0.45	0.45	-	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45

[a] Data from Nielsen et al. (2009)

[b] Calculated from data of Nielsen et al. (2009) and the DM content in above ground biomass. Example for spring barley, JB3: 10.4 kg N/ha * ha/2.86 Mg DM in above ground residues * Mg/ 1000 kg = 0.004 kg N/kg DM in above ground residues. For sugar beet top, the DM considered corresponds to the above ground with top incorporation minus the above ground residues without top incorporation, i.e. 5.34 – 3.72 = 1.62 Mg DM in sugar beet tops/ ha.

[c] Value for “maize – green fodder” taken as a best proxy for silage maize.

[d] Value for “grass- and clover field in rotation” taken as a best proxy for ryegrass.

[e] From Eckerssten et al. (2006)

[f] From Jørgensen (1997)

[g] Personal communication with Jørgen E. Olesen (2010), DJF

[h] The N content for straw is calculated from the raw protein content in straw presented in the national feedstuff tables (Møller et al., 2000). This corresponds to 4.0 % of DM for spring barley and 3.3 % of DM for winter wheat. The raw protein content is converted to nitrogen content using a nitrogen conversion factor of 6.25 (FAO, 2003), i.e. % raw protein = 6.25 * % N. The DM content of straw is obtained the same way as for sugar beet tops, i.e. by subtracting the “above ground residues without straw incorporation” from the “above ground residues with straw incorporation”. For spring barley, JB3, this corresponds to 5.19 – 2.86 = 2.33 Mg DM in spring barley straw/ha. Based on this, the N content of straw can be calculated. Example for spring barley, JB3: 0.04 kg raw protein/kg DM*(N/6.25 raw protein) = 0.0064 kg N/kg DM * 2.33 Mg DM in barley straw/ha * 1000 kg/Mg = 14.96 kg N/kg DM.

[i] Personal communication with Jørgen E. Olesen (2010), DJF

[j] Data from IPCC (2006), table 11.2

[k] C content is considered at 0.45 kg C/kg DM for all crop parts, based on Petersen (2010).

12.4 C and N returned to soil from crop residues

The amount of C and N from crop residues (in kg N/ha or kg C/ha) can be calculated from the repartition of residual DM in above and below ground residues and the content of C and N in the residues. This is presented in table 47 for miscanthus, table 48 for willow and in table 46 for all other crops.

Table 46. Inputs of N and C to soil from ryegrass and crops (residues, secondary yield and catch crop)[a]

		Spring barley, JB3	Spring barley, JB6	Catch crop	Winter wheat, JB3	Winter wheat, JB6	Silage maize, JB3	Silage maize, JB6	Sugar beet	Rye grass
DATA										
DM in above ground residues (Mg DM/ha)	(A)	2.86	3.26	-	5.69	6.90	2.13	2.11	3.72	4.15
DM in below ground residues (Mg DM/ha)	(B)	1.93	2.21	-	4.79	5.91	2.50	2.48	2.43	8.30
DM in secondary harvest and catch crop (Mg DM/ha)	(C)	2.33	2.67	0.4	3.08	3.74	-	-	1.62	-
N in above ground residues (kg N/kg DM)	(D)	0.004	0.003	-	0.003	0.002	0.003	0.003	0.026	0.006
N in below ground residues (kg N/kg DM)	(E)	0.014	0.014	-	0.009	0.009	0.007	0.007	0.014	0.012
N in secondary harvest and catch crop (kg N/kg DM)	(F)	14.96	17.07	0.034	16.29	19.75	-	-	-	-
C in all crop parts (kg C/kg DM)	(G)	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
N INPUTS TO SOIL										
Above ground residues, no incorporation straw/ top (kg N/ha)[a]	(H)	10.4	10.4	-	17.0	17.0	6.3	6.3	(A)*(D)*10^3 = 96.65	26.2
Above ground residues, with incorporation straw/top (kg N/ha)	(I)	(H)+(F) = 25.36	(H)+(F) = 27.47	-	(H)+(F) = 33.29	(H)+(F) = 36.75	-	-	(H)+(F) = 153.35	-
Below ground residues (kg N/ha)	(J)	(B)*(E)*10^3 =27.08	(B)*(E)*10^3 =30.90	-	(B)*(E)*10^3 =43.15	(B)*(E)*10^3 =52.31	(B)*(E)*10^3 =17.51	(B)*(E)*10^3 =17.34	(B)*(E)*10^3 =33.95	(B)*(E)*10^3 = 99.56
Total, no incorporation straw/top (kg N/ha)	(K)	(H)+(J) **= 37.48**	(H)+(J) **= 41.30**	(C)*(F)* 10^3 **= 13.6**	(H)+(J) **= 60.15**	(H)+(J) **= 69.31**	(H)+(J) **= 23.81**	(H)+(J) **= 23.64**	(H)+(J) **= 130.60**	(H)+(J) **= 125.76**
Total, with incorporation straw/top (kg N/ha)	(L)	(I)+(J) **= 52.44**	(I)+(J) **= 58.38**	-	(I)+(J) **= 76.45**	(I)+(J) **= 89.05**	-	-	(I)+(J) **= 187.30**	-

Table 46. Inputs of N and C to soil from ryegrass and annual crops (residues, secondary yield and catch crop) (continuation)

		Spring barley, JB3	Spring barley, JB6	Catch crop	Winter wheat, JB3	Winter wheat, JB6	Silage maize, JB3	Silage maize, JB6	Sugar beet	Rye grass, JB3
C INPUTS TO SOIL										
Above ground residues, no incorporation straw/top (kg C/ha)	(M)	(A)*(G)*10^3 =1285	(A)*(G)*10^3 =1467	-	(A)*(G)*10^3 =2560	(A)*(G)*10^3 =3103	(A)*(G)*10^3 =957	(A)*(G)*10^3 =947	(A)*(G)*10^3 =1673	(A)*(G)*10^3 =1867
Above ground residues, with incorporation straw/top (kg C/ha)	(N)	(M)+[(C)*(G)* 10^3] =2338	(M)+[(C)*(G)*10^3] =2668	-	(M)+[(C)*(G)*10^3] =3949	(M)+[(C)*(G)*10^3] =4786	-	-	(M)+[(C)*(G)*10^3] =2401	-
Below ground residues (kg C/ha)	(O)	(B)*(G)* 10^3 =870	(B)*(G)* 10^3 =993	-	(B)*(G)* 10^3 =2158	(B)*(G)* 10^3 =2615	(B)*(G)* 10^3 =1126	(B)*(G)* 10^3 =1115	(B)*(G)* 10^3 =1091	(B)*(G)* 10^3 =3733
Total, no incorporation straw/top (kg C/ha)	(P)	(M)+(O) **=2156**	(M)+(O) **=2460**	(C)*(G)* 10^3 **= 180**	(M)+(O) **=4718**	(M)+(O) **=5719**	(M)+(O) **=2083**	(M)+(O) **=2062**	(M)+(O) **=2764**	(M)+(O) =**5600**
Total, with incorporation straw/top (kg C/ha)	(Q)	(N)+(O) **=3208**	(N)+(O) **=3661**	-	(N)+(O) **=6106**	(N)+(O) **=7402**	-	-	(N)+(O) **=3492**	-

[a] Inconsistencies may occur in lines (J) to (Q) because of rounding. Calculations presented in this table have been performed without intermediary rounding.

[b] From Nielsen et al. (2009), except for sugar beet.

Table 47. Input of C and N to soil from miscanthus residues

		Miscanthus, autumn harvest[a]						Miscanthus, spring harvest[a]					
		Year 4-20		Year 2		Year 3		Year 4-20		Year 2		Year 3	
		JB3, w JB6,w&d	JB3, d	JB3, w JB6,w&d	JB3, d	JB3, w JB6,w&d	JB3, d	JB3, w JB6,w&d	JB3, d	JB3, w JB6,w&d	JB3, d	JB3, w JB6,w&d	JB3, d
DATA													
DM in above ground residues (Mg DM/ha)	(A)	5.63	4.79	2.04	1.73	3.51	2.98	10.88	9.25	3.54	3.01	5.76	4.90
DM in below ground residues (Mg DM/ha)	(B)	3.34	2.84	1.21	1.03	2.03	1.72	3.34	2.84	1.21	1.03	1.88	1.60
N in above ground residues (kg N/kg DM)	(C)	0.006	0.006	0.006	0.006	0.006	0.006	0.010	0.010	0.010	0.010	0.010	0.010
N in below ground residues (kg N/kg DM)	(D)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
C in all crop parts (kg C/kg DM)	(E)	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
N INPUTS													
Above ground residues (kg N/ha)	(F)	(A)*(C) *10^3 =33.78	(A)*(C) *10^3 =28.71	(A)*(C) *10^3 =12.24	(A)*(C) *10^3 =10.40	(A)*(C) *10^3 =21.06	(A)*(C) *10^3 =17.90	(A)*(C) *10^3 =108.8	(A)*(C) *10^3 =92.48	(A)*(C) *10^3 =35.40	(A)*(C) *10^3 =30.09	(A)*(C) *10^3 =57.60	(A)*(C) *10^3 =48.96
Below ground residues (kg N/ha)	(G)	(B)*(D) *10^3 =16.70	(B)*(D) *10^3 =14.20	(B)*(D) *10^3 =6.03	(B)*(D) *10^3 =5.13	(B)*(D) *10^3 =10.13	(B)*(D) *10^3 =8.61	(B)*(D) *10^3 =16.70	(B)*(D) *10^3 =14.20	(B)*(D) *10^3 =6.03	(B)*(D) *10^3 =5.13	(B)*(D) *10^3 =9.41	(B)*(D) *10^3 =8.00
Total (kg N/ha)	(H)	(F)+(G) **=50.48**	(F)+(G) **=42.91**	(F)+(G) **=18.27**	(F)+(G) **=15.53**	(F)+(G) **=31.19**	(F)+(G) **=26.51**	(F)+(G) **=125.5**	(F)+(G) **=106.7**	(F)+(G) **=41.43**	(F)+(G) **=35.22**	(F)+(G) **=67.01**	(F)+(G) **=56.96**
C INPUTS													
Above ground residues (kg C/ha)	(I)	(A)*(E) *10^3 =2534	(A)*(E) *10^3 =2153	(A)*(E) *10^3 =918	(A)*(E) *10^3 =780	(A)*(E) *10^3 =1580	(A)*(E) *10^3 =1343	(A)*(E) *10^3 =4896	(A)*(E) *10^3 =4162	(A)*(E) *10^3 =1593	(A)*(E) *10^3 =1354	(A)*(E) *10^3 =2592	(A)*(E) *10^3 =2203
Below ground residues (kg C/ha)	(J)	(B)*(E) *10^3 =1503	(B)*(E) *10^3 =1278	(B)*(E) *10^3 =543	(B)*(E) *10^3 =461	(B)*(E) *10^3 =912	(B)*(E) *10^3 =775	(B)*(E) *10^3 =1503	(B)*(E) *10^3 =1278	(B)*(E) *10^3 =543	(B)*(E) *10^3 =461	(B)*(E) *10^3 =847	(B)*(E) *10^3 =720
Total (kg C/ha)	(K)	(I)+(J) **=4037**	(I)+(J) **=3431**	(I)+(J) **=1461**	(I)+(J) **=1242**	(I)+(J) **=2491**	(I)+(J) **=2117**	(I)+(J) **=6399**	(I)+(J) **=5439**	(I)+(J) **=2136**	(I)+(J) **=1815**	(I)+(J) **=3439**	(I)+(J) **=2923**

[a] w: wet climate; d: dry climate.

Table 48. Inputs of C and N to soil from willow residues

		JB3		JB6	
		wet	dry	wet	dry
DATA					
DM in above ground residues (Mg DM/ha)	(A)	5.03	3.37	6.03	5.13
DM in below ground residues (Mg DM/ha)	(B)	5.21	3.49	6.25	5.31
N in above ground residues (kg N/kg DM)	(C)	0.005	0.005	0.005	0.005
N in below ground residues (kg N/kg DM)	(D)	0.005	0.005	0.005	0.005
C in all crop parts (kg C/kg DM)	(E)	0.45	0.45	0.45	0.45
N INPUTS					
Above ground residues (kg N/ha)	(F)	(A)*(C)*10^3 =25.13	(A)*(C)*10^3 =16.84	(A)*(C)*10^3 =30.16	(A)*(C)*10^3 =25.64
Below ground residues (kg N/ha)	(G)	(B)*(D)*10^3 =26.04	(B)*(D)*10^3 =17.45	(B)*(D)*10^3 =31.25	(B)*(D)*10^3 =26.57
Total (kg N/ha)	(H)	(F)+(G) **=51.18**	(F)+(G) **=34.29**	(F)+(G) **=61.41**	(F)+(G) **=52.90**
C INPUTS					
Above ground residues (kg C/ha)	(I)	(A)*(E)*10^3 =2262	(A)*(E)*10^3 =1516	(A)*(E)*10^3 =2714	(A)*(E)*10^3 =2307
Below ground residues (kg C/ha)	(J)	(B)*(E)*10^3 =2344	(B)*(E)*10^3 =1570	(B)*(E)*10^3 =2813	(B)*(E)*10^3 =2391
Total (kg C/ha)	(K)	(I)+(J) **=4606**	(I)+(J) **=3086**	(I)+(J) **=5527**	(I)+(J) **=4698**

12.5 Changes in N flows and N-related emissions

12.5.1 Overview

Figure 6 presents an overview of the N flows in the system “crop-climate-management-soil”.

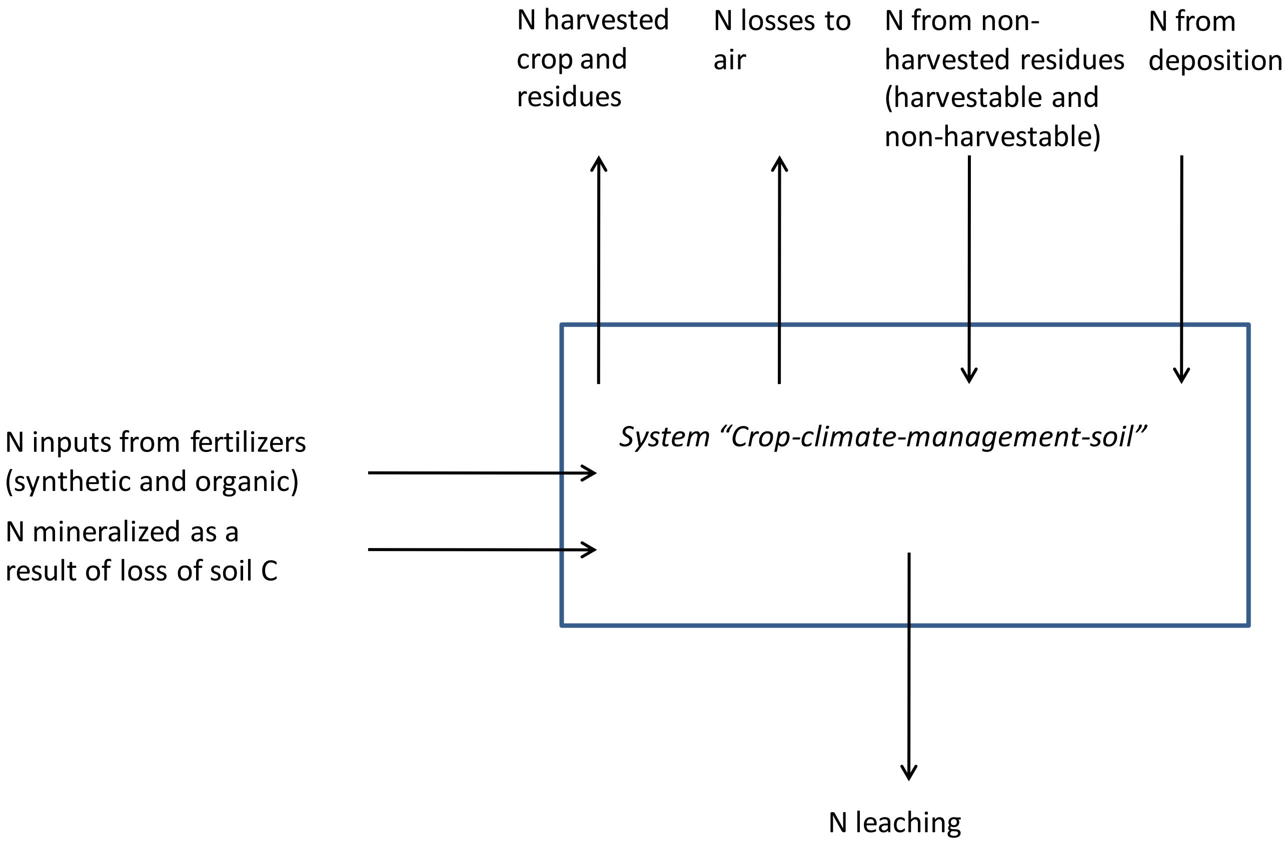

Figure 6. Schematisation of the N flows involved in the system "crop-climate-management-soil"

12.5.2 N inputs

As illustrated in figure 6, there are three main inputs of N: from fertilisers, from crop residues, and from the atmosphere. Nitrogen inputs from atmospheric deposition are not a direct input in the system, but as a result of the implementation of the different cropping system, more or less N may be deposited from the atmosphere elsewhere. This flow is considered through the so-called N_2O emissions. It is not considered as an input in the cropping system because it is not a flow that is (directly) affected as a consequence of implementing a given cropping system.

The N mineralized as a result of loss of soil C is considered as an input, conformingly with IPCC methodology (IPCC, 2006). This input is only considered for the calculations of N_2O emissions.

12.5.3 N losses to air

In agricultural systems, N losses to air consist of volatilization of ammonia (NH_3-N), emissions of nitrous oxide (N_2O-N: direct and indirect), oxides of N (NO plus NO_2) and emissions of dinitrogen (N_2) to atmosphere.

12.5.3.1 NH_3

12.5.4.1.1 Sources and emission process for NH_3

Emissions of ammonia in the field are mostly a consequence of fertiliser application (mineral and slurry). In this project, fertilization is the only emission source considered for NH_3 emissions. Other sources could however have been considered, namely the crops residues as well as the ammonia emission from the crop themselves, as further discussed below.

12.5.4.1.2 NH_3 emissions from crop foliage

As highlighted by Schjoerring and Mattsson (2001), vegetation, through crop foliage, may be both a source or a sink for NH_3 emissions depending on the concentration gradient between the atmosphere and the substomatal cavity above the mesophyll cell walls. The ammonia will flow from the less concentrated to the most concentrated compartment. This typically results in an emission rather than a sink in intensive agricultutal ecosystems, as emphasized by Sommer et al. (2004). In Denmark, Schjoerring and Mattsson (2001) did measured NH_3 fluxes over agricultural crops (oilseed rape, wheat, barley and pea) for two growing seasons. Their results showed that agricultural crops are net emitters of NH_3. The NH_3 losses from plant foliage measured by Schjoerring and Mattsson (2001) varied between 1 up to 5 kg NH_3-N per ha per season, which represents, according to these authors, between 1 and 4 % of the applied N. In contrast, van Hove et al. (2002) concluded from their study that ryegrass in intensively managed grassland in The Netherlands does not act as a source of ammonia.

As the quantification of this emission (and its actual occurrence in arable cropland) is rather uncertain, and as there are few studies to document this, it was decided **not to include crop foliage as a source for NH_3 emission**. This assumption was validated by leading experts in the area (Olesen, 2010). In the latest Danish inventory for the UNFCCC (Nielsen et al., 2009), NH_3 emissions from crops has nevertheless been assumed to 3 % for crops and 0.5 % for grass.

12.5.4.1.3 NH_3 emissions from decaying crop residues

Decomposition of crop residues lying on soil surface by microorganisms may lead to conversion of proteins in these residues to NH_4^+ which can subsequently emit as NH_3 (de Ruijter et al., 2010). In their experiment with volatilization chambers, de Ruijter et al. (2010) measured ammonia emissions varying between 4.8 and 15.9 percent of the N in crop residues (under winter conditions in the Nederlands). While 15.9 % was obtained for grass, 8.4 % of the N in sugar beet residues was emitted as ammonia. Evidences of residues (rather that the leaves still attached to the plants) acting as a source for ammonia emissions were also brought by Husted et al. (2000) as well as Nemitz et al. (2000). However, de Rujter et al. (2010) showed that residues incorporation drastically reduce the ammonia volatilization from residues (the authors measured between 98 to 100 % reductions). The explanation suggested by Rujter et al. (2010) is that $NH_4^+$of the residues is reduced through the nitrification and its concentration further decreases as a result of immobilization and adsorption. In this study**, it is considered that residues are incorporated just after harvest, thus leaving not enough time for significant ammonia releases from crop residues**.

12.5.4.1.4 NH_3 emissions from mineral fertiliser

Volatilization of ammonia is essentially a physiochemical process, and as such, the magnitude of emissions will differ upon the chemical composition of the fertilisers used and will be dependent upon several factors such as soil pH, soil cationic exchange capacity (CEC) and climate, among others. In short, the emission of ammonia will depend on whether the equilibrium between the gaseous phase (NH_3, gas) and NH_3 in solution (NH_3, aq) shift towards the gaseous or the liquid phase ($NH_3(aq) \leftrightarrow NH_3(gas)$). The NH_3 in the liquid phase ($NH_3(aq)$) can in turn combine with an hydrogen ion and produce NH_4^+ ($NH_4^+(aq) \leftrightarrow NH_3(aq) + H^+(aq)$). High pH (i.e. low H^+ concentration) will thus favour a shift towards NH_3 (aq) (and thus also NH_3(gas)) in order to restore the equilibrium, while low pH will favour the NH_4^+. The composition of the fertilizer as well as soil pH (and anything that can alter it like addition of calcium or the cationic exchange capacity of the soil) are therefore a key components controlling ammonia emissions. Temperature is also a key parameter as it controls the rate of hydrolysis for urea (Harrison and Webb, 2001). Extensive details about emissions processes are found in Harrison and Webb (2001) as well as Sommer et al. (2004).

In this study, two marginal mineral fertilisers were considered: urea and calcium ammonium nitrate.

In the Danish inventory of GHG to the UNFCCC, Nielsen et al. (2009) used an emission factor of 0.13 kg NH_3-N per kg N applied for urea and of 0.01 kg NH_3-N per kg N applied for calcium ammonium nitrate. In their research note, Mikkelsen et al. (2006) however present an emission factor of 0.15 kg NH_3-N per kg N applied for urea and of 0.02 kg NH_3-N per kg N applied for ammonium nitrate (calcium ammonium nitrate not listed).

In the German inventory (Haenel et al., 2010), the emission factors used are 0.115 kg NH_3-N per kg N applied for urea on arable crops and 0.006 kg NH_3-N per kg N applied for calcium ammonium nitrate on arable crops (for regions where mean average temperature is above 6°C and below 13°C). Haenel et al. (2010) also used specific factors when fertilisers are applied on grassland, namely 0.230 kg NH_3-N per kg N applied for urea and 0.016 kg NH_3-N per kg N applied (for regions where mean average temperature is above 6°C and below 13°C).

In their extensive review on the effect of mineral fertilizers on gaseous emissions, Harrison and Webb (2001) concluded that a distinction between grassland and arable crops for the emission factors should be made. Furthermore, they suggested that the following emission factors should be applied for ammonia:

Grassland: 0.23 kg NH_3 per kg N applied for urea (0.19 kg NH_3-N per kg N applied) and 0.016 kg NH_3 per kg N applied for ammonium nitrate and compound fertilizers (0.013 kg NH_3-N per kg N applied);

Arable cropland: 0.115 kg NH_3 per kg N applied for urea (0.0946 kg NH_3-N per kg N applied) and 0.008 kg NH_3 per kg N applied for ammonium nitrate and compounds fertilizers (0.007 kg NH_3-N per kg N applied).

In EMEP-EEA (2009) (table 3.2), equations to calculate the ammonia emission factor accounting for mineral fertiliser and foliar emissions are presented for a list of different fertilisers type. These equations are function of the mean spring temperature. This parameter was also taken into account in the inventory made by Haenel et al. (2010), whom defined mean spring temperature as the mean air temperature of March, April and May. In Denmark, this corresponds to 6.2 °C, based on data from the Danish meteorological Institute (DMI, 2010) (using data for “middeltemperatur”. Using this value in the equations presented by EMEP-EEA (2009) for urea gives 0.10 kg NH_3-N per kg N applied and 0.007 kg NH_3-N per kg N applied for calcium ammonium nitrate.

Nemecek and Kägi (2007), in the Ecoinvent report on agriculture (table 4.2), suggest an emission factor of 0.15 kg NH_3-N per kg N applied for urea and 0.02 kg NH_3-N per kg N applied for calcium ammonium nitrate.

Table 51 summarizes these various emission factors for ammonia from mineral fertilizers.

Table 49. Summary of various emission factors for ammonia from mineral fertilisers

Source	Emission factor kg NH_3-N per kg N applied		Comment
	urea	Calcium ammonium nitrate	
Nielsen et al. (2009)	0.13	0.01	
Mikkelsen et al. (2006)	0.15	0.02	The values for calcium ammonium nitrate are those for ammonium nitrate.
Haenel et al. (2010)	0.115 (arable land) 0.230 (grassland)	0.06 (arable land) 0.016 (grassland)	For region with an average spring temperature above 6 °C and below 13 °C.
Harrison and Webb (2001)	0.0946 (arable land) 0.19 (grassland)	0.007 (arable land) 0.013 (grassland)	The values for calcium ammonium nitrate are those for ammonium nitrate.
EMEP-EEA (2009)	0.10	0.007	Results from the equations in table 3.2, using a mean spring temperature of 6.2 °C. This accounts for emissions from mineral fertiliser and foliage.
Nemecek and Kägi (2007)	0.15	0.02	
Mean (arable)	0.12	0.02	
Mean (grassland)	0.21	0.04	

Based on table 51, it is considered in this study that the NH_3 emissions resulting from urea application are 0.12 kg NH_3-N per kg N applied and 0.02 kg NH_3-N per kg N applied for calcium ammonium nitrate. For ryegrass, the values considered are 0.21 kg NH_3-N per kg N applied for urea and 0.04 kg NH_3-N per kg N applied for calcium ammonium nitrate. The uncertainty is estimated as ± 50 %, based on Haenel et al. (2010).

As explained earlier, the emission factor is higher for urea than calcium ammonium nitrate since two moles of ammonia have the potential to be formed per mole of urea, in the presence of urease enzyme (Mobley and Hausinger, 1989).

12.5.4.1.4 NH_3 emissions from slurry fertiliser

Significant losses of NH_3-N occur during slurry application. As mentioned in Wesnæs et al. (2009), the data presented in Hansen et al. (2008) are considered to be state-of-the-art for ammonia emission from slurry application in Denmark. The NH_3-N loss given in Hansen et al. (2008) corresponds to 14.8 % of the NH_4^+-N content of the applied pig slurry and to 28.1 % of the NH_4^+-N content of the applied cow slurry. These values correspond to the spring application for grain and cereals crops, by trail hose. For spring application for grass, the values given by Hansen et al. (2008) correspond to 22.3 % of the NH_4^+-N content of the applied pig slurry and to 42.5 % of the NH_4^+-N content of the applied cow slurry. In both cases, Hansen et al. (2008) considered a content of 0.79 kg NH_4-N per kg N content for pig slurry and 0.58 kg NH_4-N per kg N content for cow slurry. Emissions factors are different for grain crops as compared to grass due to the effect of crop height, which is shorter for grass at the time of application.

Table 52 summarized the emission factors to be used in this study.

Table 50. Emission factor for ammonia emission due to fertilisation with animal slurry

	NH_3-N loss in % of NH_4^+-N in slurry (Hansen et al., 2008) (A)		kg NH_4^+-N per kg N (Hansen et al., 2008) (B)		Emission factor for this study (kg NH_3-N/kg N from slurry) = (A) * (B)	
	pig	cow	pig	cow	pig	cow
Cereal	14.8	28.1	0.79	0.58	0.11692	0.16298
grass	17.1	32.6	0.79	0.58	0.13509	0.18908

These emissions factors are in the range of others factors used/derived in the framework of Danish studies. For example, Mikkelsen et al. (2006) estimated, base on the average national practices, the NH_3 emissions as a percentage of the N in the manure ex-storage applied to the field. For liquid manure, this was estimated as 12.4 % for year 2002 (i.e. NH_3-N = 12.4 % of the N in the applied slurry).

The emission occurring under the application process itself is also considered. Based on Hansen et al. (2008), this NH_3-N loss corresponds to 0.5 % of the NH_4^+-N applied for trail hose application. Table 53 presents the corresponding emission factor for this ammonia emission.

Table 51. Emission factor for ammonia emission occurring under the application process itself, for fertilisation with animal slurry

	NH_3-N loss in % of NH_4^+-N in slurry (Hansen et al., 2008) (A)		kg NH_4^+-N per kg N (Hansen et al., 2008) (B)		Emission factor for this study (kg NH_3-N/kg N from slurry) = (A) * (B)	
	pig	cow	pig	cow	pig	cow
Trail hose application	0.005	0.005	0.79	0.58	0.00395	0.00290

12.5.3.2 NO-N

Most of NO-N emissions occur as a result of nitrification (Harrison and Webb, 2001; EMEP-EEA, 2009), i.e. the process by which micro-organisms oxidize ammonia to nitrite (NO_2^-) and nitrate (NO_3^-). Therefore, soil NO-N emissions are largely driven by the availability of mineral nitrogen and soil temperature, among others (EMEP-EEA, 2009; Stehfest and Bouwman, 2006).

Stehfest and Bouwman (2006) report, for Europe, NO-N emissions of 144 Gg/y for a N application of 12812 Gg/y, for cropland (table 6). Based on that, an emission factor of 0.011 kg NO-N/kg N applied can be derived. For grassland, the emission factor that can be derived from the data presented in Stehfest and Bouwman (2006) is 0.013 kg NO-N/kg N applied. These are the emission factors that will be used in this study for ryegrass (0.013 kg NO-N/kg N applied) and for all other selected crops (0.011 kg NO-N/kg N applied).

These values are in the range of the tier 1 emission factors suggested by EMEP-EEA (2009), i.e. 0.012 kg NO-N per kg of N applied.

Crops residues, however, also are a source of eventual mineral nitrogen in the soil and therefore a source for NO-N emissions. Based on Haenel et al. (2010), an emission factor of 0.007 kg NO-N/kg N input from residues is considered.

Table 54 summarizes the emission factors considered for NO-N emissions in this project.

Table 52. Emission factors used for estimation of NO-N

	NO-N from fertilizer application (0.011 kg NO-N/kg N applied)	NO-N from above ground residues (kg NO-N/kg N input from residues)
All crops, excluding ryegrass	0.011	-
Ryegrass	0.013	-
All crops	-	0.007

In their inventory, Haenel et al. (2010), who also derived their emission factor from the data of Stehfest and Bouwman (2006), estimated an uncertainty on NO of a factor 10.

12.5.3.3 NO_x –N

Nitrogen oxides consists of the sum of NO and NO_2. Once emitted from the soil, NO is quickly oxidized to NO_2 by available oxidants (e.g. ozone) (Delon et al., 2008).

Though gaseous NO_2 is emitted from biological processes occurring in the soil (Graham et al., 1997), no information has been found on NO_2 emissions from soils in the selected crop systems. Therefore, the emissions of NO-N are assumed to represent total NO_x.

12.5.3.4 N_2

As a result of the denitrification process, N_2 is returned to air. Though N_2 does not contribute to environmental impacts as such (it represents 78 % of the air), its quantification is needed in order to make a complete balance for N. In their inventory, Haenel et al (2010) quantified it as 0.1 kg N_2-N per kg N input (including fertilizers and crop residues). This estimation is used in the present study. Haenel et al. (2010) quantified the uncertainty of this estimation with a factor of 10.

12.5.3.5 N_2O (direct)

Most of the N_2O in crop systems occurs through microbiological transformation of N (Oenema et al., 2005) and this involves three main processes: nitrification, denitrification and nitrifier denitrification. In addition to these microbiological processes, N_2O may also be formed chemically through chemodenitrification, but this is generally not considered as an important source of N_2O (Yates, 2006). Figure 7, adapted from Oenema et al., 2005), illustrates the microbiological processes leading to N_2O emissions.

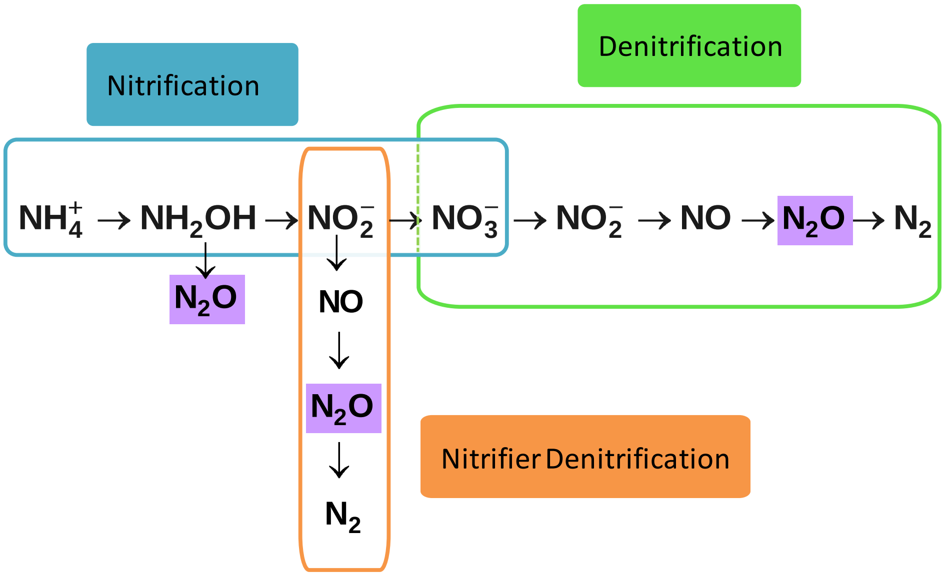

Figure 7. Illustration of the biological processes leading to N_2O emission, adapted from Oenema et al. (2005)

For denitrification to occur, anaerobic conditions are necessary, while nitrification occur under aerobic conditions. Not much is known about the nitrifier denitrification pathway, but it is believed to be similar to denitrification (Oenema et al., 2005). Under partial or transient anaerobic conditions, the denitrification reaction is uncompleted, resulting in the production of NO and N_2O. Apart the lack of oxygen availability, denitrification is also favoured by the presence of an available carbon source and warm temperature, among others (Nieder and Benbi, 2008, chapter 2). Because of this dependence upon such site-specific factors, emission of N_2O exhibits a rather high degree of spatial and temporal variability. This is one of the reasons why N_2O emissions is one of the most uncertain elements in national GHG inventories (Seufert, 2005).

Emissions of N_2O from cultivation activities are, in LCI, generally estimated based on extrapolation from measurements performed on a given field, from biogeochemical models (e.g. DNDC) or most commonly calculated based on IPCC guidelines (IPCC, 2006). However, many critics have been published about the IPCC methodology. For instance, the validity of the assumptions underlying IPCC methodology, i.e. that N_2O emitted can be directly correlated to the N inputs, has been put into doubt by measurements evidences (e.g. Jungkunst and Freibauer, 2005). Moreover, the fact that it does not take into account site-specific factors such as specific soil conditions (i.e. organic C content, pH and texture), crop types, fertilizer types and management practices has been highlighted as a major weakness of the methodology (e.g. Smeets et al., 2008; Stehfest and Bouwman, 2006). Smeets et al. (2008) also expressed concerns about the IPCC approach (i.e. the “fertilized-induced emission” approach), consisting to estimate the emissions as those arising from a fertilized plot minus the emissions arising from an unfertilized control plot (all other conditions being equal), and suggest to use a reference corresponding to the change in land use instead.

A top down approach has been suggested by Crutzen et al. (2008) as an alternative to the IPCC methodology, which is based, among others, on global N_2O budgets and a global budget of “new” N inputs from the agricultural system (i.e. synthetic fertiliser and biological nitrogen fixation). They then calculated the ratio between these “new” N inputs from agriculture to the agricultural related N_2O budget, and the conclusion from this parametrical relationship is that an average of 3 to 5 % of the new reactive agricultural related nitrogen entering the terrestrial biosphere should appear in the atmosphere as N_2O. These factors are much higher than the one used through the application of the IPCC methodology for “direct N_2O” (IPCC, 2006) (i.e. N_2O estimated as 1% of the applied N, but this has an uncertainty of a factor 3, the “true” value then being between 0.3 and 3 %). However, it applies for the “new” N from agricultural systems, and not the one from e.g. crop residues or manure, which are constantly recycling, so it cannot be compared directly with IPCC emission factor. In this study, applying the approach of Crutzen et al. (2008) would require to estimate the biological N fixation.

Because of the important global warming contribution of N_2O (298 kg CO_2 equivalent per kg CO_2 for a time horizon of 100 years, table 2.14 of Forster et al., 2007), its estimation has important implication on the final output of the LCA and may represents a rather contentious issue of LCAs of agricultural systems.

Nevertheless, according to Edwards et al. (2008), the use of IPCC default factor for estimating N_2O emission is the best methodology to use outside well-characterized area. In Denmark, IPCC default factors also approximately correlates with measured emissions.

Therefore, it is the IPCC methodology (IPCC, 2006) that will be applied in this project to estimate the N_2O emissions from the different crop systems. The methodology proposed by Crutzen et al. (2008) will however be applied as a sensitivity analysis for selected systems, using the highest factor of the interval. In that case, total N_2O-N (i.e. direct and indirect) will thus be estimated as: N_2O-N = 0.05 * (kg N mineral fertiliser input + kg N by biological fixation). The amount of N by biological fixation is estimated as 2 kg/ha*y, based on Kristensen et al. (2008), for fields without legumes.

The IPCC methodology (IPCC, 2006) recognizes six different sources for direct N_2O emissions occurring in the field, namely: synthetic fertiliser, organic fertiliser, crop residues, N mineralisation associated with loss of soil organic matter, urine and dung deposited by grazing animals and management of organic soils. The two latter are not concerned in this project. The IPCC default emission factor for synthetic fertiliser, organic fertiliser, crop residues and N mineralised as a result of soil C losses is 0.01 kg N_2O-N per kg N from these sources. The uncertainty range consists of a factor 3 (i.e. 0.003 to 0.03). In summary, the methodology, as to be applied for this study, could be summarized by:

$$N_2O - N_{N\ inputs} = (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times EF_1 \qquad \text{(Equation 8)}$$

Where F_{SN} is the amount of N (in kg N/y) added from synthetic fertiliser, F_{ON} is the amount of N added from organic fertiliser (in kg N/y), F_{CR} is the amount of N added from crop residues (in kg N/y) and F_{SOM} is the amount of N added from mineralised N through changes in soil C. The emission factor EF_1 is the amount of N_2O emitted per kg N input, i.e. 0.01 kg N_2O-N per kg N added.

The amount of N added from mineral fertilizer (F_{SN}) and animal slurry (F_{ON}) are as determined in earlier sections.

The amount of N added from above and below ground crop residues are as determined in earlier sections.

The methodology suggested by IPCC guidelines (IPCC, 2006) to determine the amount of N from mineralised N due to soil C changes consist to multiply the average annual loss of soil C (in kg of C per ha) by the inverse of the C:N ratio of the soil organic matter. These C:N ratios are taken from Petersen (2010) (table 4). Accordingly, a C:N ratio of 12.9 is considered for JB3 (weighted average for Jutland and Islands, depending on the agricultural area of both, which was taken from table 10 of Petersen (2010)) and of 10.9 for JB6.

The well-to-wheel study (JEC, 2007) developed its own N_2O emission factor based on a soil chemistry model (DNDC-Europe) applied to points from LUCAS land-cover survey of Eurostat (9000 sites in EU 15). From this, JEC (2007) calculated the N_2O emission per hectare of cultivating given crops. This bottom-up estimate was made for year 2000, selected as a year with representative crop yield over EU 15. As reported by Edwards et al. (2008), the average EU JEC emission factors are higher than what would be obtained from IPCC default factor, however, there were as many points falling below and above IPCC default values, most of them falling within the IPCC range of a factor 3 higher or lower. Average N_2O emissions presented by the well-to-wheel study (JEC; 2007) are: 1.65 kg N_2O/ha for wheat and 2.52 kg N_2O/ha for sugar beet.

12.5.3.6 N_2O (indirect)

A portion of the volatilised N (as NH_3 and NO_x) has the potential to be re-deposited and subsequently emitted as N_2O. This is referred to as an indirect N_2O emission. The IPCC methodology suggests a factor of 0.010 kg N_2O-N per kg (NH_3-N + NO_X-N) volatilised, the uncertainty range for this factor being 0.002 to 0.05 kg N_2O-N per kg (NH_3-N + NO_X-N) volatilised.

Similarly, a portion of the N losses through leaching will end up to be emitted as N_2O. These refer to indirect N_2O emissions and should be accounted for. For leaching, the factor suggested by the IPCC methodology (IPCC, 2006) is 0.0075 kg N_2O-N per kg N leaching (uncertainty range: 0.0005 to 0.025).

The well-to-wheel study (JEC, 2007), also calculated average N_2O emission factor for indirect emission due to N leaching. This corresponds to 0.58 kg N_2O/ha for wheat and 0.27 kg N_2O/ha for sugar beet.

12.5.4 N losses through water and soil

12.5.4.1 N leaching

Leaching of N is calculated with N-LES$_4$ model (Kristensen et al., 2008), an empirical model to predict N leaching from arable land based on more than 1200 leaching studies performed in Denmark during the last 15 years. Since its first version in 2000, the model has been continuously updated.

The main inputs to the model are the amount of N added (through mineral fertilization, pig and cow slurry, etc.) as well as the crop type. Others inputs relates to the fixation of N as well as the deposition of N, and site-specific parameters such as the geographical location in Denmark and its associate climate (based on the "klimagrid" of the Danish Meteorological Institute), the soil type and the C/N ratio of the soil. The model output consists of the N leaching, in kg N/ha.

Table 55 presents the leaching obtained for spring barley, spring barley and catch crop, winter wheat, silage maize, sugar beets and rye grass. The uncertainty is estimated as 60 % of the output result, based on Kristensen et al. (2008). In the modelisation, a bare soil is considered for all crops on the year before, except for spring barley & catch crop and ryegrass.

For miscanthus, values for N leaching are based on Olesen et al. (2001).

- JB3, wet climate, year 4-20, spring and autumn harvest: 14 kg N/ha (value for soil JB1 in Olesen et al., 2001)
- JB3, dry climate, year 4-20, spring and autumn harvest: an increase of 20 % of the leaching under wet climate is estimated, based on a personal communication with Uffe Jørgensen (Jørgensen, 2010), resulting in a leaching of 17 kg N/ha.
- JB6, wet and dry climate, year 4-20, spring and autumn harvest: 10 kg/ha (value for soil JB4 in Olesen et al., 2001)

- JB3, wet climate, year 2 and year 3, spring and autumn harvest: 89 kg N/ha for year 2 and 17 kg N/ha for year 3 (respective values for year 1 and year 2 of Olesen et al. (2001) for JB1).
- JB3, dry climate, year 2 and year 3, spring and autumn harvest: same procedure as for year 4-20 (i.e. leaching of 106.8 kg N/ha for year 2 and 20.4 kg N/ha for year 3)
- JB6, wet and dry climate, year 2 and 3, spring and autumn harvest: 75 kg N/ha for year 2 and 20 kg N/ha for year 3 (respective values for year 1 and year 2 of Olesen et al. (2001) for JB1).

Nitrate leaching values for willow are estimated to be the same as for miscanthus (year 4-20).

For both miscanthus and willow, N leaching is the highest in year where the first fertilisation occured (here corresponding to year 2 of the life cycle in the case of miscanthus, but often referred to as "year 1"). For this reason, a different leaching value is used for willow, year 3 of the lifecycle, where the values of year 2 for miscanthus are used, i.e. 89 kg and 106.8 N/ha on wet and dry JB3 and 75 kg N/ha on wet and dry JB6.

Table 56 presents the leaching for miscanthus and willow.

Table 53. Nitrate leaching (kg N/ha*y) for spring barley, spring barley & catch crops, winter wheat, silage maize, sugar beets and ryegrass

Climate	Wet (Jyndevad, climate grid number 10181)																			
Crop type	Spring barley		Spring barley, straw incorporation		Spring barley & catch crop		Spring barley & catch crop, straw incorporation		Winter wheat		Winter wheat, straw incorporation		Silage maize		Sugar beets		Sugar beets, top incorporated		Ryegrass	
Soil type	JB3	JB6	JB3	JB6	JB3	JB6	JB3	JB6	JB3	JB6	JB3	JB6	JB3	JB6	JB3	JB6	JB3	JB6	JB3	JB6
Leaching (kg N/ha*y)	113	134	120	143	62	74	68	81	99	111	106	119	131	132	110	112	138	138	216	211
Climate	Dry (Roskilde, climate grid number 10547)																			
Leaching (kg N/ha*y)	100	69	107	71	48	26	53	28	106	65	114	68	93	57	80	34	102	39	171	84

Table 54. Nitrate leaching (kg N/ha*y) for miscanthus and willow

Climate	Wet (Jyndevad, climate grid number 10181)							
Crop type	Miscanthus, autumn and spring harvest, year 4-20		Miscanthus, autumn and spring harvest, year 3		Miscanthus, autumn and spring harvest, year 2		Willow (year 3 in parenthesis)	
Soil type	JB3	JB6	JB3	JB6	JB3	JB6	JB3	JB6
Leaching (kg N/ha*y)	14	10	17	20	89	75	14 (89)	10 (75)
Climate	Dry (Roskilde, climate grid number 10547)							
Leaching (kg N/ha*y)	17	10	20.4	20	106.8	75	17 (106.8)	10 (75)

12.6 Changes in C flows and C-related emissions

12.6.1 Overview

Figure 8 presents an overview of the C flows in the system "crop-climate-management-soil".

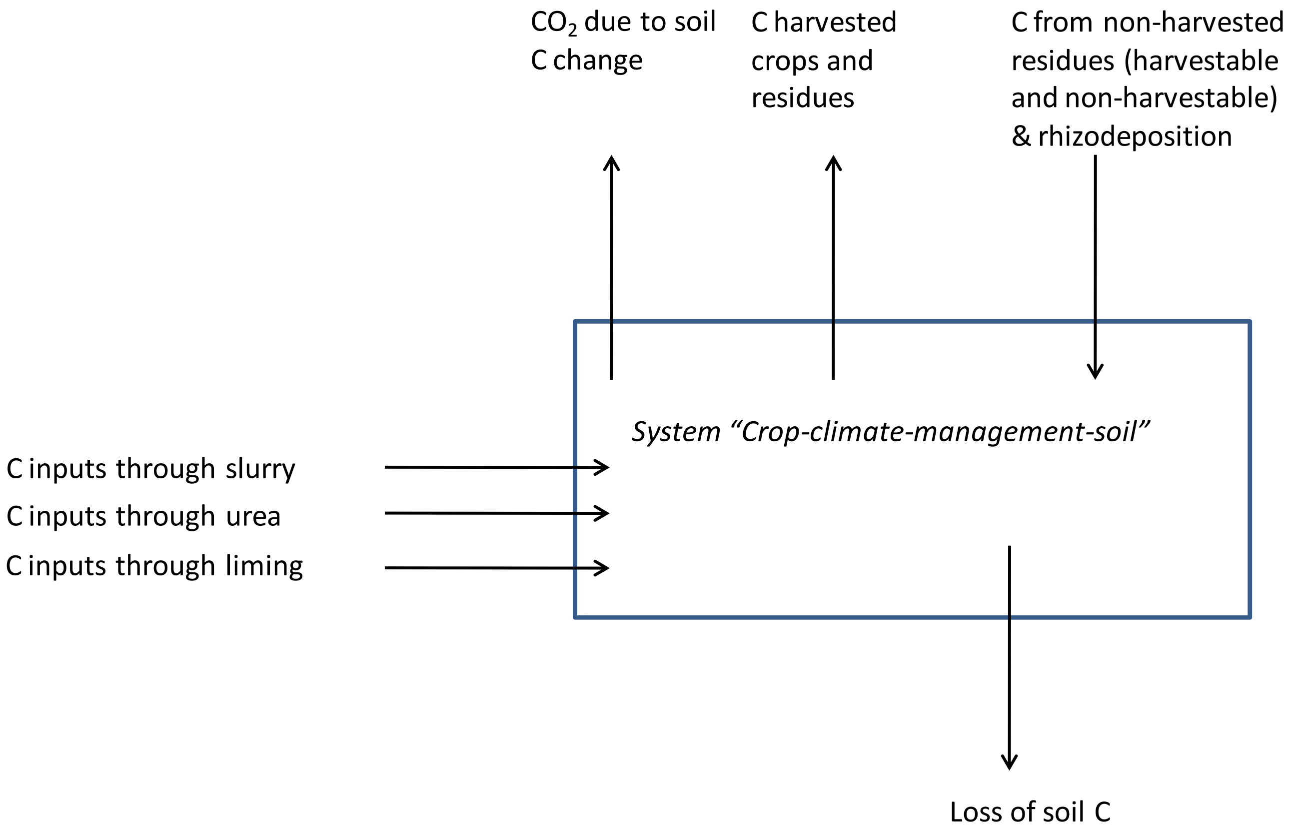

Figure 8. Overview of the involved C flows in the crop system

12.6.2 C inputs

As illustrated in figure 8, there are four main inputs of N: from fertilisers (slurry and urea when this is the mineral fertiliser considered), from crop residues, and from lime.

12.6.3 C losses through air

12.6.3.1 CO2

12.6.3.1.1 CO_2 as a result of changes in soil C

Changes in soil C and related CO_2 emissions were estimated through the use of the dynamic soil model C-TOOL, developed to calculate the soil carbon dynamics in relation to the Danish commitments to UNFCCC. This model is parameterized and validated against long-term field experiments conducted in Denmark, UK and Sweden. Further description of C-TOOL are available in Petersen et al. (2002) as well as Petersen et al. (2005). Changes in soil C were estimated over two time horizons: 20 years and 100 years. Moreover, an initial “high” “medium” and “low” soil C content are considered. Results for the soil C changes, with an annualization of 20 years, are presented in Figures 9 to 11. In these figures, “inc” means incorporation and “rem” means removal.

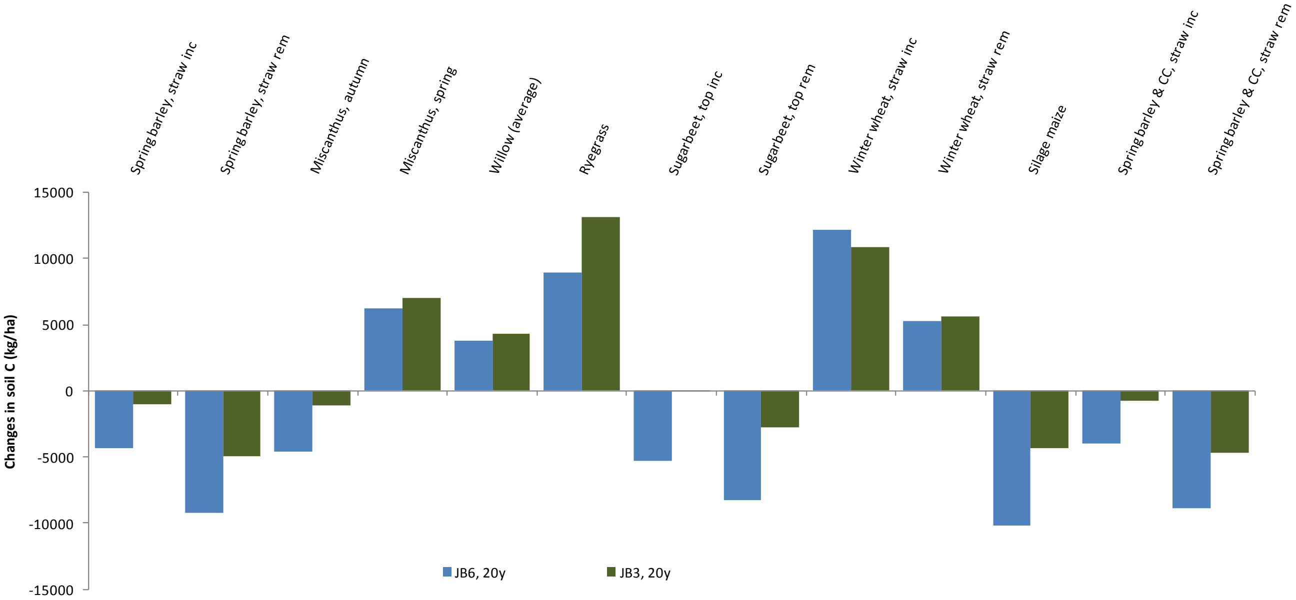

Figure 9. MEDIUM INITIAL SOIL C (143.92 t C/ha on JB3 and 144.71 t C/ha on JB6)

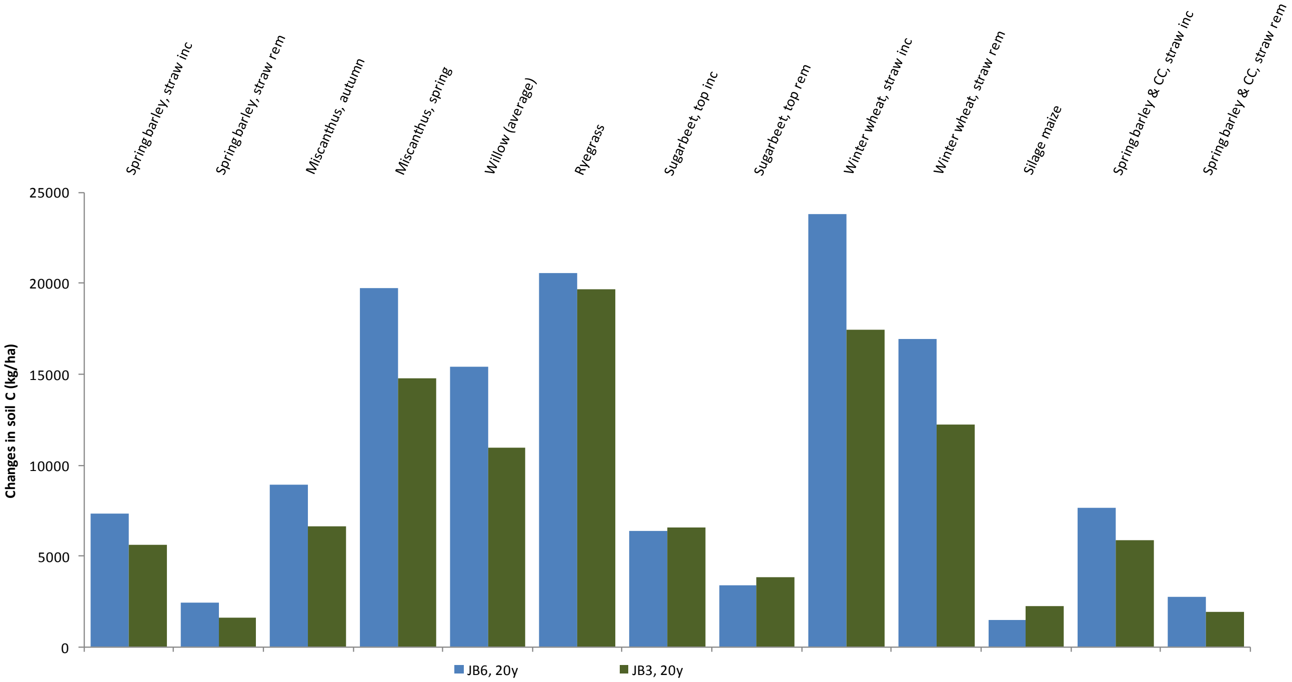

Figure 10. LOW INITIAL SOIL C (84.74 t C/ha on JB3 and 68.31 t C/ha on JB6)

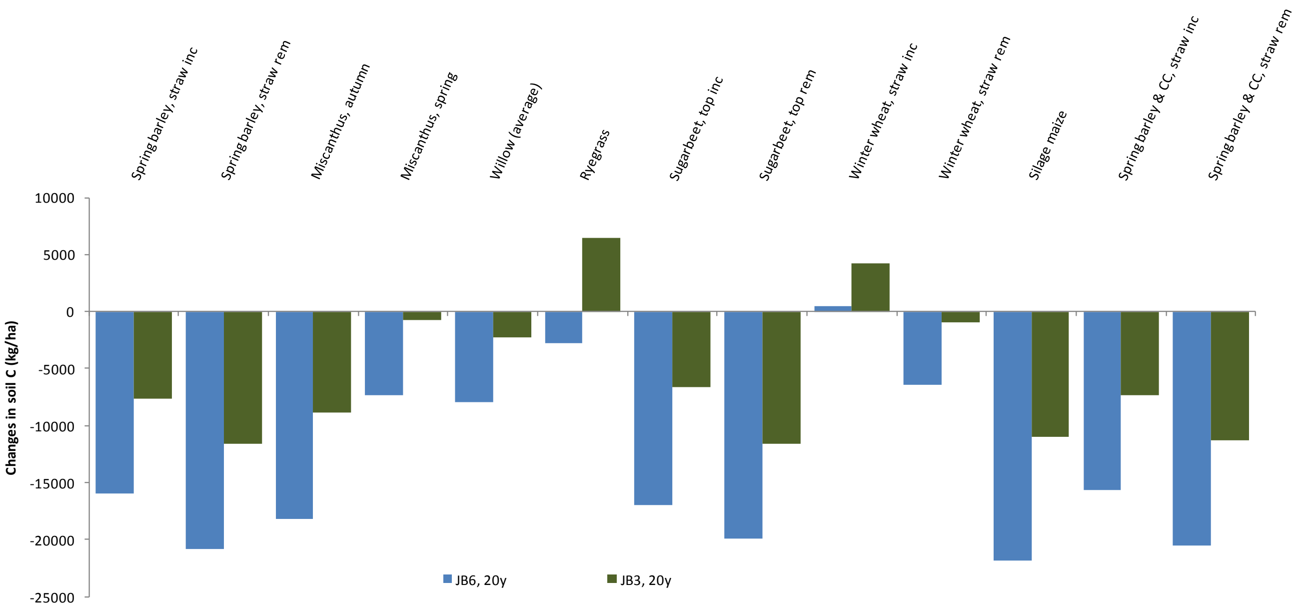

Figure 11. HIGH INITIAL SOIL C (203.1 t C/ha on JB3 and 221.12 t C/ha on JB6)

12.6.3.1.2 CO_2 as a result of lime application

Each mole of lime applied to soil has the net potential to contribute to the addition of 1 mole of CO_2 to the atmosphere, based on the following equation (EMEP, 2007):

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- \rightarrow Ca^{2+} + 2OH^- + 2CO_2 \qquad \text{(Equation 9)}$$

The net result of applying 1 mole of $CaCO_3$ can thus be simplified as:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad \text{(Equation 10)}$$

Considering the molecular weights (100.086 kg for $CaCO_3$ and 44.009 kg for CO_2), it can be assumed that applying 1 kg of $CaCO_3$ contributes to 0.44 kg of CO_2 (44.009 kg / 100.086 kg). This estimation implies the assumption that all the lime applied reacts, which may not necessarily be the case in practice. Emissions of CO_2 from application of $CaCO_3$ to the field are estimated by similar rationale in the IPCC guidelines (IPCC, 2006) as well as in EMEP (2007).

The emission of CO_2-C from lime is therefore estimated as: CO_2-C = 0.12 * amount of $CaCO_3$ applied.

Table 63 summarizes the CO_2 emission from liming for all crops.

Table 55. Emissions of CO_2 from liming

Crops	Lime application kg CaCO$_3$/ha (per application)	Number of liming in 20 years	Number of liming in 100 years	CO_2 emissions		
				per liming kg CO_2-C/ha	In 20 y kg CO_2-C/ha	In 100 y kg CO_2-C/ha
Spring barley	835.7	4	20	100.28	401.14	2005.68
Spring barley & catch crop	835.7	4	20	100.28	401.14	2005.68
Winter wheat	835.7	4	20	100.28	401.14	2005.68
Willow	835.7	1	5	100.28	100.28	501.42
Miscanthus (autumn)	835.7	1	5	100.28	100.28	501.42
Miscanthus (spring)	835.7	1	5	100.28	100.28	501.42
Maize silage	835.7	4	20	100.28	401.14	2005.68
Sugar beet	835.7	4	20	100.28	401.14	2005.68
Rye grass	835.7	1	5	100.28	100.28	501.42

12.6.3.1.3 CO_2 as a result of urea fertilisation

Urea, in the presence of water and urease enzyme (which is present in animal feces), has the potential to generate two moles of ammonia and ultimately, one mole of CO_2. This is based on the following reactions (Mobley and Hausinger, 1989):

$$(H_2N)_2CO + H_2O \xrightarrow{urease} NH_3 + COOHNH_2 \qquad \text{(Equation 11)}$$

$$COOHNH_2 + H_2O \rightarrow NH_3 + H_2CO_3 \qquad \text{(Equation 12)}$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \qquad \text{(Equation 13)}$$

The bicarbonate (HCO_3^-) will react just as in the case of lime:

$$HCO_3^- \rightarrow OH^- + CO_2 \qquad \text{(Equation 14)}$$

These equations may be summarized as:

$$(H_2N)_2CO + H_2O \rightarrow 2NH_3 + CO_2 \qquad \text{(Equation 15)}$$

When urea is considered as the marginal fertiliser, this CO_2 release has to be accounted for. Considering the molecular weights (60 kg for urea and water and 44 kg for CO_2), it can be assumed that applying 1 kg of urea contributes to 0.73 kg of CO_2 (44 kg / 60 kg). The approach described in IPCC (IPCC, 2006) yields to the same final factor. This again involves the assumption of full degradation, which is unlikely to always be the case. In fact, under field conditions, urease may not necessary be present in quantities ensuring the full urea conversion rate (i.e. urease activity).

The emission of CO_2-C from urea is therefore estimated as: CO_2-C = 0.20 * amount of urea applied.

Table 64 summarizes the CO_2 emission from urea application for all crops.

Table 56. Emissions of CO_2 from fertilisation with urea

Crops	Soil	Urea application kg urea-N/ha (per application)	Number of application in 20 years	Number of application in 100 years	CO_2 emissions		
					per application kg CO_2-C/ha	In 20 y kg CO_2-C/ha	In 100 y kg CO_2-C/ha
Spring barley	JB3	63	20	100	27.00	540.00	2700.00
	JB6	57			24.43	488.57	2442.86
Spring barley & catch crop	JB3	54.5	20	100	23.36	467.14	2335.71
	JB6	48.5			20.79	415.71	2078.57
Winter wheat	JB3	83	20	100	35.57	711.43	3557.14
	JB6	80.5			34.50	690.00	3450.00
Willow (100 % mineral)	JB3 & JB6	120	5.7[a]	28.6	51.43	293.89	1469.43
Miscanthus, autumn, 4-20	JB3 & JB6	45	17	85	19.29	327.86	1639.29
Miscanthus, autumn, y. 2	JB3 & JB6	15	1	5	6.43	6.43	32.14
Miscanthus, autumn, y. 3	JB3 & JB6	30	1	5	12.86	12.86	64.29
Miscanthus, spring, 4-20	JB3 & JB6	30	17	85	12.86	218.57	1092.86
Miscanthus, spring, y. 2	JB3 & JB6	15	1	5	6.43	6.43	32.14
Miscanthus, spring, y. 3	JB3 & JB6	30	1	5	12.86	12.86	64.29
Maize silage	JB3	81	20	100	34.71	694.29	3471.43
	JB6	69.5			29.79	595.71	2978.57
Sugar beet	JB3	61.5	20	100	26.36	527.14	2635.71
	JB6	51			21.86	437.14	2185.71
Rye grass	JB3	171	20	100	73.29	1465.71	7328.57
	JB6	162.5			69.64	1392.86	6964.29

[a] 6 fertilisations with 100 % synthetic fertiliser over the 24 years life cycle (years 3, 7, 10,13, 16, 19), meaning (6/21) * 20 = 5.7 urea application in a 20 year period.

12.7 Other substance flows

12.7.1 NMVOC

This category includes losses of nutrients from organic fertiliser inputs as well as biogenic non-methane volatile organic compounds (NMVOC) emitted from photosynthesising leaves of crops (particularly isoprene and monoterpene). The inclusion of NMVOC, though the data are rather uncertain, was judged important given the magnitude of the differences between the emissions of biogenic NMVOC from woody crops and arable crops. As an example, Jungbluth et al. (2007b) estimated, based on a model allowing to account for regional difference in Europe, an annual emission of 53.1 kg isoprene per ha for willow (willow-salix) while the annual emission for miscanthus and wheat was of 21.6 and 20.1 kg isoprene per ha, respectively (in Switzerland) (increase of 155 % from the average of miscanthus and wheat to the emission from willow). Annual monoterpene emissions estimated by Jungbluth et al. (2007b) amount to 2.7 kg monoterpene per ha for willow, 1.1 kg monoterpene per ha for miscanthus and 1.0 kg monoterpene per ha for wheat. In the Ecoinvent database, biogenic emissions of NMVOC are not considered (Jungbluth et al., 2007).

Nielsen et al. (2009) used, in their estimation for the National greenhouse gas Inventory Report to the UNFCCC, an overall emission factor for biogenic NMVOC of 393 g NMVOC per ha for land with arable crops and 2120 g NMVOC per hectare for grassland. The former is based on Fenhann and Kilde (1994) and the latter is based on Priemé and Christensen (1991).

The approach used in the German Inventory (Haenel et al., 2010) also end up with an output in terms of NMVOC per ha per year, but is detailed in function of the crop type and the NMVOC type. This consists to multiply the primary yield (in DM/ha) by an emission factor for a given crop (kg NMVOC/kg DM*h) by the fraction of year during which the crop is emitting. The crop emission factor and fraction of year data are given in table 11.7 of Haenel et al. (2010) and presented in Table 65. The calculation of NMVOC for this study based on the methodology of Haenel et al. (2010) is also presented in table 65. Miscanthus and willow are not included in the data presented by Haenel et al. (2010).

Table 57. Data presented by Haenel et al. (2010) for estimating biogenic NMVOC. Empty cells are assumed to correspond to zero values.

Crop	Isoprene (kg/kg DM*h)	Terpene (kg/kg DM*h)	Alcohols (kg/kg DM*h)	Alde-hydes (kg/kg DM*h)	Ketones (kg/kg DM*h)	Ethers and others (kg/kg DM*h)	Fraction of year emitting (y^{-1})	Primary yield (JB3) (this study) (Mg DM/ha)	Primary yield (JB6) (this study) (Mg DM/ha)	NMVOC (JB3) for this study (kg/ha)	NMVOC (JB6) for this study (kg/ha)
Wheat			$8*10^{-10}$	$2.8*10^{-9}$	$2.2*10^{-9}$	$5.1*10^{-9}$	0.3	5.61	6.8	0.161	0.195
Spring barley			$8*10^{-10}$	$2.8*10^{-9}$	$2.2*10^{-9}$	$5.1*10^{-9}$	0.3	4.25	4.85	0.122	0.139
grass	$2*10^{-10}$	$6.3*10^{-9}$	$7.5*10^{-10}$	$1.3*10^{-9}$		$1.8*10^{-9}$	0.5	9.98	8.82	0.452	0.400
Silage maize										0	0
Sugar beet										0	0

For 2008, Haenel et al. (2010) present an overall German emission factor of 0.13 kg NMVOC per ha (Table IEF 1001.11). The factors estimated above are a bit lower than the 0.393 kg NMVOC per hectare for arable crops presented by Nielsen et al. (2009), but for grass, it is far lower than the 2.120 kg/ha presented by Nielsen et al. (2009). In Switzerland, from the data of Jungbluth et al. (2007b), it appears that emissions are much higher. This could however be explained, at least partly, by the difference in terms of irradiation and sunshine hours, as well as primary yield.

The NMVOC impact the environment in 2 main categories: global warming (factor of 3 kg CO_2 eq. per kg NMVOC in the EDIP 2003 method) and ozone formation (smog) (factor of 0.059 person*ppm*h per kg NMVOC in the EDIP 2003 method, for ozone affecting human). Looking at isoprene alone, it only impacts photochemical ozone formation, but it does so with a rather important factor (0.118 person*ppm*h/kg isoprene).

For this study, the NMVOC are considered as a whole (not only for isoprene), and they are calculated based on the methodology presented by Haenel et al. (2010). This has the advantage to differentiate between crop types, crop yield, and consequently soil types. These data are judged to be representative for Danish conditions and are judged as best proxy under current data availability.

Based on the results of Jungbluth et al. (2007b), the emission factors for miscanthus are assumed identical to those of wheat. For willow, emission factors are taken as those of grass, which give final NMVOC emissions close to the increase of 155 % as compare to emissions from wheat obtained by Jungbluth et al. (2007b). This approach is a rough estimate, but should be seen as an attempt to include NMVOC emissions from crops into LCA, which is seldom taken into account. The uncertainty for these emissions is estimated as a factor of 30 by Haenel et al. (2010), which is rather considerable.

Table 66 summarises the NMVOC emissions for each crop types and soil types, and distinguishes for the weather in the case of willow and miscanthus (based on primary yield data).

Table 58. NMVOC from crops, as used in this study.

Crop	NMVOC (JB3) (kg/ha)	NMVOC (JB6) (kg/ha)	Comments
Spring barley	0.122	0.139	From factors presented in Table 65.
Spring barley & catch crop	0.122	0.139	NMVOC from catch crop assumed neglible.
Winter wheat	0.161	0.195	From factors presented in Table 65.
Miscanthus (autumn harvest, year 4-20)	0.437 (wet) 0.371 (dry)	0.437 (wet & dry)	From factors presented in Table 65, for wheat.
Miscanthus (autumn harvest, year 3)	0.262 (wet) 0.223 (dry)	0.262 (wet & dry)	From factors presented in Table 65, for wheat.
Miscanthus (autumn harvest, year 2)	0.158 (wet) 0.134 (dry)	0.158 (wet & dry)	From factors presented in Table 65, for wheat.
Miscanthus (Spring harvest, year 4-20)	0.286 (wet) 0.243 (dry)	0.286 (wet & dry)	From factors presented in Table 65, for wheat.
Miscanthus (Spring harvest, year 3)	0.172 (wet) 0.146 (dry)	0.172 (wet & dry)	From factors presented in Table 65, for wheat.
Miscanthus (Spring harvest, year 2)	0.115 (wet) 0.097 (dry)	0.115 (wet & dry)	From factors presented in Table 65, for wheat.
Willow	0.481 (wet) 0.322 (dry)	0.576 (wet) 0.490 (dry)	From factors presented in Table 65, for grass.
Sugar beet	0	0	From factors presented in Table 65.
Silage maize	0	0	From factors presented in Table 65.
Permanent ryegrass	0.452	0.400	From factors presented in Table 65.

12.7.2 PM emissions

Haenel et al. (2010) used an overall annual emission factor of 1.56 kg PM_{10}/ha and 0.06 kg $PM_{2.5}$/ha (estimated uncertainty of 100 % in both case). These same factors are also those used by Hutchings et al. (2009) in the EMEP-EEA emission inventory guidebook 2009. Emissions of PM arises particularly during harvesting and cultivation (Hutchings et al., 2009).

As the cultivation and harvesting operations are already taken into account, PM emissions are included under these, and it is considered that there are negligible PM emission due to the biogenic field processes as such.

12.7.3 P leaching

The amount of slurry applied involves, for both soil JB3 and JB6, a surplus of P for willow and rye grass. As emphasized by Wesnæs et al. (2009), it is not clear from the current state of knowledge how much of this surplus P will leach, and whether or not there is leaching from soil where P is not applied in excess.

Different approaches can be found in the literature as regarding how to treat the P leaching in LCA, as presented in table 67.

Table 59. Approaches inventoried in the literature as regarding the estimation of P leaching in LCA

Reference	Assumption for P leaching	Remark
Nielsen and Wenzel (2007)	P leaching = 5 % of the net surplus application.	Rough estimation based on the Danish figures for P-surplus and P leaching to aquatic recipients (0.4 to 0.5 kg P/ha*y), assuming that P surpluses are directly proportional to P leaching. Surplus application is estimated as average P by manure application (30 kg P/ha) minus average plant uptake (20 kg P/ha).
Dalgaard (2007)	P leaching as phosphate = 2.9 % of P surplus	Rough estimation based on the Danish figures for P-surplus and P emissions to aquatic recipients, assuming P surpluses are directly proportional to P leaching. Seen as an "average" for Danish agriculture (including both livestock and crop farms).
SenterNovem (2005)	P leaching as phosphate = 9 % of P surplus	Estimation based on a Dutch study (Van Zeijts and Reus, 1996).
Thomassen et al. (2009)	P leaching = 100% of P surplus	Assumption based on the Dutch context, based on the fact that most of the Dutch soils are phosphorus-saturated.
Hauschild and Potting (2005)	P leaching to soil = 0.10 kg per kg of P applied. (Annex 6.3) P leaching to water (inland and marine): 0.06*kg P leaching to soil (table 6.2).	This is in the case uptake and binding is unknown. If the actual amount of P leaving the top soil is known, it is recommended to use such figures.
Basset-Mens et al. (2007)	P losses to water = 1 % of P in runoff losses Runoff losses = 50 % of P excreted	Applies when P is from animal manure. Based on Rossier (1998).
Nemecek and Kägi (2007)	P leaching to ground water (kg/ha*y) = 0.07*[1+(0.2/80)*P_2O_5 in slurry] P run-off to surface waters (kg/ha*y) = 0.175*[1+(0.2/80)*P_2O_5 in mineral fertilisers + (0.7/80)* P_2O_5 in slurry]	The factor 0.07 is for arable land. A factor of 0.06 is used for permanent pastures. The factor 0.175 is for arable land. A factor of 0.25 is used for (intensive) permanent pastures. The original formulation also includes a term for solid manure applied, but this is not considered in this project. A methodology for estimating P losses by water erosion is also presented.

From table 67, it can be seen that most of the approaches for estimating P leaching are based on the amount of surpluses, implicitly assuming that the P surpluses are directly proportional to P leaching. Of course, the validity of this linearity assumption may be discussed, and part of the P applied in non-surplus situations may also leak.

Yet, it is not possible, under the current status of research, to relate the P losses from agricultural fields to the amount of P added through fertilization.

Based on this, the estimation of 5 % of the net surplus application presented by Nielsen and Wenzel (2005) has been used in this project. As a sensitivity analysis, the approach of Hauschild and Potting (2005), which is based on the total amount of P added instead of being based on P surpluses, will be applied on selected combinations. This will allow highlighting the importance of the “type” of methodology used for estimating P leaching, based on P surpluses or on total P inputs. **For perennial crops, P leaching is estimated as 2.5 % of surplus.** This is based on Sørensen et al. (2010), who highlight lower P leaching of 0.06 to 0.25 kg P/ha with perennial crops, combined to the figure used by Nielsen and Wenzel (2005) to derive the estimation of P leaching corresponding to 5 % of the net surplus (i.e. assuming average surplus of 10 kg P/ha).

Table 60. Estimation of P leaching to water recipients, soil JB3, for both residues management practices. All values for both climate types, unless otherwise specified.

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry) [f]	Misc[a,f], year 4 to 20 (autumn)	Misc.[a,f], year 4 to 20 (spring)	Maize silage	Sugar beet	Rye grass	Misc., Year 2	Misc., Year 3
P to be applied, (from norm)	22	22	22	15	15	15	44	43	36	15	15
Amount from slurry, total [A]	16.49	14.26	21.72	31.40	11.78	7.85	21.20	16.09	44.75	3.93	7.85
Amount from minerals [B]	5.51	7.74	0.28	0	3.22	7.15	22.80	26.91	0	11.07	7.15
Uptake, primary yield[b] [c]	12.75	12.75[c]	15.71	8.48 (w) 5.68 (d)	9.15 (w) 7.78 (d)	6.00 (w) 5.10 (d)	31.33	21.17	39.90[d]	3.3 (w, fall) 2.4 (w, spring) 2.8 (d, fall) 2.0 (d, spring)	5.5 (w, fall) 3.6 (w, spring) 4.7 (d, fall) 3.1 (d, spring)
Uptake, secondary yield[e] [D]	2.106	2.106	2.78	0	0	0	0	4.37	0	0	0
Surplus, secondary yield harvested [E] = [(A+B)-C-D]	7.14	7.14	3.51	-	-	-	-	17.46	-	-	-
Surplus, secondary yield left on-field [F] = [(A+B)-C]	9.25	9.25	6.29	22.9 (w) 25.7 (d)	2.63 (w) 4.00 (d)	1.85 (w) 2.75 (d)	12.67	21.84	4.85	0.6 (w, fall) 1.5 (w, spring) 1.1 (d, fall) 1.9 (d, spring)	2.4 (w, fall) 4.3 (w, spring) 3.2 (d, fall) 4.8 (d, spring)
P leaching to water recipients, secondary yield harvested [0.05*E]	***0.36***	***0.36***	***0.18***	-	-	-	-	***0.87***	-	-	-
P leaching to water recipients, secondary yield left on-field or no secondary yield [0.05*F] or [0.025*F]	***0.46***	***0.46***	***0.31***	0.57 (w) 0.64 (d)	0.07 (w) 0.10 (d)	0.05 (w) 0.07 (d)	***0.63***	***1.09***	***0.17***	0.02 (w, fall) 0.04 (w, spring) 0.03 (d, fall) 0.05 (d, spring)	0.06 (w, fall) 0.11 (w, spring) 0.08 (d, fall) 0.12 (d, spring)
P leaching, sensitivity analysis [0.1*0.06*(A+B)]	***0.13***	***0.13***	***0.13***	***0.19***	***0.09***	***0.09***	***0.26***	***0.26***	***0.27***	***0.02***	***0.05***

[a] Misc. stems for miscanthus

[b] P in primary yield are taken from Møller et al. (2000): spring barley: 3 g P/kg DM; winter wheat: 2.8 g P/kg DM; silage maize: 2.6 g P/kg DM; sugar beet: 1.7 g P/kg DM; ryegrass: 4 g P/kg DM. For miscanthus, the value of 0.6 g P/kg DM is used for both autumn and spring harvest, based on Beale and Long (1997). Content of P for willow seems to vary considerably with the site-specific P-availability, but 0.8 g P/kg DM is a typical value for Danish soil (Sanders, 2010). To obtain the uptake in g P/ha, these values are multiplied by the corresponding primary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Primary yields are taken from table 43.

[c] Since the catch crop is not harvested, there is no withdrawal of P considered from the catch crop.

[d] Value for durable grass ("varigt enggræs") in Møller et al. (2000).

[e] P in secondary yield are taken from Møller et al. (2000): spring barley: 0.9 g P/kg DM; winter wheat: 0.9 g P/kg DM; sugar beet: 2.7 g P/kg DM. To obtain the uptake in kg P/ha, these values are multiplied by the corresponding secondary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Secondary yields are taken from table 43.

[f] w: wet; d: dry

Table 61. Estimation of P leaching to water recipients, soil JB6, for both residues management practices. All values for both climate types, unless otherwise specified.

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry) [f]	Misc[a,f], year 4 to 20 (autumn)	Misc[a,f], year 4 to 20 (spring)	Maize silage	Sugar beet	Rye grass	Misc., Year 2	Misc., Year 3
P to be applied, (from norm)	22	22	22	15	15	15	44	43	36	15	15
Amount from slurry, total [A]	14.92	12.69	21.07	15.70	11.78	7.85	18.19	13.35	42.53	3.93	7.85
Amount from minerals [B]	7.08	9.31	0.93	0	3.22	7.15	25.81	29.65	0	11.07	7.15
Uptake, primary yield[b] [c]	14.55	14.55[c]	19.04	10.18 (w) 8.65 (d)	9.15 (w and d)	6.00 (w and d)	31.02	21.17	35.26[d]	3.3 (w and d, fall) 2.4 (w and d, spring)	5.5 (w and d, fall) 3.6 (w and d, spring)
Uptake, secondary yield[e] [D]	2.40	2.40	3.37	0	0	0	0	4.37	0	0	0
Surplus, secondary yield harvested [E] = [(A+B)-C-D]	5.05	5.05	0	-	-	-	-	17.46	-	-	-
Surplus, secondary yield left on-field [F] = [(A+B)-C]	7.45	7.45	2.96	21.23 (w) 22.75 (d)	2.63 (w and d)	1.85 (w and d)	12.98	21.84	7.26	0.63 (w and d, fall) 1.53 (w and d, spring)	2.36 (w and d, fall) 4.25 (w and d, spring)
P leaching to water recipients, secondary yield harvested [0.05*E]	**0.25**	**0.25**	**0**	**-**	**-**	**-**	**-**	**0.87**	**-**	-	-
P leaching to water recipients, secondary yield left on-field or no secondary yield [0.05*F] or [0.025*F]	**0.37**	**0.37**	**0.15**	0.53 (w) 0.57 (d)	0.07 (w and d)	0.05 (w and d)	**0.65**	**1.09**	**0.25**	0.02 (w and d, fall) 0.04 (w and d, spring)	0.06 (w and d, fall) 0.11 (w and d, spring)
P leaching, sensitivity analysis [0.1*0.06*(A+B)]	**0.13**	**0.13**	**0.13**	0.09	0.09	0.09	**0.26**	**0.26**	**0.26**	**0.02**	**0.05**

[a] Misc. stems for miscanthus

[b] P in primary yield are taken from Møller et al. (2000): spring barley: 3 g P/kg DM; winter wheat: 2.8 g P/kg DM; silage maize: 2.6 g P/kg DM; sugar beet: 1.7 g P/kg DM; ryegrass: 4 g P/kg DM. For miscanthus, the value of 0.6 g P/kg DM is used for both autumn and spring harvest, based on Beale and Long (1997). Content of P for willow seems to vary considerably with the site-specific P-availability, but 0.8 g P/kg DM is a typical value for Danish soil (Sanders, 2010). To obtain the uptake in g P/ha, these values are multiplied by the corresponding primary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Primary yields are taken from table 43.

[c] Since the catch crop is not harvested, there is no withdrawal of P considered from the catch crop.

[d] Value for durable grass ("varigt enggræs") in Møller et al. (2000).

[e] P in secondary yield are taken from Møller et al. (2000): spring barley: 0.9 g P/kg DM; winter wheat: 0.9 g P/kg DM; sugar beet: 2.7 g P/kg DM. To obtain the uptake in kg P/ha, these values are multiplied by the corresponding secondary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Secondary yields are taken from table 43.

[f] w: wet; d: dry

12.7.4 K leaching

As acknowledged by Arienzo et al. (2009), the number of studies assessing the fate of K in the soil plant system following the application of organic fertilizer (from different sources) is rather limited. According to these authors, the risk of K leaching is rather low given the high propensity of K ions to be adsorbed by soil particles. Johnston and Goulding (2002), quoted in Arienzo et al. (2009), report that almost all exchangeable and non-exchangeable soil sites would have to be potassium-saturated before there is a serious risk of leaching. In two regional field studies carried out in the Netherlands, Griffioen (2001) measured an increase in the potassium adsorption ratio values (ratio K+ to square root of sum of calcium, magnesium and iron (II); see Griffioen 2001 for details) in the ground waters below areas of agricultural land use as compared to pristine ground waters. These results suggest leaching of K may be taking place. Askegaard and Eriksen (2008) explain that due to a low cationic exchange capacity on coarse sandy soils, there is a potentially high risk of K losses through leaching.

Askegaard et al. (2008) measured, for spring barley crops fertilized by a KCl salt on a coarse sandy soil, leaching of K varying between approximately 21 and 36 kg/ha (values estimated from a graph). The authors calculated from their results that catch crops reduce the K leaching by 28 %.

In another study, Askegaard et al. (2003) highlight the propensity of K leaching for crops on sandy soils with less that 5 % of clay. Askegaard et al. (2003) report a study from Olesen and Vester (1995) where the K leaching losses from such soils have been estimated at 30 kg per hectare per year. The annual leaching measured by Askegaard et al. (2003) varied between 13 to 47 kg K/ha for crops (barley, grass clover and winter wheat) fertilized with manure on a coarse sandy soil (with less than 5 % clay). However, the authors highlight that a major part of the leach probably came from the straw residues. From their experimental results, Askegaard et al. (2009) significantly correlated the K leaching from crop rotations to the initial amount of exchangeable K in the soil.

Though the importance of understanding the fate of K on an agronomical perspective is recognized, K leaching towards soils and waters is not a flow affecting any of the environmental impacts categories described in the EDIP method. The fate of K (between soil and water) is therefore not considered further in this study.

12.7.5 Cu and Zn fate

It is considered that 100 % of the Cu and Zn surplus is leaching towards soil. Part of this will bind with negatively charged particles of the soil, and another part may reach the aquatic recipients, depending, among other, on soil physicochemical properties and precipitations. Hao et al. (2008) highlight that heavy irrigation or precipitation combined with intensive organic fertilisation increase the propensity for heavy metal leaching. As for P, the amount of Cu and Zn uptaked by plants is taken from Møller et al. (2000). For willow, values are taken from Mleczek et al. (2010), i.e. an average of 55.0464 mg Zn/kg and 6.0559 mg Cu/kg. These values are based on field trials, and correspond to the average of 11 different values (table 4 of Mleczek et al., 2010). For miscanthus, a value of 0.0022 g Cu/kg DM is used and 0.0301 g Zn/kg DM, based on Smith and Slater (2010).

Table 62. Estimation of Cu leaching to water recipients, soil JB3, for both residues management practices. All values for both climate types, unless otherwise specified.

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)[g]	Misc.[a,g], year 4 to 20 (autumn)	Misc.[a,g], year 4 to 20 (spring)	Maize silage	Sugar beet	Rye grass	Misc., Year 2[f,g]	Misc., Year 3[f,g]
Amount from slurry, total [A]	0.3338	0.2887	0.4397	0.3179	0.2384	0.1589	0.4291	0.3258	0.9059	0.0795	0.1589
Uptake, primary yield[b] [B]	0.013	0.013 [c]	0.011	0.064(w) 0.043(d)	0.034(w) 0.029(d)	0.022(w) 0.019(d)	0.060	0.050	0 [d]	0.012(A,w) 0.009(S,w) 0.010(A,d) 0.007(S,d)	0.020(A,w) 0.013(S,w) 0.017(A,d) 0.011(S,d)
Uptake, secondary yield[e] [C]	0.007	0.007	0.009	0	0	0	0	0.021	0	0	0
Surplus, secondary yield harvested [D] = [A-B-C]	0.3140	0.3140	0	-	-	-	-	0.2550	-	-	-
Surplus, secondary yield left on-field [E] = [A-B]	0.3210	0.2760	0.4285	0.572(w) 0.593(d)	0.205(w) 0.210(d)	0.137(w) 0.140(d)	0.3689	0.2760	0.9059	0.067(A,w) 0.071(S,w) 0.069(A,d) 0.072(S,d)	0.139(A,w) 0.146(S,w) 0.142(A,d) 0.148(S,d)
Cu leaching to water recipients, secondary yield harvested [D]	**0.3140**	**0.3140**	**0**	**-**	**-**	**-**	**-**	**0.2550**	**-**	**-**	**-**
Cu leaching to water recipients, secondary yield left	**0.3210**	**0.2760**	**0.4285**	**0.572(w)** **0.593(d)**	**0.205(w)** **0.210(d)**	**0.137(w)** **0.140(d)**	**0.3689**	**0.2760**	**0.9059**	**0.067(A,w)** **0.071(S,w)** **0.069(A,d)** **0.072(S,d)**	**0.139(A,w)** **0.146(S,w)** **0.142(A,d)** **0.148(S,d)**

on-field or no secondary yield [E]

---

[a] Misc. stems for miscanthus

[b] Cu in primary yield are taken from Møller et al. (2000): spring barley: 3 mg Cu/kg DM; winter wheat: 2 mg Cu/kg DM; silage maize: 5 mg Cu/kg DM; sugar beet: 4 mg Cu/kg DM; ryegrass: no data. To obtain the uptake in kg Cu/ha, these values are multiplied by the corresponding primary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Primary yields are taken from table 43.

[c] Since the catch crop is not harvested, there is no withdrawal of Cu considered from the catch crop.

[d] Value for durable grass ("varigt enggræs") in Møller et al. (2000). However, there is no value for Cu uptake, so a 0 value was assumed.

[e] Cu in secondary yield are taken from Møller et al. (2000): spring barley: 3 mg Cu/kg DM; winter wheat: 3 mg Cu/kg DM; sugar beet: 13 mg Cu/kg DM. To obtain the uptake in kg Cu/ha, these values are multiplied by the corresponding secondary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Secondary yields are taken from table 43.

[f] (A) if for autumn harvested miscanthus, (S) is for spring harvested miscanthus and data without this specification applied for both spring and autumn harvested miscanthus.

Table 63. Estimation of Cu leaching to water recipients, soil JB6, for both residues management practices. All values for both climate types, unless otherwise specified.

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Misc.[a], year 4 to 20 (autumn)	Misc., year 4 to 20 (spring)	Maize silage	Sugar beet	Rye grass	Misc., Year 2	Misc., Year 3
Amount from slurry, total [A]	0.3020	0.2569	0.4265	0.3179	0.2384	0.1589	0.3682	0.2702	0.8609	0.0795	0.1589
Uptake, primary yield[b] [B]	0.015	0.015[c]	0.014				0.060	0.050	0 [d]		
Uptake, secondary yield[e] [C]	0.008	0.008	0.011	0	0	0	0	0.021	0	0	0
Surplus, secondary yield harvested [D] = [A-B-C]	0.2794	0.2344	0.4016	-	-	-	-	0.1993	-	-	-
Surplus, secondary yield left on-	0.2874	0.2424	0.4129				0.3085	0.2204	0.8609		

field [E] = [A-B]											
Cu leaching to water recipients, secondary yield harvested [D]	**0.2794**	**0.2344**	**0.4016**	**-**	**-**	**-**	**-**	**0.1993**	**-**	**-**	**-**
Cu leaching to water recipients, secondary yield left on-field or no secondary yield [E]	**0.2874**	**0.2424**	**0.4129**	**0.559(w)** **0.570(d)**	**0.205**	**0.137**	**0.3085**	**0.2204**	**0.8609**	**0.012(A)** **0.009(S)**	**0.020(A)** **0.013(S)**

---

[a] Misc. stems for miscanthus

[b] Cu in primary yield are taken from Møller et al. (2000): spring barley: 3 mg Cu/kg DM; winter wheat: 2 mg Cu/kg DM; silage maize: 5 mg Cu/kg DM; sugar beet: 4 mg Cu/kg DM; ryegrass: no data. To obtain the uptake in kg Cu/ha, these values are multiplied by the corresponding primary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Primary yields are taken from table 43.

[c] Since the catch crop is not harvested, there is no withdrawal of Cu considered from the catch crop.

[d] Value for durable grass ("varigt enggræs") in Møller et al. (2000). However, there is no value for Cu uptake, so a 0 value was assumed.

[e] Cu in secondary yield are taken from Møller et al. (2000): spring barley: 3 mg Cu/kg DM; winter wheat: 3 mg Cu/kg DM; sugar beet: 13 mg Cu/kg DM. To obtain the uptake in kg Cu/ha, these values are multiplied by the corresponding secondary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Secondary yields are taken from table 43.

Table 64. Estimation of Zn leaching to water recipients, soil JB3, for both residues management practices. All values for both climate types, unless otherwise specified.

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Misc.[a], year 4 to 20 (autumn)	Misc., year 4 to 20 (spring)	Maize silage	Sugar beet	Rye grass	Misc., Year 2	Misc., Year 3
Amount from slurry, total [A]	0.7259	0.6279	0.9563	0.6913	0.5185	0.3456	0.9332	0.7086	1.9702	0.2141	0.4281
Uptake, primary yield[b] [B]	0.132	0.132[c]	0.146				0.856	0.896	0 [d]		
Uptake, secondary yield[e] [C]	0.344	0.344	0.142	0	0	0	0	0.073	0	0	0
Surplus, secondary yield harvested [D] = [A-B-C]	0.4233	0.3020	0.8965	-	-	-	-	0	-	-	-
Surplus, secondary yield left on-field [E] = [A-B]	0.7673	0.6460	1.0386				0.3004	0	2.4403		
Zn leaching to water recipients, secondary yield harvested [D]	**0.4233**	**0.3020**	**0.8965**	**-**	**-**	**-**	**-**	**0**	**-**	**-**	**-**
Zn leaching to water recipients, secondary yield left on-field or no secondary yield [E]	**0.7673**	**0.6460**	**1.0386**	**1.129(w)** **1.322(d)**	**0.183(w)** **0.252(d)**	**0.127(w)** **0.172(d)**	**0.3004**	**0**	**2.4403**		

[a] Misc. stems for miscanthus

[b] Zn in primary yield are taken from Møller et al. (2000): spring barley: 31 mg Zn/kg DM; winter wheat: 26 mg Zn/kg DM; silage maize: 71 mg Zn/kg DM; sugar beet: 72 mg Zn/kg DM; ryegrass: no data. To obtain the uptake in kg Zn/ha, these values are multiplied by the corresponding primary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Primary yields are taken from table 43.

[c] Since the catch crop is not harvested, there is no withdrawal of Zn considered from the catch crop.

[d] Value for durable grass ("varigt enggræs") in Møller et al. (2000). However, there is no value for Zn uptake, so a 0 value was assumed.

[e] Zn in secondary yield are taken from Møller et al. (2000): spring barley: 147 mg Zn/kg DM; winter wheat: 46 mg Zn/kg DM; sugar beet: 45 mg Zn/kg DM. To obtain the uptake in kg Zn/ha, these values are multiplied by the corresponding secondary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Secondary yields are taken from table 43.

Table 65. Estimation of Zn leaching to water recipients, soil JB6, for both residues management practices. All values for both climate types, unless otherwise specified.

Nutrients needs (kg/ha)	Spring barley	Spring barley & Catch crop	Winter wheat	Willow (100 % slurry)	Misc.[a], year 4 to 20 (autumn)	Misc., year 4 to 20 (spring)	Maize silage	Sugar beet	Rye grass	Misc., Year 2	Misc., Year 3
Amount from slurry, total [A]	0.8134	0.6921	1.1488	0.8562	0.6422	0.4281	0.9918	0.7278	2.3190	0.2141	0.4281
Uptake, primary yield[b] [B]	0.150	0.150[c]	0.177				0.847	0.896	0 [d]		
Uptake, secondary yield[e] [C]	0.392	0.392	0.172	0	0	0	0	0.073	0	0	0
Surplus, secondary yield harvested [D] = [A-B-C]	0.2706	0.1493	0.8000	-	-	-	-	0	-	-	-
Surplus, secondary yield left on-field [E] = [A-B]	0.6631	0.5418	0.9702				0.1448	0	2.3190		
Zn leaching to water recipients,	0.2706	0.1493	0.8000	-	-	-	-	0	-	-	-

secondary yield harvested [D]											
Zn leaching to water recipients, secondary yield left on-field or no secondary yield [E]	0.6631	0.5418	0.9702	**1.013(w)** **1.118(d)**	**0.183**	**0.127**	**0.1448**	**0**	**2.3190**	**0.049(A)** **0(S)**	**0.153(A)** **0(w)**

---

[a] Misc. stems for miscanthus

[b] Zn in primary yield are taken from Møller et al. (2000): spring barley: 31 mg Zn/kg DM; winter wheat: 26 mg Zn/kg DM; silage maize: 71 mg Zn/kg DM; sugar beet: 72 mg Zn/kg DM; ryegrass: no data. To obtain the uptake in kg Zn/ha, these values are multiplied by the corresponding primary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Primary yields are taken from table 43.

[c] Since the catch crop is not harvested, there is no withdrawal of Zn considered from the catch crop.

[d] Value for durable grass ("varigt enggræs") in Møller et al. (2000). However, there is no value for Zn uptake, so a 0 value was assumed.

[e] Zn in secondary yield are taken from Møller et al. (2000): spring barley: 147 mg Zn/kg DM; winter wheat: 46 mg Zn/kg DM; sugar beet: 45 mg Zn/kg DM. To obtain the uptake in kg Zn/ha, these values are multiplied by the corresponding secondary yields (in Mg DM/ha) and a unit conversion factor (1000 kg/Mg). Secondary yields are taken from table 43.

12.7.6 Fate of Ca from lime

Here, it is assumed that lime addition does not contribute to a net surplus in relation to plant uptake and that consequently, there are no losses towards water compartment. This assumption has a minor effect given that Ca is not considered as contributing to any environmental categories in most impact assessment methodologies.

12.8 Summary of life cycle inventory for growing cycle

Tables 74 to 81 summarize the growing cycle inventory data for all crops, on the different soil and climate type considered.

Table 66. Summary of emissions from the growing cycle: Annuals crops and rye grass on JB3, wet climate

Emissions from growing cycle	Initial soil C	Spring barley		Spring barley and catch crop		Winter wheat		Silage maize	Sugar beets		Rye-grass	Estimated uncertainty	Comments
		SR[a]	SI[a]	SR	SI	SR	SI		TR[a]	TI[a]			
Losses to air													
NH_3-N, mineral fertiliser, CAN[b] (kg/ha*y) (urea)	-	1.26 (7.56)	1.26 (7.56)	1.09 (6.54)	1.09 (6.54)	1.66 (9.96)	1.66 (9.96)	1.62 (9.72)	1.23 (7.38)	1.23 (7.38)	6.84 (35.91)	± 50 %	EF[d] based on average from literature (see text).
NH_3-N, slurry (kg/ha*y) (including losses at application)	-	12.54	12.54	10.85	10.85	16.52	16.52	16.12	12.24	12.24	39.30	Factor 2	EF based on Hansen et al. (2008) (see text)
NO_x-N (estimated as total NO-N) (kg/ha*y)	-	1.91	2.02	1.78	1.89	2.59	2.71	2.29	2.52	2.92	6.17	Factor 10	EF based on Stehfest and Bouwman (2006) and Haenel et al. (2010)
N_2-N (kg/ha*y)	-	18.75	20.24	18.08	19.58	25.78	27.41	21.67	27.70	33.37	53.29	Factor 10	Based on Haenel et al. (2010)
N_2O-N (direct, fertilisers and crop residues) (kg/ha*y)	-	1.875	2.024	1.808	1.958	2.578	2.741	2.167	2.770	3.337	5.329	Factor 3	IPCC (2006) methodology
N_2O-N (direct, from N mineralized because of soil C losses, 20 years)[c] (kg/ha*y)	Low	0.063										Factor 3	IPCC (2006) methodology
	High											Factor 3	
N_2O-N (indirect, volatilisation) [b] (kg/ha*y)	-	0.16 (0.22)	0.16 (0.22)	0.14 (0.19)	0.14 (0.19)	0.21 (0.29)	0.21 (0.29)	0.20 (0.28)	0.16 (0.22)	0.16 (0.23)	0.52 (0.81)	Factor 5	IPCC (2006) methodology
N_2O-N (indirect, leaching) (kg/ha*y)	-	0.848	0.900	0.465	0.510	0.743	0.795	0.983	0.825	1.035	1.620	Factor 3.3 (plus); factor 15 (minus)	IPCC (2006) methodology
*N_2O-N, overall, sensitivity analysis (kg/ha*y)*	-	*3.25*	*3.25*	*2.83*	*2.83*	*4.25*	*4.25*	*4.15*	*3.18*	*3.18*	*8.65*		*Based on Crutzen et al. (2008), EF=5%*
CO_2-C (lime) (kg/ha*y)	-	20.06	20.06	20.06	20.06	20.06	20.06	20.06	20.06	20.06	5.01	Minus 50 %	Based on degradation reaction (see text)
CO_2-C (urea) (kg/ha*y)	-	(27.0)	(27.0)	(23.4)	(23.4)	(35.6)	(35.6)	(34.7)	(26.4)	(26.4)	(73.3)	Minus 50 %	Based on degradation reaction (see text)
CO_2-C, soil C changes, 20 years[c] (kg/ha*20y)	Low												Modelled with C-TOOL
	High												Modelled with C-TOOL
CO_2-C, soil C changes, 100 years[c] (kg/ha*100y)	Low												Modelled with C-TOOL
	High												Modelled with C-TOOL
NMVOC (kg/ha*y)	-	0.122	0.122	0.122	0.122	0.161	0.161	0	0	0	0.452	Factor 30	Based on Haenel et al. (2010)
Losses to soil & water													
N leaching (kg N/ha*y)	-	113	120	62	68	99	106	131	110	138	216	± 60 %	Based on N-LES4 model (see text)
P leaching (kg P/ha)	-	0.357	0.463	0.357	0.463	0.786	0.139	1.567	1.059	0.219	0.998		2.5 to 5 % of surpluses
Cu leaching (kg Cu/ha)	-	0.314	0.321	0.269	0.276	0.419	0.429	0.369	0.255	0.276	0.9059		100 % of Cu surpluses
Zn leaching (kg Zn/ha)		0.423	0.767	0.302	0.646	0.897	1.044	0.300	0	0	2.4403		100 % of Zn surpluses

[a]SR: straw removal; SI: straw incorporated; TR: top removal; TI: top incorporated
[b]CAN: Calcium ammonium nitrate. In parenthesis are the values when urea is the mineral fertiliser used
[c] In parenthesis are the values for a 100 years horizon time
[d] EF: Emission factor

Table 67. Summary of emissions from the growing cycle: Perennial crops on JB3, wet climate

Emissions from growing cycle	Initial soil C	Miscanthus (autumn)			Miscanthus (spring)			Willow		Estimated uncertainty	Comments
		Year 4-20	Year 2	Year 3	Year 4-20	Year 2	Year 3	100 % slurry	100 % mineral		
Losses to air											
NH_3-N, mineral fertiliser, CAN[a] (kg/ha*y) (urea)	-	0.9 (5.4)	0.3 (1.8)	0.6 (3.6)	3.6 (0.6)	0.3 (1.8)	0.6 (3.6)	0 (0)	2.4 (14.4)	± 50 %	EF[c] based on average from literature (see text).
NH_3-N, slurry (kg/ha*y) (including losses at application)	-	8.96	2.99	5.97	5.97	2.99	5.97	23.89	0.0	Factor 2	EF based on Hansen et al. (2008) (see text)
NO_x-N (estimated as total NO-N) (kg/ha*y)	-	1.53	0.52	1.00	1.66	0.68	1.25	2.19	1.68	Factor 10	EF based on Stehfest and Bouwman (2006) and Haenel et al. (2010)
N_2-N (kg/ha*y)	-	15.76	5.40	10.26	19.69	7.71	13.84	21.76	17.19	Factor 10	Based on Haenel et al. (2010)
N_2O-N (direct, fertilisers and crop residues) (kg/ha*y)	-	1.576	0.540	1.026	1.969	0.771	1.384	2.176	1.719	Factor 3	IPCC (2006) methodology
N_2O-N (direct, from N mineralized because of soil C losses, 20 years)[b] (kg/ha*y)	Low									Factor 3	IPCC (2006) methodology
	High									Factor 3	
N_2O-N (indirect, volatilisation) [a] (kg/ha*y)	-	0.11 (0.16)	0.04 (0.05)	0.08 (0.11)	0.08 (0.11)	0.04 (0.05)	0.08 (0.11)	0.26 (0.26)	0.04 (0.16)	Factor 5	IPCC (2006) methodology
N_2O-N (indirect, leaching) (kg/ha*y)	-	0.105	0.113	0.128	0.105	0.113	0.128	0.105	0.105	Factor 3.3 (plus); factor 15 (minus)	IPCC (2006) methodology
*N_2O-N, overall, sensitivity analysis (kg/ha*y)*	-	*2.35*	*0.85*	*1.60*	*1.60*	*0.85*	*1.60*	*0.10*	*6.10*		*Based on Crutzen et al. (2008), EF=5%*
CO_2-C (lime) (kg/ha*y)	-	5.01	5.01	5.01	5.01	5.01	5.01	5.01	5.01	Minus 50 %	Based on degradation reaction (see text)
CO_2-C (urea) (kg/ha*y)	-	(19.3)	(6.4)	(12.9)	(12.9)	(6.4)	(12.9)	(0)	(51.4)	Minus 50 %	Based on degradation reaction (see text)
CO_2-C, soil C changes, 20 years[b] (kg/ha*20y)	Low										Modelled with C-TOOL
	High										Modelled with C-TOOL
CO_2-C, soil C changes, 100 years[b] (kg/ha*100y)	Low										Modelled with C-TOOL
	High										Modelled with C-TOOL
NMVOC (kg/ha*y)	-	0.437	0.158	0.262	0.286	0.115	0.172	0.481	0.481	Factor 30	Based on Haenel et al. (2010)
Losses to soil & water											
N leaching (kg N/ha*y)	-	14	15	17	14	15	17	14	14		Based on Olesen et al. (2001) (see text)
P leaching (kg P/ha)	-										2.5 % of surpluses
Cu leaching (kg Cu/ha)	-										100 % of surpluses
Zn leaching (kg Zn/ha)											100 % of surpluses

[a]CAN: Calcium ammonium nitrate. In parenthesis are the values when urea is the mineral fertiliser used

[b] In parenthesis are the values for a 100 years horizon time

[c] EF: Emission factor

Table 68. Summary of emissions from the growing cycle: Annuals crops and rye grass on JB3, dry climate[e]

Emissions from growing cycle	Initial soil C	Spring barley		Spring barley and catch crop		Winter wheat		Silage maize	Sugar beets		Rye-grass	Estimated uncertainty	Comments
		SR[a]	SI[a]	SR	SI	SR	SI		TR[a]	TI[a]			
Losses to air													
NH$_3$-N, mineral fertiliser, CAN[b] (kg/ha*y) (urea)	-	1.26 (7.56)	1.26 (7.56)	1.09 (6.54)	1.09 (6.54)	1.66 (9.96)	1.66 (9.96)	1.62 (9.72)	1.23 (7.38)	1.23 (7.38)	6.84 (35.91)	± 50 %	EF[d] based on average from literature (see text).
NH$_3$-N, slurry (kg/ha*y) (including losses at application)	-	12.54	12.54	10.85	10.85	16.52	16.52	16.12	12.24	12.24	39.30	Factor 2	EF based on Hansen et al. (2008) (see text)
NO$_x$-N (estimated as total NO-N) (kg/ha*y)	-	1.91	2.02	1.78	1.89	2.59	2.71	2.29	2.52	2.92	6.17	Factor 10	EF based on Stehfest and Bouwman (2006) and Haenel et al. (2010)
N$_2$-N (kg/ha*y)	-	18.75	20.24	18.08	19.58	25.78	27.41	21.67	27.70	33.37	53.29	Factor 10	Based on Haenel et al. (2010)
N$_2$O-N (direct, fertilisers and crop residues) (kg/ha*y)	-	1.875	2.024	1.808	1.958	2.578	2.741	2.167	2.770	3.337	5.329	Factor 3	IPCC (2006) methodology
N$_2$O-N (direct, from N mineralized because of soil C losses, 20 years)[c] (kg/ha*y)	Low											Factor 3	IPCC (2006) methodology
	High											Factor 3	
N$_2$O-N (indirect, volatilisation) [b] (kg/ha*y)	-	0.16 (0.22)	0.16 (0.22)	0.14 (0.19)	0.14 (0.19)	0.21 (0.29)	0.21 (0.29)	0.20 (0.28)	0.16 (0.22)	0.16 (0.23)	0.52 (0.81)	Factor 5	IPCC (2006) methodology
N$_2$O-N (indirect, leaching) (kg/ha*y)	-	**0.750**	**0.803**	**0.360**	**0.398**	**0.795**	**0.855**	**0.698**	**0.600**	**0.765**	**1.283**	Factor 3.3 (plus); factor 15 (minus)	IPCC (2006) methodology
*N$_2$O-N, overall, sensitivity analysis (kg/ha*y)*	-	*3.25*	*3.25*	*2.83*	*2.83*	*4.25*	*4.25*	*4.15*	*3.18*	*3.18*	*8.65*		*Based on Crutzen et al. (2008), EF=5%*
CO$_2$-C (lime) (kg/ha*y)	-	20.06	20.06	20.06	20.06	20.06	20.06	20.06	20.06	20.06	5.01	Minus 50 %	Based on degradation reaction (see text)
CO$_2$-C (urea) (kg/ha*y)	-	(27.0)	(27.0)	(23.4)	(23.4)	(35.6)	(35.6)	(34.7)	(26.4)	(26.4)	(73.3)	Minus 50 %	Based on degradation reaction (see text)
CO$_2$-C, soil C changes, 20 years[c] (kg/ha*20y)	Low												Modelled with C-TOOL
	High												Modelled with C-TOOL
CO$_2$-C, soil C changes, 100 years[c] (kg/ha*100y)	Low												Modelled with C-TOOL
	High												Modelled with C-TOOL
NMVOC (kg/ha*y)	-	0.122	0.122	0.122	0.122	0.161	0.161	0	0	0	0.452	Factor 30	Based on Haenel et al. (2010)
Losses to soil & water													
N leaching (kg N/ha*y)	**-**	**100**	**107**	**48**	**53**	**106**	**114**	**93**	**80**	**102**	**171**	± 60 %	Based on N-LES4 model (see text)
P leaching (kg P/ha)	-	0.357	0.463	0.357	0.463	0.786	0.139	1.567	1.059	0.219	0.998		2.5 to 5 % of surpluses
Cu leaching (kg Cu/ha)	-	0.314	0.321	0.269	0.276	0.419	0.429	0.369	0.255	0.276	0.9059		100 % of Cu surpluses
Zn leaching (kg Zn/ha)		0.423	0.767	0.302	0.646	0.897	1.044	0.300	0	0	2.4403		100 % of Zn surpluses

[a]SR: straw removal; SI: straw incorporated; TR: top removal; TI: top incorporated

[b]CAN: Calcium ammonium nitrate. In parenthesis are the values when urea is the mineral fertiliser used
[c] In parenthesis are the values for a 100 years horizon time
[d] EF: Emission factor
[e] In bold: flows that are different than on JB3, wet climate

Table 69. Summary of emissions from the growing cycle: Perennial crops on JB3, dry climate[d]

Emissions from growing cycle	Initial soil C	Miscanthus (autumn)			Miscanthus (spring)			Willow		Estimated uncertainty	Comments
		Year 4-20	Year 2	Year 3	Year 4-20	Year 2	Year 3	100 % slurry	100 % mineral		
Losses to air											
NH_3-N, mineral fertiliser, CAN[a] (kg/ha*y) (urea)	-	0.9 (5.4)	0.3 (1.8)	0.6 (3.6)	3.6 (0.6)	0.3 (1.8)	0.6 (3.6)	0 (0)	2.4 (14.4)	± 50 %	EF[c] based on average from literature (see text).
NH_3-N, slurry (kg/ha*y) (including losses at application)	-	8.96	2.99	5.97	5.97	2.99	5.97	23.89	0.0	Factor 2	EF based on Hansen et al. (2008) (see text)
NO_x-N (estimated as total NO-N) (kg/ha*y)	**-**	**1.48**	**0.50**	**0.97**	**1.53**	**0.64**	**1.18**	**2.07**	**1.56**	Factor 10	EF based on Stehfest and Bouwman (2006) and Haenel et al. (2010)
N_2-N (kg/ha*y)	**-**	**15.01**	**5.12**	**9.79**	**17.81**	**7.09**	**12.84**	**20.05**	**15.48**	Factor 10	Based on Haenel et al. (2010)
N_2O-N (direct, fertilisers and crop residues) (kg/ha*y)	**-**	**1.501**	**0.512**	**0.979**	**1.781**	**0.709**	**1.284**	**2.005**	**1.548**	Factor 3	IPCC (2006) methodology
N_2O-N (direct, from N mineralized because of soil C losses, 20 years)[b] (kg/ha*y)	Low									Factor 3	IPCC (2006) methodology
	High									Factor 3	
N_2O-N (indirect, volatilisation) [a] (kg/ha*y)	-	0.11 (0.16)	0.04 (0.05)	0.08 (0.11)	0.08 (0.11)	0.04 (0.05)	0.08 (0.11)	0.26 (0.26)	0.04 (0.16)	Factor 5	IPCC (2006) methodology
N_2O-N (indirect, leaching) (kg/ha*y)	**-**	**0.128**	**0.113**	**0.128**	**0.128**	**0.113**	**0.128**	**0.128**	**0.128**	Factor 3.3 (plus); factor 15 (minus)	IPCC (2006) methodology
*N_2O-N, overall, sensitivity analysis (kg/ha*y)*	-	*2.35*	*0.85*	*1.60*	*1.60*	*0.85*	*1.60*	*0.10*	*6.10*		*Based on Crutzen et al. (2008), EF=5%*
CO_2-C (lime) (kg/ha*y)	-	5.01	5.01	5.01	5.01	5.01	5.01	5.01	5.01	Minus 50 %	Based on degradation reaction (see text)
CO_2-C (urea) (kg/ha*y)	-	(19.3)	(6.4)	(12.9)	(12.9)	(6.4)	(12.9)	(0)	(51.4)	Minus 50 %	Based on degradation reaction (see text)
CO_2-C, soil C changes, 20 years[b] (kg/ha*20y)	Low										Modelled with C-TOOL
	High										Modelled with C-TOOL
CO_2-C, soil C changes, 100 years[b] (kg/ha*100y)	Low										Modelled with C-TOOL
	High										Modelled with C-TOOL
NMVOC (kg/ha*y)	**-**	**0.371**	**0.134**	**0.223**	**0.243**	**0.097**	**0.146**	**0.322**	**0.322**	Factor 30	Based on Haenel et al. (2010)
Losses to soil & water											
N leaching (kg N/ha*y)	-	**17**	**15**	**17**	**17**	**15**	**17**	**17**	**17**		Based on Olesen et al. (2001) (see text)
P leaching (kg P/ha)	-										2.5 % of surpluses
Cu leaching (kg Cu/ha)	-										100 % of surpluses
Zn leaching (kg Zn/ha)											100 % of surpluses

[a]CAN: Calcium ammonium nitrate. In parenthesis are the values when urea is the mineral fertiliser used

[b] In parenthesis are the values for a 100 years horizon time

[c] EF: Emission factor

[d] In bold: flows that are different than on JB3, wet climate

Table 70. Summary of emissions from the growing cycle: Annuals crops and rye grass on JB6, wet climate

Emissions from growing cycle	Initial soil C	Spring barley		Spring barley and catch crop		Winter wheat		Silage maize	Sugar beets		Rye-grass	Estimated uncertainty	Comments
		SR[a]	SI[a]	SR	SI	SR	SI		TR[a]	TI[a]			
Losses to air													
NH_3-N, mineral fertiliser, CAN[b] (kg/ha*y) (urea)	-	1.14 (6.84)	1.14 (6.84)	0.97 (5.82)	0.97 (5.82)	1.61 (9.66)	1.61 (9.66)	1.39 (8.34)	1.02 (6.12)	1.02 (6.12)	6.50 (34.13)	± 50 %	EF[d] based on average from literature (see text).
NH_3-N, slurry (kg/ha*y) (including losses at application)	-	11.35	11.35	9.65	9.65	16.02	16.02	13.84	10.15	10.15	37.35	Factor 2	EF based on Hansen et al. (2008) (see text)
NO_x-N (estimated as total NO-N) (kg/ha*y)	-	1.78	1.90	1.65	1.77	2.59	2.73	1.99	2.25	2.65	5.91	Factor 10	EF based on Stehfest and Bouwman (2006) and Haenel et al. (2010)
N_2-N (kg/ha*y)	-	17.70	19.41	17.04	18.75	26.10	28.07	18.91	25.20	30.87	51.27	Factor 10	Based on Haenel et al. (2010)
N_2O-N (direct, fertilisers and crop residues) (kg/ha*y)	-	1.770	1.941	1.704	1.875	2.610	2.807	1.891	2.520	3.087	5.127	Factor 3	IPCC (2006) methodology
N_2O-N (direct, from N mineralized because of soil C losses, 20 years)[c] (kg/ha*y)	Low											Factor 3	IPCC (2006) methodology
	High											Factor 3	
N_2O-N (indirect, volatilisation) [b] (kg/ha*y)	-	0.14 (0.20)	0.14 (0.20)	0.12 (0.17)	0.12 (0.17)	0.20 (0.28)	0.20 (0.28)	0.17 (0.24)	0.13 (0.19)	0.14 (0.19)	0.50 (0.77)	Factor 5	IPCC (2006) methodology
N_2O-N (indirect, leaching) (kg/ha*y)	-	1.005	1.073	0.555	0.608	0.833	0.893	0.990	0.840	1.035	1.583	Factor 3.3 (plus); factor 15 (minus)	IPCC (2006) methodology
*N_2O-N, overall, sensitivity analysis (kg/ha*y)*	-	*2.950*	*2.950*	*2.525*	*2.525*	*4.125*	*4.125*	*3.575*	*2.650*	*2.650*	*8.225*		*Based on Crutzen et al. (2008), EF=5%*
CO_2-C (lime) (kg/ha*y)	-	20.06	20.06	20.06	20.06	20.06	20.06	20.06	20.06	20.06	5.01	Minus 50 %	Based on degradation reaction (see text)
CO_2-C (urea) (kg/ha*y)	-	24.43	24.43	20.79	20.79	34.50	34.50	29.79	21.86	21.86	69.64	Minus 50 %	Based on degradation reaction (see text)
CO_2-C, soil C changes, 20 years[c] (kg/ha*20y)	Low												Modelled with C-TOOL
	High												Modelled with C-TOOL
CO_2-C, soil C changes, 100 years[c] (kg/ha*100y)	Low												Modelled with C-TOOL
	High												Modelled with C-TOOL
NMVOC (kg/ha*y)	-	0.139	0.139	0.139	0.139	0.195	0.195	0	0	0	0.400	Factor 30	Based on Haenel et al. (2010)
Losses to soil & water													
N leaching (kg N/ha*y)	-	134	143	74	81	111	119	132	112	138	211	± 60 %	Based on N-LES4 model (see text)
P leaching (kg P/ha)	-	0.253	0.373	0.253	0.373	0.000	0.148	0.649	0.873	1.092	0.182		2.5 to 5 % of surpluses
Cu leaching (kg Cu/ha)	-	0.279	0.287	0.234	0.242	0.402	0.413	0.309	0.199	0.220	0.861		100 % of Cu surpluses
Zn leaching (kg Zn/ha)		0.271	0.663	0.149	0.542	0.800	0.972	0.145	0.000	0.000	2.319		100 % of Zn surpluses

[a]SR: straw removal; SI: straw incorporated; TR: top removal; TI: top incorporated
[b]CAN: Calcium ammonium nitrate. In parenthesis are the values when urea is the mineral fertiliser used
[c] In parenthesis are the values for a 100 years horizon time
[d] EF: Emission factor

Table 71. Summary of emissions from the growing cycle: Perennial crops on JB6, wet climate

Emissions from growing cycle	Initial soil C	Miscanthus (autumn)			Miscanthus (spring)			Willow		Estimated uncertainty	Comments
		Year 4-20	Year 2	Year 3	Year 4-20	Year 2	Year 3	100 % slurry	100 % mineral		
Losses to air											
NH$_3$-N, mineral fertiliser, CAN[a] (kg/ha*y) (urea)	-	0.9 (5.4)	0.3 (1.8)	0.6 (3.6)	3.6 (0.6)	0.3 (1.8)	0.6 (3.6)	0 (0)	2.4 (14.4)	± 50 %	EF[c] based on average from literature (see text).
NH$_3$-N, slurry (kg/ha*y) (including losses at application)	-	8.96	2.99	5.97	5.97	2.99	5.97	23.89	0.0	Factor 2	EF based on Hansen et al. (2008) (see text)
NO$_x$-N (estimated as total NO-N) (kg/ha*y)	-	1.53	0.69	1.10	1.66	1.24	1.64	2.26	1.76	Factor 10	EF based on Stehfest and Bouwman (2006) and Haenel et al. (2010)
N$_2$-N (kg/ha*y)	-	15.76	7.84	11.70	19.69	15.64	19.37	22.80	18.22	Factor 10	Based on Haenel et al. (2010)
N$_2$O-N (direct, fertilisers and crop residues) (kg/ha*y)	-	1.576	0.784	1.170	1.969	1.564	1.937	2.280	1.822	Factor 3	IPCC (2006) methodology
N$_2$O-N (direct, from N mineralized because of soil C losses, 20 years)[b] (kg/ha*y)	Low									Factor 3	IPCC (2006) methodology
	High									Factor 3	
N$_2$O-N (indirect, volatilisation) [a] (kg/ha*y)	-	0.11 (0.16)	0.04 (0.05)	0.08 (0.11)	0.08 (0.11)	0.05 (0.06)	0.08 (0.11)	0.26 (0.26)	0.04 (0.16)	Factor 5	IPCC (2006) methodology
N$_2$O-N (indirect, leaching) (kg/ha*y)	-	0.128	0.113	0.128	0.128	0.113	0.128	0.128	0.128	Factor 3.3 (plus); factor 15 (minus)	IPCC (2006) methodology
*N$_2$O-N, overall, sensitivity analysis (kg/ha*y)*	-	*2.35*	*0.85*	*1.60*	*1.60*	*0.85*	*1.60*	*0.10*	*6.10*		*Based on Crutzen et al. (2008), EF=5%*
CO$_2$-C (lime) (kg/ha*y)	-	5.01	5.01	5.01	5.01	5.01	5.01	5.01	5.01	Minus 50 %	Based on degradation reaction (see text)
CO$_2$-C (urea) (kg/ha*y)	-	(19.3)	(6.4)	(12.9)	(12.9)	(6.4)	(12.9)	(0)	(51.4)	Minus 50 %	Based on degradation reaction (see text)
CO$_2$-C, soil C changes, 20 years[b] (kg/ha*20y)	Low										Modelled with C-TOOL
	High										Modelled with C-TOOL
CO$_2$-C, soil C changes, 100 years[b] (kg/ha*100y)	Low										Modelled with C-TOOL
	High										Modelled with C-TOOL
NMVOC (kg/ha*y)	-	0.437	0.158	0.262	0.286	0.115	0.172	0.576	0.576	Factor 30	Based on Haenel et al. (2010)
Losses to soil & water											
N leaching (kg N/ha*y)	-	10	12	20	10	12	20	10	10		Based on Olesen et al. (2001) (see text)
P leaching (kg P/ha)	-										2.5 % of surpluses
Cu leaching (kg Cu/ha)	-										100 % of surpluses
Zn leaching (kg Zn/ha)											100 % of surpluses

[a]CAN: Calcium ammonium nitrate. In parenthesis are the values when urea is the mineral fertiliser used

[b] In parenthesis are the values for a 100 years horizon time

[c] EF: Emission factor

Table 72. Summary of emissions from the growing cycle: Annuals crops and rye grass on JB6, dry climate[e]

Emissions from growing cycle	Initial soil C	Spring barley		Spring barley and catch crop		Winter wheat		Silage maize	Sugar beets		Rye-grass	Estimated uncertainty	Comments
		SR[a]	SI[a]	SR	SI	SR	SI		TR[a]	TI[a]			
Losses to air													
NH_3-N, mineral fertiliser, CAN[b] (kg/ha*y) (urea)	-	1.14 (6.84)	1.14 (6.84)	0.97 (5.82)	0.97 (5.82)	1.61 (9.66)	1.61 (9.66)	1.39 (8.34)	1.02 (6.12)	1.02 (6.12)	6.50 (34.13)	± 50 %	EF[d] based on average from literature (see text).
NH_3-N, slurry (kg/ha*y) (including losses at application)	-	11.35	11.35	9.65	9.65	16.02	16.02	13.84	10.15	10.15	37.35	Factor 2	EF based on Hansen et al. (2008) (see text)
NO_x-N (estimated as total NO-N) (kg/ha*y)	-	1.78	1.90	1.65	1.77	2.59	2.73	1.99	2.25	2.65	5.91	Factor 10	EF based on Stehfest and Bouwman (2006) and Haenel et al. (2010)
N_2-N (kg/ha*y)	-	17.70	19.41	17.04	18.75	26.10	28.07	18.91	25.20	30.87	51.27	Factor 10	Based on Haenel et al. (2010)
N_2O-N (direct, fertilisers and crop residues) (kg/ha*y)	-	1.770	1.941	1.704	1.875	2.610	2.807	1.891	2.520	3.087	5.127	Factor 3	IPCC (2006) methodology
N_2O-N (direct, from N mineralized because of soil C losses, 20 years)[c] (kg/ha*y)	Low											Factor 3	IPCC (2006) methodology
	High											Factor 3	
N_2O-N (indirect, volatilisation) [b] (kg/ha*y)	-	0.14 (0.20)	0.14 (0.20)	0.12 (0.17)	0.12 (0.17)	0.20 (0.28)	0.20 (0.28)	0.17 (0.24)	0.13 (0.19)	0.14 (0.19)	0.50 (0.77)	Factor 5	IPCC (2006) methodology
N_2O-N (indirect, leaching) (kg/ha*y)	**-**	**0.518**	**0.533**	**0.195**	**0.210**	**0.488**	**0.510**	**0.428**	**0.255**	**0.293**	**0.630**	Factor 3.3 (plus); factor 15 (minus)	IPCC (2006) methodology
*N_2O-N, overall, sensitivity analysis (kg/ha*y)*	-	*2.950*	*2.950*	*2.525*	*2.525*	*4.125*	*4.125*	*3.575*	*2.650*	*2.650*	*8.225*		*Based on Crutzen et al. (2008), EF=5%*
CO_2-C (lime) (kg/ha*y)	-	20.06	20.06	20.06	20.06	20.06	20.06	20.06	20.06	20.06	5.01	Minus 50 %	Based on degradation reaction (see text)
CO_2-C (urea) (kg/ha*y)	-	24.43	24.43	20.79	20.79	34.50	34.50	29.79	21.86	21.86	69.64	Minus 50 %	Based on degradation reaction (see text)
CO_2-C, soil C changes, 20 years[c] (kg/ha*20y)	Low												Modelled with C-TOOL
	High												Modelled with C-TOOL
CO_2-C, soil C changes, 100 years[c] (kg/ha*100y)	Low												Modelled with C-TOOL
	High												Modelled with C-TOOL
NMVOC (kg/ha*y)	-	0.139	0.139	0.139	0.139	0.195	0.195	0	0	0	0.400	Factor 30	Based on Haenel et al. (2010)
Losses to soil & water													
N leaching (kg N/ha*y)	**-**	**69**	**71**	**26**	**28**	**65**	**68**	**57**	**34**	**39**	**84**	± 60 %	Based on N-LES4 model (see text)
P leaching (kg P/ha)	-	0.253	0.373	0.253	0.373	0.000	0.148	0.649	0.873	1.092	0.182		2.5 to 5 % of surpluses
Cu leaching (kg Cu/ha)	-	0.279	0.287	0.234	0.242	0.402	0.413	0.309	0.199	0.220	0.861		100 % of Cu surpluses
Zn leaching (kg Zn/ha)		0.271	0.663	0.149	0.542	0.800	0.972	0.145	0.000	0.000	2.319		100 % of Zn surpluses

[a]SR: straw removal; SI: straw incorporated; TR: top removal; TI: top incorporated
[b]CAN: Calcium ammonium nitrate. In parenthesis are the values when urea is the mineral fertiliser used
[c] In parenthesis are the values for a 100 years horizon time
[d] EF: Emission factor
[e] In bold: flows that are different than on JB6, wet climate

Table 73. Summary of emissions from the growing cycle: Perennial crops on JB6, dry climate[d]

Emissions from growing cycle	Initial soil C	Miscanthus (autumn)			Miscanthus (spring)			Willow		Estimated uncertainty	Comments
		Year 4-20	Year 2	Year 3	Year 4-20	Year 2	Year 3	100 % slurry	100 % mineral		
Losses to air											
NH_3-N, mineral fertiliser, CAN[a] (kg/ha*y) (urea)	-	0.9 (5.4)	0.3 (1.8)	0.6 (3.6)	3.6 (0.6)	0.3 (1.8)	0.6 (3.6)	0 (0)	2.4 (14.4)	± 50 %	EF[c] based on average from literature (see text).
NH_3-N, slurry (kg/ha*y) (including losses at application)	-	8.96	2.99	5.97	5.97	2.99	5.97	23.89	0.0	Factor 2	EF based on Hansen et al. (2008) (see text)
NO_x-N (estimated as total NO-N) (kg/ha*y)	**-**	**1.53**	**0.52**	**0.68**	**1.66**	**1.00**	**1.25**	**2.19**	**1.69**	Factor 10	EF based on Stehfest and Bouwman (2006) and Haenel et al. (2010)
N_2-N (kg/ha*y)	**-**	**15.76**	**5.40**	**10.26**	**19.69**	**7.71**	**13.84**	**21.86**	**17.29**	Factor 10	Based on Haenel et al. (2010)
N_2O-N (direct, fertilisers and crop residues) (kg/ha*y)	**-**	**1.576**	**0.540**	**1.026**	**1.969**	**0.771**	**1.384**	**2.186**	**1.729**	Factor 3	IPCC (2006) methodology
N_2O-N (direct, from N mineralized because of soil C losses, 20 years)[b] (kg/ha*y)	Low									Factor 3	IPCC (2006) methodology
	High									Factor 3	
N_2O-N (indirect, volatilisation) [a] (kg/ha*y)	-	0.11 (0.16)	0.04 (0.05)	0.08 (0.11)	0.08 (0.11)	0.05 (0.06)	0.08 (0.11)	0.26 (0.26)	0.04 (0.16)	Factor 5	IPCC (2006) methodology
N_2O-N (indirect, leaching) (kg/ha*y)	**-**	**0.075**	**0.09**	**0.15**	**0.075**	**0.09**	**0.15**	**0.075**	**0.075**	Factor 3.3 (plus); factor 15 (minus)	IPCC (2006) methodology
*N_2O-N, overall, sensitivity analysis (kg/ha*y)*	-	*2.35*	*0.85*	*1.60*	*1.60*	*0.85*	*1.60*	*0.10*	*6.10*		*Based on Crutzen et al. (2008), EF=5%*
CO_2-C (lime) (kg/ha*y)	-	5.01	5.01	5.01	5.01	5.01	5.01	5.01	5.01	Minus 50 %	Based on degradation reaction (see text)
CO_2-C (urea) (kg/ha*y)	-	(19.3)	(6.4)	(12.9)	(12.9)	(6.4)	(12.9)	(0)	(51.4)	Minus 50 %	Based on degradation reaction (see text)
CO_2-C, soil C changes, 20 years[b] (kg/ha*20y)	Low										Modelled with C-TOOL
	High										Modelled with C-TOOL
CO_2-C, soil C changes, 100 years[b] (kg/ha*100y)	Low										Modelled with C-TOOL
	High										Modelled with C-TOOL
NMVOC (kg/ha*y)	**-**	**0.437**	**0.158**	**0.262**	**0.286**	**0.115**	**0.172**	**0.576**	**0.576**	Factor 30	Based on Haenel et al. (2010)
Losses to soil & water											
N leaching (kg N/ha*y)	**-**	**10**	**12**	**20**	**10**	**12**	**20**	**10**	**10**		Based on Olesen et al. (2001) (see text)
P leaching (kg P/ha)	-										2.5 % of surpluses
Cu leaching (kg Cu/ha)	-										100 % of surpluses
Zn leaching (kg Zn/ha)											100 % of surpluses

[a]CAN: Calcium ammonium nitrate. In parenthesis are the values when urea is the mineral fertiliser used

[b] In parenthesis are the values for a 100 years horizon time

[c] EF: Emission factor

[d] In bold: flows that are different than on JB6, wet climate

13. Harvesting

The environmental impacts from harvesting operations are modeled through the Ecoinvent process “Combine harvesting/CH U” **for spring barley and winter wheat.** This process is adjusted to consider the specific diesel consumption involved in this study. In this study, the value used is based on Dalgaard et al. (2001): 14 L diesel/ha*y (value uncorrected for soil type). This means the diesel consumption is 14 L diesel/ha*y for soil JB6 (correction factor of 1 for sandy loam) and 12.6 L diesel/ha*y for soil JB3 (correction factor of 0.9 for sandy soils). The process used from the Ecoinvent database estimates many of the emissions to air based on the diesel consumed. These were corrected accordingly, as illustrated in the case of lime.

Harvesting of **maize** is modelled through the Ecoinvent process **“Chopping, maize/CH U”,** with a diesel consumption of 35 L/ha*y for soil JB3 and of 39 L/ha*y for soil JB6. This is based on Dalgaard et al. (2001) and adjusted for soil type. Since the values in Dalgaard et al. (2001) for “chopping” are expressed in l/t, the primary yield for maize (average for soil JB3 and JB6) were used for the conversion in l/ha, considering a DM content of 31.0 %, based on Møller et al. (2000) (value for “medium content of digestible carbohydrate”). Loading the maize is included through the Ecoinvent process **“Fodder loading, by self-loading trailer/CH U”.** No changes are performed for the diesel consumption (0.106 kg/m^3 fodder). However, the process is expressed per m^3. The ecoinvent process “silage maize IP, at farm” assumed 0.004 m^3 fodder loading per kg fresh weight of silage maize. **Based on this, and on the yield data for JB3 and JB6, this would correspond to 160.65 m3/ha on JB3 and 153.94 on JB6**. (Example for JB3: 12.45 t dm/ha * kg fw/0.31 kg dm * 0.004 m^3 fodder loading/kg fw * 1000 kg/t = 160.45 m^3/ha).

For **sugar beets**, the process used is the Ecoinvent process “Harvesting, by complete harvester, beets/CH U”, with a diesel consumption adjusted to 27 l/ha (soil JB6) and 24.3 L/ha (soil JB3), based on Dalgaard et al. (2001). This includes cutting the beet tops. This is somewhat much lower than what was considered in the ecoinvent process originally, where a diesel consumption of 103 kg/ha is considered (122.6 L/ha).

Due to its high moisture content, **miscanthus harvested in autumn** is not suited for being harvested by big baling system (Kristensen, 2003). Therefore, it is considered that autumn harvest miscanthus is harvested by exact chopper, so it can be used directly in a combustion plant. The Ecoinvent process **“Chopping, maize/CH U”**, is used as a best proxy for modelling the impacts related to harvesting. The diesel consumption is adjusted based on a fuel use of 52 l/h (Smeets et al., 2009: two 75 kw tractors consuming 17 l/h of fuel each and 1 chopper consuming 18 l/h) and a net capacity of 11.4 t DM/h (Kristensen, 2003: average of the three values presented). Based on yields for autumn harvest miscanthus, the diesel consumption is therefore:

- JB6, wet and dry climate: 69.6 L/ha (year 4-20), 0 (year 2: no harvest), 25.0 L/ha (year 3);
- JB3, wet climate: 62.6 L/ha (year 4-20), 0 (year 2: no harvest), 22.5 L/ha (year 3);
- JB3, dry climate: 53.2 L/ha (year 4-20), 0 (year 2: no harvest), 19.2 L/ha (year 3)[3]

---

[3] Example for wet climate, JB6, year 4-20: 15.25 t DM/ha * h/11.4 t DM * 52 l/h *1.0 (correction factor JB6) = 69.6 L/ha.

These numbers include the correction for soil type.

The chopped miscanthus is then transported to the nearest CHP plant, without intermediate storage. This is because there is a heat demand in autumn, and the storage would require energy consumption for drying the chopped miscanthus. The density of chopped miscanthus is considered at 80 kg DM/m^3, based on Kristensen (2003). Chopped miscanthus may also be transferred to a pelletting plant where it can be pelletted and the pellets may further be used for combustion. Addition of glue or other adhesive is not necessary for pelletting miscanthus (Kristensen, 2003).

Miscanthus harvested in spring is mowed and baled by a big baler. The bale density is between 140 to 170 kg/m^3 and the power requirement is about 20.6 kW (at PTO) (Kristensen, 2003). The diesel consumption is based on a fuel use of 52.5 l/h (Smeets et al., 2009: three 75 kw tractors consuming 17 l/h of fuel each and 1 big baler consuming 1.5 l/h) and a net capacity of 13.2 t DM/h (Kristensen, 2003: average of the three values presented). Based on yields for spring harvest miscanthus, the diesel consumption is therefore:

- JB6, wet and dry climate: 39.8 L/ha (year 4-20), 0 (year 2: no harvest), 14.3 L/ha (year 3)
- JB3, wet climate: 35.8 L/ha (year 4-20), 0 (year 2, no harvest), 12.9 L/ha (year 3)
- JB3, dry climate: 30.4 L/ha (year 4-20), 0 (year 2, no harvest), 11.0 L/ha (year 3)

In order to model this process, the process **"Baling/ CH U"** from the Ecoinvent database has been used. The environmental flows involved by this process are, however, expressed per bale (instead of per ha as in this project), considering 160 kg (fresh weight) per bale (table 14.7, Nemecek and Kägi, 2007). To express the flows per ha, the primary yield as well as the moisture content are needed. Moisture content are taken from Kristensen (2003), i.e. 0.85 kg dm/kg fresh weight for spring harvest miscanthus (JB3) and 0.904 kg dm/kg fresh weight for spring harvest miscanthus (JB6). The flows inventoried in the Ecoinvent process should therefore be multiplied by:

- JB3, wet climate: 73.5 bale/ha (year 4-20) and 26.5 bale/ha (year 3)
- JB3, dry climate: 62.5 bale/ha (year 4-20) and 22.5 bale/ha (year 3)
- JB6, wet and dry climate: 69.1 bale/ha (year 4-20) and 24.9 bale/ha (year 3)

Apart from the adjustment for diesel consumption and the conversion of flows from bale based to ha based, another modification was performed to adapt the process to the present project. This consisted to take out the polyethylene wrapping foil and plastic extrusion inputs.

Harvesting of willow occurs during vegetative rest periods, i.e. in the period around November to February (Aebiom, 2008). There are different harvesting techniques (Nordh and Dimitriou, 2003) and these are constantly improving, as this is a relatively new energy crop. As for miscanthus, the Ecoinvent process **"Chopping, maize/CH U"**, is used as a best proxy for modelling the impacts related to harvesting (this basically is to reflect the tractor use and machinery use). The diesel consumption is estimated as for planting, i.e. based on Heller et al. (2003). Therefore, a consumption of 89.06 L/ha (JB3) and 98.96 L/ha (JB6) is used. A sensitivity analysis is to be performed with values from Elsayed (2003) (20.475 L/ha on JB3 and 22.75 L/ha on JB6).

When **straw** is not incorporated, the harvested field needs to be swath and then the cut straw can be bale. The process used for swathing is the Ecoinvent process **"swath, by rotary windrower/CH U",** which assumed a diesel consumption of 2.94 kg/ha. This is the value considered for JB6, and is adjusted by a factor 0.9 for JB3, meaning a diesel consumption of 2.65 kg/ha for JB3. It is the whole ha that needs to be swath.

For baling the straw, the process **"Baling/ CH U"** from the Ecoinvent database has been used. It needs to be adjusted just as described above for harvesting of spring miscanthus, i.e. by determining the number of bales per ha of the main crop. As a result, all values in the Ecoinvent process will need to be multiply by:

- Spring barley straw, JB3: 3.956 bale/ha (with or without catch crop)
- Spring barley straw, JB6: 4.508 bale/ha
- Winter wheat straw, JB3: 5.221 bale/ha
- Winter wheat straw, JB6: 6.325 bale/ha

The values above were calculated based on the straw yield and the ratio fw/dm. A factor of 0.23 has also been applied, as recommended by Nemecek and Kägi (2007) (table A.9, p.189), since it is straw bales that it is loaded and not silage bale, for what the process was originally design for.

(Example for spring barley, JB3: 2.34 t dm straw/ha *bale/160 kg fw * kg fw/0.85 kg DM * 1000 kg/t * 0.23 = 3.956 bale/ha)

The diesel consumption assumed is 0.743 kg/bale, and is not adjusted.

For loading, the Ecoinvent process "Loading bales" is used, which is also expressed per bale. The diesel consumption assumed is 0.0811 kg/bale. The transformation per ha is done as for above, but without the 0.23 factor, as recommended by Nemecek and Kägi (2007). This results to:

- Spring barley straw, JB3: 17.2 bale/ha (with or without catch crop)
- Spring barley straw, JB6: 19.6 bale/ha
- Winter wheat straw, JB3: 22.7 bale/ha
- Winter wheat straw, JB6: 27.5 bale/ha

The process used for **ryegrass harvesting** is the same as for straw, i.e. the grass is **swath and baled**, and bales are **loaded** afterwards. For baling, the number of bale per ha is:

- Rye grass, on JB3: 346.5 bale/ha
- Rye grass, on JB6: 306.25 bale/ha.

For loading bales, the same values, in terms of bale/ha, applies. (The factor 0.23 does not apply here since it is the equivalent of silage).

The harvesting of **beet tops** is considered as for common silage, i.e. bales are made from the tops (process baling) and these are afterwards loaded. For **baling**, the number of bale per ha is:

- Sugar beet top, on JB3 and JB6: 84.4 bale/ha

For loading bales, the same values, in terms of bale/ha, applies. (The factor 0.23 does not apply here since it is the equivalent of silage).

References

(this list is to be completed in next versions)

Aebiom (2008). New dedicated energy crops for solid biofuels. [Online] http://www.aebiom.org/wp/wp-content/uploads/file/Publications/Dedicated_energy_crops_for_solid_biofuels_2008_January.pdf Accessed 12.11.2010.

Beale C V and S P Long (1997). Seasonal dynamics of nutrient accumulation and partitioning in the perennial C_4-grasses miscanthus x giganteus and spartina cynosuroides. *Biomass and Bioenergy*, 12 (6), 419-428.

Bullard M J, M C Heath and P M I Nixon (1995). Shoot growth, radiation interception and dry matter production and partitioning during the establishment phase of miscanthus-sinensis giganteus grown at 2 densities in the UK. *Annals of Applied Biology*, **126 (2)**, 365-378.

Burger B and C Brauer (2007). Teil XIII Windkraft. Data v2.0. Ecoinvent report no 6-XIII. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Clancy D and F Thorne (2010). Outlook tillage 2010. Rural Economy Research Centre, January 15th. [Online] http://www.teagasc.ie/publications/2010/20100118/Outlook_2010_Tillage.pdf Accessed 30.06.2010

Dalgaard R, J Schmidt, N Halberg, P Christensen, M Thrane and W A Pengue (2007). LCA of soybean meal. *The International Journal of Life Cycle Assessment*, **13 (3)**, 240-254.

De Ruijter F J, J F M Huijsmans and B Rutgers (2010). Ammonia volatilization form crop residues and frozen green manure crops. *Atmospheric Environment*, **44**, 3362-3368.

DMI (2010). Klimanormaler for Danmark. Hele landet. [Online] http://www.dmi.dk/dmi/index/danmark/klimanormaler.htm Accessed 04.08.2010.

Dones R, C Bauer and A Röder (2007). Teil VI. Kohle. Data v2.0. Ecoinvent report no 6-VI. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

European Comission (2008). IRENA Indicator fact sheet. Irena 08 – Mineral fertiliser consumption. [Online] http://epp.eurostat.ec.europa.eu/portal/page/portal/agri_environmental_indicators/documents/IRENA%20IFS%2008%20-%20Mineral%20fertiliser%20consumption_FINAL.pdf

European Comission (2009). Eurostats. Agricultural statistics. Main results – 2007-08. European Communities. [Online] http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-ED-09-001/EN/KS-ED-09-001-EN.PDF

EMFA (2009b) http://www.efma.org/documents/Forecast2009.pdf

Faist-Emmenegger M, T Heck, N Jungbluth and M Tuchschmid (2007). Teil V Erdgas. Data v2.0. Ecoinvent report no. 6-v. Paul Scherrer Institut Villigen, Swiss Centre for life cycle inventories, Dübendorf, Switzerland.

FAO (2003). Food energy – methods of analysis and conversion factors. FAO food and nutrition paper 77. FAO, Rome, Italy. [Online] ftp://ftp.fao.org/docrep/fao/006/y5022e/y5022e00.pdf Accessed 31.07.2010.

FAOSTAT (2010). Concepts and definition. Glossary (search). Permanent meadows and pastures. [Online]. http://faostat.fao.org/site/379/DesktopDefault.aspx?PageID=379

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland (2007): Changes in Atmospheric Constituents and in Radiative Forcing. *In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Haenel H S (2010): Calculations of emissions from German agriculture. National Emission Inventory Report (NIR) 2010 for 2008. Special issue 334. Johann Heinrich von Thünen-Institut, Federal Research Institute for Rural Areas, Forestry and Fisheries (vTI), Braunschweig, Germany.

Hao X-Z, D-M Zhou, H-M Chen and Y-H Dong (2008). Leaching of cooper and zinc in a garden soil receiving poultry and livestock manures form intensive farming. Pedosphere. 18 (1): 69-76.

HGCA (2010). HGCA winter crop gross margin estimates. [Online] http://www.hgca.com/publications/documents/markets/2010_GM's.pdf

Hillier J, C Whittaker, G Dailey, M Aylott, E Casella, G M Richter, A Riche, R Murphy, G Taylor and P Smith (2009). Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. *Global Change Biology Bioenergy*, **1**, 267-281.

Hodgson E M, S J Lister, A V Bridgwater, J Clift-Brown and I S Donnison (2010). Genotypic and environmentally derived variation in cell wall composition of Miscanthus in relation to its use as a biomass feedstock. *Biomass and Bioenergy*, **34**, 652-660.

Jacobs A, R Rauber and B Ludwig (2009). Impact of reduced tillage on carbon and nitrogen storage of two Haplic Luvisols after 40 years. *Soil & Tillage Research*, **102**, 158-164.

Jungkunst H F and Freibauer A (2005). Overview on emissions observations in Europe. In: N_2O from agriculture. Report on the expert meeting on “improving the quality for greenhouse gas inventories from N_2O emissions from agricultural soils” under the mandate of the working group on annual inventories, Climate Change Committee. Luxembourg, European Communities.

Jungbluth N, Chudacoff M, Dauriat A, Dinkel F, Doka G, Faist Emmenegger M, Gnansounou E, Kljun N, Schleiss K, Spielmann M, Stettler C, Sutter J (2007): Life cycle inventories of bioenergy, Ecoinvent report no. 17; Swiss Centre for Life Cycle Inventories: Dübendorf, 2007.

KALI (2010). Granular, fine and foliate fertilisers. K+S KALI Products. Mineral fertilisers for agriculture use. Agricultural Advisory department and Sales Department K+S KALI GmbH, Kassel, Germany. [Online]. http://www.kali-gmbh.com/export/sites/kali-gmbh.com/en/pdf-broschures/en_int_fertiliser_range_A4_0804.pdf Accessed 27.05.2010

Kristensen K, J Waagepetersen, C Duus Børgesen, F Pilgaard Vinther, R Grant and G Blicher-Mathiesen (2008). Reestimation and further development in the model N-LES. N-LES_3 to N-LES_4. DJF Plant Science. 139.

Kristian Aase J (2007). Tillage systems. In Access Science, doi 10.1036/1097-8542.YB980795. The McGraw-Hill Companies, New York, USA.

Lund H, B V Mathiesen, P Christensen and J H Schmidt (2010). Energy system analysis of marginal electricity supply in consequential LCA. *International Journal of Life Cycle Assessment*, **15**, 260-271.

Møller J, R Thøgersen, A M Kjeldsen, M R Weisbjerg, K Søegaard, T Hvelplung and C F Børsting. 2000. Fodermiddeltabel. Sammensætning og foderværdi af fodermidler til kvæg. Rapport 91. Landbrugets Rådgivningscenter, lansdkontoret for kvæg, Århus, Denmark.

Nemecek T, Kägi T (2007): Life Cycle Inventory of Agricultural Production Systems. Data v 2.0 (2007). Ecoinvent report No. 15. Agrosope Reckenholz-Tänikon Research Station ART. Zürich and Dübendorf, December 2007.

Nemitz E, M A Sutton, A Gut, R San José, S Husted and J K Schjoerring (2000). Sources and sinks of ammonia within an oilseed rape canopy. *Agricultural and Forest Meteorology*, **105**, 385-404.

Nichols, M L (2007). Agricultural soil and crop practices. In Access Science, doi 10.1036/1097-8542.016000. The McGraw-Hill Companies, New York, USA.

Nielsen P H, A M Nielsen, B P Weidema, R Dalgaard and N Halberg N (2005), *LCA food database*. www.lcafood.dk. The database is available in the LCA pc-software SimaPro 7.0.

Nielsen et al. 2008 http://www.springerlink.com/content/p3r27t677m71l116/fulltext.pdf

Nordh N-E and I Dimitriou (2003). Harvest techniques in Europe. Short rotation crops for bioenergy workshop, New Zeland, p-115-120. [Online] http://www.shortrotationcrops.org/PDFs/2003Mtg/16-HarvestTechniques.pdf Accessed 12.11.2010.

O'Mahony J and O'Donovan T (2010). Crops costs and returns 2010. Teagasc agriculture and food development authority. [Online]. http://www.teagasc.ie/publications/2010/12/12_CropsCostsReturns2010Final_20jan10.pdf Accessed 30.06.2010.

Plantedirektoratet (2009): Vejledning om gødsknings-og harmoniregler. Planperioden 1. august 2009 til 31. juli 2010. Ministeriet for fødevarer, landbrug og fiskeri.

Roberts T L and W M Stewart (2002). Inorganic phosphorus and potassium production and reserves. Better Crops. 86(2): 6-7.

Rossier D (1998). Ecobilan. Adaptation de la methode écobilan pour la gestion environnementale de l'exploitation agricole. Service Romand de Vulgarisation Agricole, Lausanne, Switzerland.

Sanders B (2010). Personal communication between Uffe Jørgensen, Faculty of Agricultural Sciences, Aahrus University and Bo Sanders, DONG Energy.

Schjoerring J K and M Mattsson (2001). Quantification of ammonia exchange between agricultural cropland and the atmosphere: measurements over two complete growth cycles of oilseed rape, wheat, barley and pea. *Plant and Soil*, **228**, 105-115.

Seufert G (2005). EUROGRID. Consistency of scales with regard to Kyoto implementation. In: N_2O from agriculture. Report on the expert meeting on “improving the quality for greenhouse gas inventories from N_2O emissions from agricultural soils” under the mandate of the working group on annual inventories, Climate Change Committee. Luxembourg, European Communities.

Sinclair T (1998). Historical changes in harvest index and crop nitrogen accumulation. Crop Science, 38, 638-643.

Sommer S G, J K Schjoerring and O T Denmead (2004). Ammonia emission from mineral fertilizers and fertilized crops. *Advances in Agronomy*, **82**, 557-622.

Thorup-Kristensen K, J Magid and L Stoumann Jensen (2003). Catch crop and green manures as biological tools in nitrogen management in temperate zones. *Advances in Agronomy*, **79**, 227-302.

University of Hertfordshire (2010). http://sitem.herts.ac.uk/aeru/footprint/en/index.htm

Van Hove L W A, P Heeres and M E Bossen (2002). The annual variation in stomatal ammonia compensation point of rye grass (*Lolium perenne* L.) leaves in an intensively managed grassland. *Atmospheric Environment*, **26**, 2965-2977.

Van Zeijts H and J Reus (2005). Application of LCA for agricultural products: 4a: experiences with the methodology in the arable agriculture case. LEI-DLO, CML, Leiden, The Netherlands.

Villegas M S, M C Area and R M Marlats (2009). Caracterización de la Madera de Salix. 1: Influencia del sitio, clon, edad y altura de muestro. *Investigación agraria: Sistemas y recursos Forestales*, **18 (2)**, 192-203.