Environmental impacts of producing maize, grass-clover, grass and winter wheat based straw for biorefinery

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Abstract:

The aim of this study was to assess the environmental impacts of producing different crops: Maize, grass-clover, grass, and winter wheat based straw for biorefinery. The Life Cycle Assessments (LCA) included the following impact categories: Global Warming Potential (GWP_{100}), Eutrophication Potential (EP), Non-Renewable Energy (NRE) use, Potential Fresh Water Ecotoxicity (PFWTox) and Potential Biodiversity Damages (PBD). The results showed that GWP_{100} ($kgCO_2eq$, including soil C change) per ton of dry matter (t DM) was the highest in MZ (i.e. 273), followed by grass (242), grass-clover (234) and straw (34). The higher GWP for maize was partly due to soil C changes and nitrous oxide emissions. The PBD (PDF/ t DM) was the highest for maize (686), followed by grass-clover (117), straw (105) and grass (103). The PFWTox (CTU_e/ t DM) was the highest for maize (0.6), followed by straw (0.2) and were significantly lower in the rest of the biomass types. On the contrary, the EP (kg PO_4eq/t DM) was the highest for grass-clover (1.55), followed by maize (1.19), grass (1.16) and straw (0.21). Nitrogen and phosphorous emission at field level contributed 72%-84% of the EP. Likewise, the NRE use (MJeq/t DM) was the highest for grass (1747), followed by grass-clover (1736), maize (1511) and straw (195). This was partly related to field preparation and production of agro-chemicals processes.

Keywords: Life Cycle Assessment (LCA), biorefineries, biomass feedstocks, environmental impacts, toxicity

1. Introduction

Current sustainability goals of EU are targeted to address the energy insecurity issues and the promotion of a green growth economy through measures including (i) displacement of fossil fuels, and (ii) establishment of a strong biobased economy (Nebe, 2011). In line with this, the European Biorefinery Vision and Roadmap for 2030 (Kircher, 2012) demonstrates the importance of diversifying biomass production and supply, and thus also shows the significance of biorefineries to deliver cascades of renewable products for the growing bio-economy. Biomass as being principal input to a biorefinery, makes it relevant to assess the sustainability of producing agricultural crops and their sustainable conversion in related biorefinery value chains (Parajuli et al., 2015a).

Life Cycle Assessment (LCA) is an analytical tool to calcualte the environmental impacts of a production system (Rebitzer et al., 2004), and is one of the best available tool used in EU for the sustainability assessment of different sectors including agriculture. Few LCA studies have compared the environmental impacts in the value chain of producing several biomass feedstocks. Vellinga et al. (2013) compared environmental performance of fresh grass, grass silage and maize (silage), but focussed on Global Warming Potential (GWP), and assumed constant rate soil C change, despite in general changes in Soil Organic Carbon (SOC) mainly depend on the land use change history (Guo and Gifford, 2002). Mogensen et al. (2014) made a comparision of different types of crops, but was concentrated to assess carbon footprint. Despite the assessment of greenhouse gas balances and emissions are important, there are additional important sustainability concerns, e.g. related to the effects of agro-chemicals to the environment, potential land use change effects and biodiversity changes. Furthermore, very few studies have made distinction between different timings of emissions (Petersen et al., 2013; Schmidt and Brandao, 2013) in the assessment of carbon footprints (and LCAs). In this study, these concerns are captured. These impacts are relevant in the context of increasing demand of biomass and in their sustainable conversions (Parajuli et al., 2015b). The aim of this study thus is to assess environmental impacts of producing different biomass types: maize (MZ), grass-clover grown in crop rotation (GC), pure grass (G), Winter Wheat (WW) based straw (WW-S), as potential biorefinery feedstocks. This aim can be categorized as (i) assess and compare the related environmental impacts of producing 1 t DM of the selected biomass types until farm gate, and (ii) assess hotspots of this environmental burden.

2. Materials and Methods

2.1. Goal and scope of the study

2.1.1. System boundary and functional unit

The defined system boundary of the biomass production is illustrated in Figure 1. The functional unit of the assessment is 1 t DM of the respective biomass types. In addition, the results are precented per ha and per MJ energy content of the biomasses.

2.1.2. Environmental impact categories and assessment methods

The environmental impact categories are: Global Warming Potential-100 years perspective (GWP_{100}) (with and without contribution from soil C changes), Eutrophication Potential (EP), Non-Renewable Energy (NRE) use, Potential Freshwater Ecotoxicity (PFWTox) and Potential Biodiversity Damage (PBD). The overall assessment is carried out with the use of the computer software “SimaPRO 8.0.4” (PRé Consultants, 2015). The “EPD 2013” method (Environdec, 2015) is used to calculate the impact categories, except for the NRE use, which is calculated with the method “EPD 2008”. The models PestLCI 2.0.6 (Dijkman et al., 2012) and USEtox 2,0 (Rosenbaum et al., 2008) are jointly used to calculate the PFWTox.

Figure 1: The farm gate system boundary defined for the environmental impact assessment of biomass production.

2.2. Life cycle inventory

2.2.1. Crop production data

The crops are assumed to be grown in arable farm with Danish sandy and loamy sand soils, i.e. the soil type JB1-JB4 (NaturErhvervstyrelsen, 2015); where the clay content (< 2 µm particles) is less than 10%. The yields of maize, grass-clover and grass are based on the average Danish yields (2007-2011) (Kristensen, 2015 (a)) and for the winter wheat-grain (Oksen, 2012; Statistics Denmark, 2013) (Table 1). Straw represents 55% of the net cereal yield (Taghizadeh-Toosi et al., 2014a). For straw, 5% of the impacts assessed for winter wheat (grain and straw) per ha are economically allocated. Economic values of the grain is the main driver for the farmers, as also assumed in Mogensen et al. (2014), and the value of the straw was assumed to be the fertilizer value hereof. Types of farm machineries for the field preparation and harvesting are based on Hamelin et al. (2012) and the frequency of their operations are based on Jørgensen (2011). The production cycles for maize and winter wheat are 1 year. The rest of the biomass are with 2 years and the frequency of cuts is four times in a year (Jørgensen, 2011). Diesel consumption for the farm operations are based on Dalgaard et al. (2001).

Table 1: Input-output of the materials flow assumed for the crop production, per 1 ha

The synthetic fertilizer (N, P, K) input follows the Danish regulation (NaturErhvervstyrelsen, 2015) (Table 1). The assumed synthetic fertilizer are: N=calcium ammonium nitrate (CAN) (NPK 26.5 at plant/RER/Economic), P= triple super phosphate (RER/Economic) and K= potassium chloride (Agri-footprint, 2014). Types of pesticides and mass of active ingredients (a.is.) are based on Ørum and Samsøe-Petersen (2014), and are detailed in the Supporting Information (SI).

2.2.2. Calculation of soil carbon changes

Carbon input to the soil is calculated according to the method suggested by Petersen et al. (2013), accounting that 9.7% of the added carbon to the soil will be sequestered in 100 years. C input from the crop residues are calculated based on the residues parameters, as reported in Taghizadeh-Toosi et al. (2014a). The net C sequestration is calculated as the differences between C input from the reference crop and from the residues of the main crops. Spring barley (with 100% straw incorporated to soil) is assumed as the reference crop (Table 2).

Table 2: Carbon sequestration as a result of soil C changes between the reference crop and the production of the main crop

2.2.3. Calculation of N and P emissions

N balance method is used to calculate the N-leaching, after accounting all the N-related inputs and outputs (Table 4). Direct and indirect nitrous-oxide emission (N_2O-N) are based on emissions factors reported in IPCC (2006) (Table 3). Factors assumed for NH_3 emission from: N-fertilizer are based on reports (EEA, 2013; Nemecek and Kägi, 2007) and plants (Sommer et al., 2004) (Table 3). Denitrification is from the SimDen model (Vinther, 2005).

Table 3: Emisson factors used in the study

The C-tool model (Petersen et al., 2013) is used to calculate Soil Organic Nitrogen (SON) changes, which is as a result of changes in SOC stocks calculated after 20 years growth with the same assumed yields and corresponding plant residues (Table 2). The required C-tool parameters and values to run the model are based on Taghizadeh-Toosi et al. (2014a), but in the current study the intial SOC stock is assumed as 90 t C/ha (to the soil depth of 0-100 cm) (Taghizadeh-Toosi et al., 2014b). Detailed methods to run the model are described in Taghizadeh-Toosi et al. (2014a).

Table 4: N balances and emissions, per 1 ha

2.2.4. Toxicity assessment

Emission distribution of active ingredients (a.is) to air (f_a), surface water (f_{sw}), ground water (f_{gw}) and the degradation fraction (f_{uptake}) (Birkved and Hauschild, 2006) are calculated using the model PestLCI 2.0.6 (Dijkman et al., 2012) (see SI Table S3- Table S5). For the a.is not developed in the PestLCI2.0.6, mixing partners are choosen, decided based on SEGES (2015). For such a.is, average emission distribution fractions are calculated from the emissions simulated in different field scenarios (see SI, Table S2). Potential fresh water ecotoxicity (Hauschild et al., 2013; Henderson et al., 2011) is then calculated by multiplying the emission distribution fractions (air and surface water) with the respective comparative ecotoxicity units (CTU_e) per kg of emission. The CTU_e is expressed as $PAF.m^3.day.kg_{emitted}^{-1}$) (Rosenbaum et al., 2008), and are modelled using USEtox2.0 (Rosenbaum et al., 2008) (see SI Table S6). The toxicity impact score, as expressed as PFWTox in this study is calculated based on method as suggested in Fantke et al. (2015) and Nordborg et al. (2014).

2.2.5. Biodiversity changes

De Schryver et al. (2010) proposed the characterization factor for the arable land as: 0.44 (conventional, less intensive), 0.79 (conventional, intensive). In this study, CF are adapted from Knudsen et al. (under review), which suggested that for cereal crops in arable land (conventional-intensive) the CF is 0.68 PDF/m^2 , which are close to the global average values (de Baan et al., 2012). The CF for grass-clover (conventional) is assumed as 0.09 PDF/m^2 and similar for the grass.

3. Results and discussion

3.1. Environmental impacts

A substantial amount of C sequestration takes place with grass-clover and grass, and followed by winter wheat compared to maize (Table 5) (Figure 3.a). N_2O-N emission is found as the principal contributor to the GWP_{100} (Table 5), as also aired in the same line in Mogensen et al. (2014). GWP_{100} per MJ of biomass are insignificantly different, however the highest GWP_{100}/MJ is for grass-clover, and this is followed in the lowering order for: grass, maize and straw (Figure 2). The impact for the selected crops are differnet compared to Vellinga et al. (2013). The difference is partly because of the fact that they assumed constant level of soil C sequestration (i.e 30 kg C). Likewise, Mogensen et al. (2014) suggested that the GWP_{100} (excluding iLUC), in kg CO_2 per t DM (expressed in feed units) for maize was 307, while GC= 417, G= 512 and WW= 520. Reasons behind these differences could be explained by the following three points: (i) different amount of soil C sequestration, resulted from the differences in the yields and residues, (ii) different reference crop and whether straw is incorporated to soil, and (iii) assumed differnet types of N-synthetic fertilizers, with different characterization factors per kg of fertilizer production. Similarly, Knudsen et al. (2014) reported that the average carbon foot print for winter wheat (grown in conventional farming system) as 385 kg CO_2eq/t DM/y. Tuomisto et al. (2012) reported 401 kg CO_2eq/ t DM for winter wheat, and in the similar range in Kramer et al. (1999). Likewise, in Nemecek et al. (2011) it was 692 kg CO2eq/ t DM. Most of these studies calculated the impact per ton of grain only.

The eutrophication potential per ha is highest for winter wheat, followed in the decreasing order for: grass-clover, maize and grass (Table 5 and Figure 2). The impact is primarily related to the field based emissions (nitrate, ammonia and phosphate emissions) (Table 4), thus contributing in the range of 72-79% to the net impact. The EP/ t DM is the highest for grass-clover, followed by grass, maize and the winter wheat-straw (Figure 3.b) in lower order.

In contrast, the NRE use/t DM is higher for grass, followed by grass-clover, winter wheat and maize (Table 6 and Figure 2). The result is connected with the ratio of N-fertilizer input to biomass output (see Table 2). The total energy input for winter wheat crop and grass-clover, as suggested in Pugesgaard et al. (2015) were 13.8 and 15.7 GJ/ha/y respectively, which are fairly comparable with this study. Nemecek et al. (2011) reported that the energy demand for winter wheat production was 3.7 GJ/ t DM (equivalent to 23 GJ/ha/y).

Maize and winter wheat have higher PBD/ t DM (Table 5 and Table 6), and this can be argued as in relation to the release of higher eutrophying and toxic compounds to the environment. In spite of this, solutions to impacts related to critical load of nutrients (Hauschild and Potting, 2005) that is responsible to eutrophy the environment, involve increase in the nutrient-use efficiency per quantity of N and P added to the crop production (Dalgaard et al., 2014).

Finally, the PFWTox (CTUe/ha/y) was highest for winter wheat crop compared to rest of the crops (Table 5). With respect to the yield of the biomass, the lowest impact is however for grases, followed by straw and highest for the maize (Table 6). The reasons behind having a higher PFWTox per ha for winter wheat crop is the higher emission distribution fractions and related higher comparative ecotoxicity units for the assumed a.is (see detailed in the SI). In Nordborg et al. (2014) for maize and wheat crops the fresh water ecotoxicity was approximately 40-75 and 215 CTUe/ha/y respectively, where the applied pesticides were also significantly higher and the types of a.is were also different. The selection of the type of a.is thus found significant role to change the level of ecotoxicity impact.

Table 5: Environmental impacts of the selected crops, per 1 ha

Table 6: Environmental impacts of the selected biomass feedstocks, per t DM and per MJ of the energy content

Figure 2: Environmental impacts of producing the biomass types (GWP_{100} includes soil C change).

3.2. Environmental hotspots assessments

About 43%-61% of the gross GWP_{100} (excluding the soil C change) is due to the contribution from N_2O-N emissions. Maize, with relatively lower N_2O-N emissions (Table 4) represents the lowest range (Figure 3.a). In the same line, Knudsen et al. (2014) also reported that the effect of soil C sequestration and N_2O-N emission to the carbon foot print of cereal crops are in a significant amount. Furthermore, the contribution of N_2O-N assessed in this study is fairly comparable to Kramer et al. (1999). Nontheless, Hauggaard-Nielsen et al. (2016) suggested that the impact can be lowered by about 40-50% with the low N input system than with the high input system. In addition, the field preparation processes (see Table 1) contributed in the range of 11%-17% of the gross impact. In the case of maize the “harvesting” and “loading and handling” processes alone covered 20% of the net GWP_{100}, which is the highest, compared to rest of the crops (Figure 3.a). The production of agro-chemicals contributed in the range of 14%-21% of the gross impact for the biomasses. Transportation of assumed material inputs (seeds and agro-chemicals) contributed about 3% to the gross impact.

The field based emissions, particularly nitrate, ammonia and phosphate contributed in the range of 72%-81% of the total EP for the selected biomasses (Figure 3.b). The highest range is for grass-clover with relatively higher level of NH_3, and N_2O-N (Table 4), as the characterization factors to the EP are higher for NH_3, and N_2O-N compared to nitrate emissions (Environdec, 2015). These values, however generally depend with a number of parameters, e.g. temperature, months and methods of fertilizer application, crop rotation history and changes in soil N. Furthermore, the result may change with the adoption of the field experiment based data on nitrate leaching compared to the calculated amount. For instance, under different agro-climatic conditions the nitrate leaching for maize can be 10-214 kg N/ha/y (Manevski et al., 2015); for GC 4-21 kg N/ha for (Eriksen et al., 2004); and for WW between 42-75 kg N/ha (Elsgaard et al., 2010; Thomsen et al., 1993). The potential rate at which the impact varies because of changes in the N-leaching is 0.1 kg PO_4eq per kg of the nitrate emission (Environdec, 2015). Improvements in agricultural management practices (Martinez-Alier et al., 1998) can control the nitrate leaching and thus the eutrophication potential (McLenaghen et al., 1996).

Finally, the field preparation processes contributed about 24%-32% of the NRE use for the selected biomass production. Of this range, about 16%-72% is related to the diesel; winter wheat possessing the highest per ha (Table 1 and Table 5). Production of agro-chemicals covered 25%-47% of the net NRE use. Harvesting and the loading processes jointly contributed 16%-33% of the impact. Transportation activities contributed 8%-

11% of the net NRE use. The contribution from the seed produciton is significantly lower; however, for winter wheat it contributed 3% and 6% of the gross GWP_{100} and NRE use respectively (Table 5 and Figure 3.c).

Figure 3: Environmental impacts in related value chains of crop production.

3.3. Sensitivity Analysis

Sensitivity analyses are carried out primarily to cover the uncertainities related to GWP. The uncertainities are assessed with respect to the assumptions made in the basic scenario.

3.3.1. Effect of indirect land use change:

Impacts of the indirect land use change (iLUC) (Searchinger et al., 2008) in the occupied 1 ha of agricultural land to produce the selected crops are assessed. Considering the uncertaininties in the iLUC models (Berndes et al., 2003), in the current study two different iLUC factors are assumed. Considering the iLUC factor of 8.97 t CO_2eq/ha (Schmidt. J. H. et al., 2012), the net GWP_{100} (including soil C change) is found increased by 4-6 times, depending on the yields of the selected crops; whereas with 1.73 t CO_2eq/ha (Audsley et al., 2009) it doubled (Table 7).

3.3.2. Effect of different timings of emissions:

In contrast to the 100-years perspective, 19.8% of C is sequestered in a 20 years (Petersen et al., 2013), thus the level of C sequestration is doubled (Table 7), as also argued in same line in Knudsen et al. (2014).

3.3.3. Effect of changing the type of N-fertilizer:

Instead of the CAN (as assumed in the basic scenario), if the "N fertilizer, as N (GLO) market for Alloc Def, U" (Weidema et al., 2013) is assumed, the net GWP_{100} is increased by two-fold for the selected crops (Table 7).

3.3.4. Consequential behaviour of straw removal:

The consequences of removing straw, instead of ploughing back to field (Petersen and Knudsen, 2010) are generally argued in two major areas: (i) displacement of nutrient (N,P,K) (Nguyen et al., 2013; Schmidt and Brandao, 2013) and (ii) loss of soil organic carbon (Dick et al., 1998). In this context, assuming that 30% of the N and 100% for P and K contents of straw are available to crop (Nguyen et al., 2013), the removal of straw would add 9 kg CO_2eq/t DM. Likewise, the avoidance of soil C sequestration is 139 kg CO_2eq/t DM of the straw removed (Table 7). This is in the similar range as reported in Petersen and Knudsen (2010) and Parajuli et al. (2014).

Table 7: Senstivity analysis with respect to the basic scenario

4. Conclusion and perspectives

The net GWP_{100} (including soil C change) and the gross impact (excluding the soil C change) were respectively, 234 vs 361 kg CO_2eq/t DM/y in grass-clover, 242 vs 385 kg CO_2eq/t DM/y in grass and 34 vs 39 in straw. Meanwhile in maize it was 273 kg CO_2eq and 231 kg CO_2eq with and without soil C changes. N_2O-N emission was the major contributor to the GWP_{100}, covering 43%-61% of the gross impact. Eutrophication potential was lowest for winter wheat straw (0.21 kg PO_4/t DM). The higher eutrophication potential is connected with the biomass having higher N related emissions. Field based emissions (realted to N and P) contributed in the range of 78-81% to the total EP. Farm operations contributed about 41%-61% of the total NRE use. About 25%-47% of the NRE use was related to the production of agro-chemicals. PFWTox related to straw was lower than maize, but higher than grass and grass-clover. Finally, the PBD was the highest for maize, followed by grass clover, straw and grass.All the biomasses assessed here can serve as animal feed and thus their respective impacts can be accounted with respect to their feed units. This opens avenues to compare them from the different conversion perspectives: fuel vs. food or feed. It is thus relevant to aptly connect the environmental burden of biomass production with the impacts of producing renewable products from biorefineries, as the biomass selected are suitable in different biorefinery product platforms. In further studies, we thus expect to integrate the environmental impacts of producing biomass until farm gate level with the impacts of biomasses conversions in related biorefinery platforms.

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Table 1: Input-output of the materials flow assumed for the crop production, per 1 ha

Particulars	Unit	Amount				Comments/Remarks
		Maize	Grass-clover	Grass	Winter wheat	
Inputs						
Land (ha.a)	ha-a	1	1	1	1	ha.a = hectare of land in a year
Seed[a]	kg seed ha^{-1}	13	8	9	179	
Synthetic fertilizer	kg ha^{-1}					Section 2.2.1
N		141	193[b]	279[b]	144	
P_2O_5		103	76	73	44	
K_2O		165	394	490	86	
Lime	kg ha^{-1}	167	84	84	167	(Hamelin et al., 2012)
Pesticides	kg ha^{-1}	0.21	0.03	0.03	1.72	
Direct primary energy input	MJ ha^{-1}	4955	3555	3594	3126	as diesel (a + b)
a. Field preparation[c]	MJ ha^{-1}	3064	1984	1984	2135	
b. Harvesting + loading and handling[d]	MJ ha^{-1}	1891	1571	1610	992	
c. Transport	t km					(Weidema et al., 2013)
- seeds[e]	t km	2.5	1.6	1.8	35.8	
- agro-chemicals[f]	t km	95	149	186	89	
- biomass (field to farm)[g]	t km	30	23	26	27	
d. Drying						(Kristensen and Grundtoft, 2003)
- Electricity	kWh ha^{-1}	-	-	-	111	
- Heat	MJ ha^{-1}	-	-	-	364	
Output						
Net biomass yield	t DMy^{-1}	9.91	7.71	8.75	9.1	
Net biomass yield[h]	kg N $ha^{-1}y^{-1}$	204	231	119	204	
Net biomass yield[i]	GJ $ha^{-1}y^{-1}$	161	125	142	52*	

[a] Seed quantity after Hamelin et al. (2012). (DM content based on Thøgersen and Kjeldsen (2014)).

- MZ (kg seed/ha) = $4.4*10^{-4}$ kg per kg (wet) primary yield (PY) * kg PY/0.347 kg DM * t DM yield * 10^3 kg DM/ha.
- GC: (kg seed/ha) = $3.7*10^{-4}$ kg per kg (wet) PY * kg PY/0.35 kg DM * t DM yield * 10^3 kg DM/ha. Proportion of grass: clover (80:20) assumed for the seed mass.
- G: similar to GC (100 % of the grass-seed).
- WW: $2.6*10^{-4}$ kg per kg (wet) PY* kg PY/0.85 kg DM * t DM yield.

[b] N-fertilizer: GC and G = N-norm – reduced quota (40.5 kg N/ha/y) in the crop following the grasses (Kristensen, 2015, pers.comm.).

[c] Includes tillage and application of agro-chemicals. Heating value of diesel= 35.95 MJl^{-1}, Density= 0.84 kg/l (Weidema et al., 2013).

[d] Calculation for the loading and handling :

[†] Baling WW-S= DM of straw/ha * bale/160 kgfw/0.85 kg DM *1000 kg/t * 0.23 (Hamelin et al., 2012) = 5 bales/ha. Diesel = 0.743 kg/bale

[ρ] Bale loading= (Number of bales/ha /0.23) * 0.0811 kg/bale (Hamelin et al., 2012) = 3 l/ha.

[↓] Loading for MZ, GC and G= 0.119 lm^{-3} fodder (Møller et al., 2000). Fodder (m^3) = DM/ha * kgfw/DM% * 0.004 m^3 fodder loading/kgfw *1000 kg/t (Hamelin et al., 2012). Loading for WW is for the grain only.

[e] Mass of seed * distance (= 200 km) (Parajuli et al., 2014).

[f] Fertilizer + lime + pesticides) * distance (200 km)

[g] t DM * 3 km. Distance assumed, as in Mogensen et al. (2014).

[h] Crude N content (% DM)= MZ=7.9; GC and G= 16.5 (average of years 2000-2013, based on (Møller et al., 2005a); Thøgersen and Kjeldsen (2015); WW= 10.9 and WW-S= 3.3. average of years 2007-2013, based on reports (Møller et al., 2012; Møller and Sloth, 2013, 2014; Vils and Sloth, 2003)).

[i] Lower heating value (MJ/kg): MZ= 19 (FORCE Technology, 2010), GC=11.8 (Jørgensen et al., 2008), G=16 (Fødevareministeriet., 2008), WW-S= 15.01(Nielsen, 2004). * Values represent for WW-S.

Table 2: Carbon sequestration as a result of soil C changes between the reference crop and the production of the main crop

Parameters/Crop types	Unit	Maize	Grass-clover	Grass	Winter wheat	Barley[a]
Biomass yield	t DM/ha/y	9.91	7.71	8.75	5.87 (grain)	4.01
Straw (100% removed, excluding barley)	t DM/ha/y	-	-	-	3.23 (straw)	2.24
Total available non-harvestable residues						
Plant growth, total[b]	t DM/ha/y	13.72	20.04	22.73	17.38	10.44
Root[b]	t DM/ha/y	2.06	9.02	10.23	4.33	1.77
Stubble, chaff, straw left in the field[c]	t DM/ha/y	1.75	3.31	3.75	3.91	4.58
Total plant residues[d]	t DM/ha/y	3.81	12.32	13.98	8.25	6.36
Plant residues N[e]	kg N/ha/y	36	264	300	75	52
C input from DM from the crop residue[f]	kg C/ha/y	1751	5668	6429	3794	2924
C input (sequestered) compared to the reference crop[g]	kg C/ha	-1173	2744	3505	870	-
C sequestration (100-years)[h]	kg CO_2/ha/y	-417	976	1247	310	-

Assumptions:

[a] 100% of the straw for Barley incorporated to the soil.

[b] Harvest index (alpha) and root mass (beta) of the selected main crop relative to above ground residues are based on Taghizadeh-Toosi et al. (2014a).

[c] Calculated as: Total plant residues - root residues.

[d] Total Plant residues = Crop yield * Parameter† for stubble+root/(net yield). Parameter†: MZ (0.384), GC and G (1.597), WW (1.406) (Mikkelsen et al., 2011).

[e] Calculated from the "Total plant residue", see footnote [d]). Norms of crude protein (% DM) in (stubble/straw, root), respectively = MZ (7.7, 3.8); GC (16.8, 14.7); G (16.2, 14.7); WW and Barely (10.6, 3.3) (Mikkelsen et al., 2011).

[f] Calculated from the total C assimilation (Taghizadeh-Toosi et al., 2014a).

[g] C input from the main crops minus C input from the reference crop.

[h] 9.7% of the C_{input} (sequestered) (Petersen et al., 2013) * mol.weight of CO_2 to C (44/12).

Table 3: Emisson factors considered in the study

Parameters	Pollutants	Unit related	Emission factors/values	Reference
kg NH_3-N	N-fertilizer volatilization	kg N/ha/y	0.02	(EEA, 2013; Nemecek and Kägi, 2007);
kg NH_3-N	Plant	kg N/ha residues[a]	2 (cereals) 0.5 (grasses)[b]	(Sommer et al., 2004).
NO_x-N: NH_3-N[c]			12:88	(Schmidt and Dalgaard, 2012)
N_2O-N_{direct}	Synthetic N Crop residues[d]	kg N/ha kg N/ha	0.01 0.01	(IPCC, 2006)
N_2O-$N_{indirect}$	From leaching From NH_3	kg NO_3-N kg NH_3-N	0.0075 0.01	(IPCC, 2006)
P-uptake by plant[e]	MZ WW GC and G	g P/kg DM g P/kg DM g P/kg DM	2.6 2.8† and 0.9†† 4	(Hamelin, 2011; Møller et al., 2000)
P losses[f]	All crops	Surplus[f], g P/ha	0.05	(Nielsen and Wenzel, 2007)

[a] See kg N/ha from residues (Table 2).

[b] NH_3 emission for grasses: average of summer and spring application for grasses) (Hansen et al., 2008).

[c] NO_x-N = (NO+NO_2), where NO_2 is assumed to be negligible, and calculated as NO_x-N: NH_3-N.

[d] fraction of total area under crop that are renewed every 2 years ($Frac_{renew}$) = 0.5 (IPCC, 2006) is multiplied to the N_2O-N_{direct} emission from the crop residues.

[e] P-uptake by plant in WW are respectively for the † primary and ††secondary yields.

[f] P surplus = P-input from fertiliser minus P uptake by plant.

Table 4: N balances and emissions, per 1 ha

Particulars	Unit	Amount				Comments/Remarks
		Maize	Grass-clover	Grass	Winter wheat	
Total N-input[a]	kg N $ha^{-1}y^{-1}$	157	288	294	208	
Output	kg N $ha^{-1}y^{-1}$	125	204	231	119	Table 2
Field balance	kg N $ha^{-1}y^{-1}$	32	84	63	89	N_{input}-N_{output}
N losses	kg N $ha^{-1}y^{-1}$					
NH_3-N		4.8	4.4	6.1	4.9	Emission factors in Table 3
NOx-N		0.7	0.6	0.8	0.7	Emission factors in Table 3
Denitrification		6.2	9.8	13.3	8.1	(Vinther, 2005).
Soil change, N	kg N $ha^{-1}y^{-1}$	-17	25	33	5	see section 2.2.3
Potential leaching	kg N $ha^{-1}y^{-1}$	37	44	9	70	Field balance – losses
Total N_2O-N losses (direct +indirect)	kg N $ha^{-1}y^{-1}$	2.1	3.6	4.4	2.8	Emission factors in Table 3
P losses	kg P $ha^{-1}y^{-11}$	2.2	1.6	1.6	0.9	Emission factors in Table 3

Assumptions:

[a] Total N-input = F_{SN} + $N_{fixation}{}^{\rho}$ + $N_{deposition}{}^{\dagger}$ + $N_{seed}{}^{\pm}$.

[ρ] $N_{fixation}$ GC = 80 kg N/ha/y (Høgh-Jensen and Kristensen, 1995).

[†] N deposition = 15 kg Nha^{-1} (Ellermann et al., 2005)

[±] N_{seed} (kg N/ha/y) = 1 (MZ); 0.2 (GC); 0.2 (G); 49 (WW), based on Farm-N model (Jorgensen et al., 2005).

Table 5: Environmental impacts of the selected crops, per 1 ha

Environmental impacts	Units	Maize	Grass-clover	Grass	Winter wheat
Net GWP_{100}, including soil C change	kg CO_2eq/ha	2710	1805	2119	2214
Net GWP_{100}, excluding soil C change	kg CO_2eq/ha	2293	2782	3366	2524
GWP related to N_2O-N emission	kg CO_2eq/ha	983	1686	2060	1311
GWP related to diesel consumption[a]	kg CO_2eq/ha	93	67	67	59
EP	kg PO_4 eq/ha	11.8	11.9	10.1	14.6
NRE use	GJeq/ha	14.97	13.38	15.28	13.4
- related to diesel consumption[a]	GJeq/ha	9	7	7	6
PBD	PDF/ha	6800	900	900	6800
PFWTox	CTU_e/ha	6	0.16	0.16	116

[a] Diesel consumption related to field preparation + harvesting and loading and handling (Table 1).

CF for 1 kg diesel: GWP_{100} = 0.57 kg CO_2eq; NRE Use = 56.6 MJeq (Weidema et al., 2013))

Table 6: Environmental impacts of the selected biomass feedstocks per t DM and per MJ

Environmental impacts	Unit	Maize	Grass-clover	Grass	Winter wheat-straw
Net GWP_{100}, including soil C change	kg CO_2 eq/t DM	273	234	242	34
	kg CO_2 eq/MJ	0.017	0.017	0.017	0.002
Net GWP_{100}, excluding soil C change	kg CO_2 eq/t DM	231	361	385	39
	kg CO_2 eq/MJ	0.01	0.03	0.03	0.003
EP	kg PO_4 eq/t DM	1.19	1.55	1.16	0.21
	kg PO_4 eq/MJ	$7.3*10^{-5}$	$1.1*10^{-4}$	$8.4*10^{-5}$	$1.4*10^{-5}$
NRE Use	MJeq/t DM	1511	1736	1747	195
	MJeq/MJ	0.09	0.12	0.13	0.01
PBD	PDF/t DM	686	117	103	105
	PDF/MJ	0.04	0.01	0.007	0.002
PFWTox	CTU_e/t DM	0.6	0.02	0.02	0.2
	CTU_e/MJ	$3.7*10^{-5}$	$1.5*10^{-6}$	$1.3*10^{-6}$	$1.3*10^{-5}$

Table 7: Senstivity analysis with respect to the basic scenario

Scenarios	Maize	Grass-clover	Grass	Winter wheat-straw
Basic scenario:				
Net GWP_{100} (including soil C change), kg CO_2eq /t DM	274	232	241	35
Soil C sequestration (100 years), kg CO_2eq /t DM	-417	976	1247	15
Changed assumptions:				
a. Net GWP_{100}: including soil C change (kg CO_2eq/t DM)				
- iLUC factor (Audsley et al., 2009)	448	459	440	61
- iLUC factor (Schmidt. J. H. et al., 2012)	1179	1396	1266	178
b. Net GWP_{100} (including soil C change): use of N fertilizer (kg CO_2eq/t DM)	428	544	619	22
c. Soil C sequestration in 20-years perspective (kg CO_2eq/t DM)	-86	258	291	1[a]
d. Impact of removing 1 t DM of straw (kg CO_2eq/tDM straw removed)	-	-	-	148
(i) Avoided soil C sequestration[b]	-	-	-	139
(ii) Fertilizer compensation[c]	-	-	-	9[d]
- *N*				*2.7*
- P_2O_5				*0.9*
- K_2O				*5.1*

[a] Value for winter wheat crop is 632 kg CO_2eq/ha.

[b] Soil C sequestration = C content in straw (Taghizadeh-Toosi et al., 2014a) * 0.85 * emission reduction potential (Petersen et al., 2013) = 0.46*1 t*0.85*9.7% = 38.99 kg C = 139 kg CO_2-eq.

[c] Compensation based on nutrient content in the removed straw, elemental compositon of straw are based on Møller et al. (2005b):

- N = 30% * Total N in straw (Nguyen et al., 2013) = 30%* 0.6% * 1 t * 0.85.
- P_2O_5 = kg P in straw * Ratio of mol. wt) = 0.09% * 1 t straw * 0.85 * (142/62)= 1.75 kg
- K_2O = Kg of K in 1 t of straw (85% DM) * (Ratio of mol. wt) = 1.5% * 1 (kg) * 0.85 * (94/78) = 15.36.

[d] Characterization factors (kg CO_2eq)

- 1 kg CAN (NPK 26.5 at plant/RER/Economic) = 1.75(Agri-footprint, 2014).
- 1 kg P_2O_5 (Triple super phosphate/RER/Economic) = 0.55 (Weidema et al., 2013).
- 1 kg K_2O (Potassium chloride/RER/Alloc, Def/U) = 0.33 (Weidema et al., 2013).

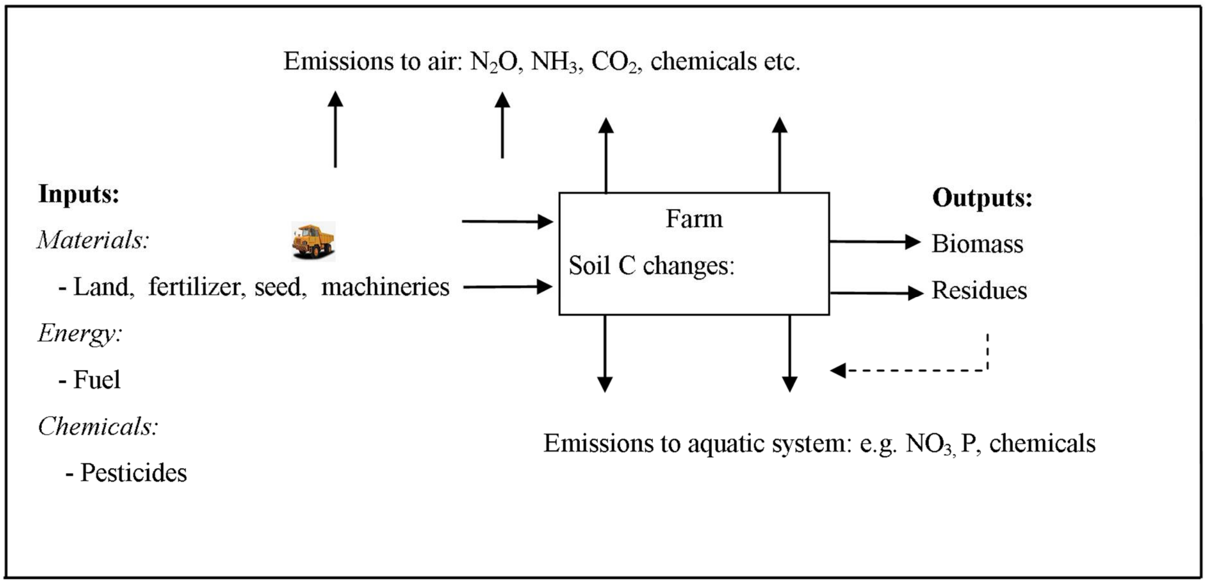
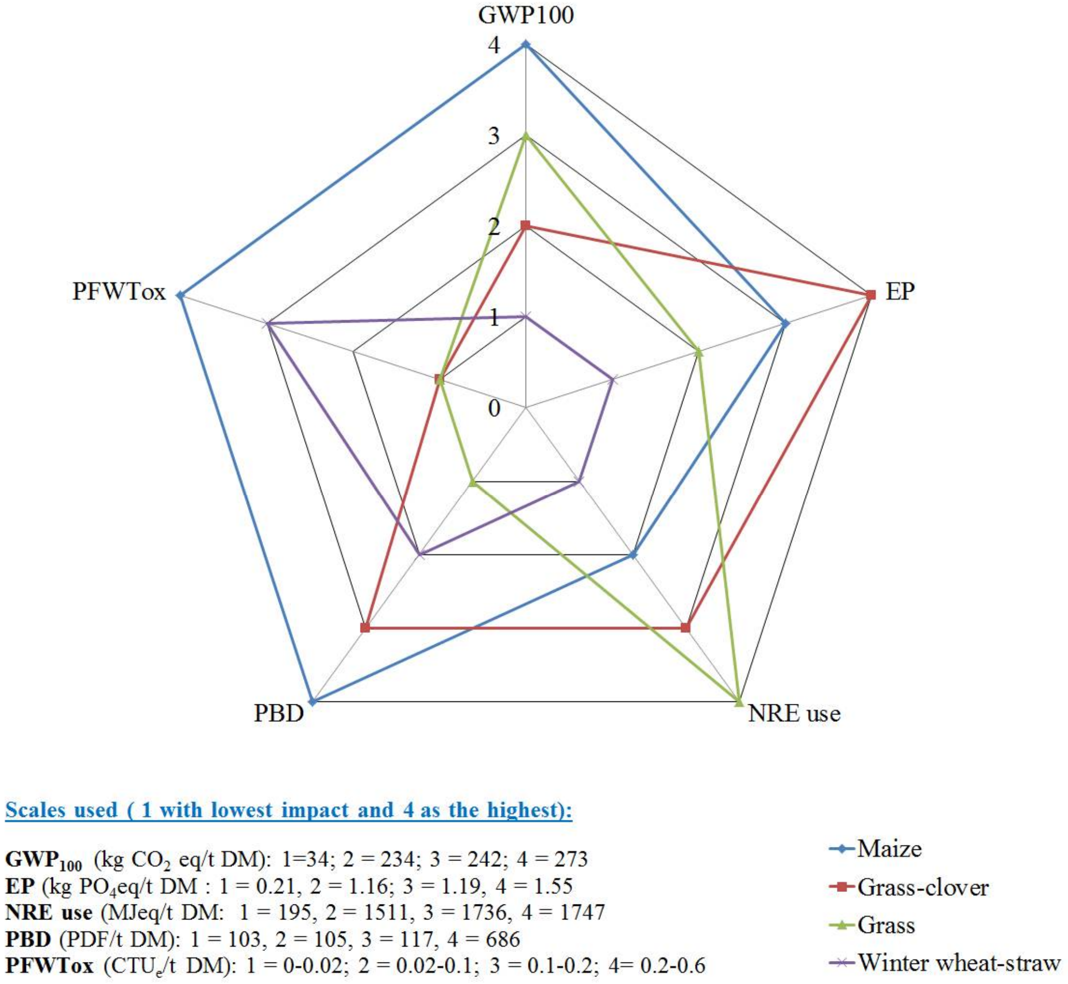


Figure 1: The farm gate system boundary defined for the environmental impact assessment of biomass production**.**



Scales used (1 with lowest impact and 4 as the highest):

GWP$_{100}$ (kg CO_2 eq/t DM): 1=34; 2 = 234; 3 = 242; 4 = 273
EP (kg PO_4eq/t DM : 1 = 0.21, 2 = 1.16; 3 = 1.19, 4 = 1.55
NRE use (MJeq/t DM: 1 = 195, 2 = 1511, 3 = 1736, 4 = 1747
PBD (PDF/t DM): 1 = 103, 2 = 105, 3 = 117, 4 = 686
PFWTox (CTU$_e$/t DM): 1 = 0-0.02; 2 = 0.02-0.1; 3 = 0.1-0.2; 4= 0.2-0.6

1

Figure 2: Environmental impacts of producing the biomass types (GWP$_{100}$ includes soil C change).

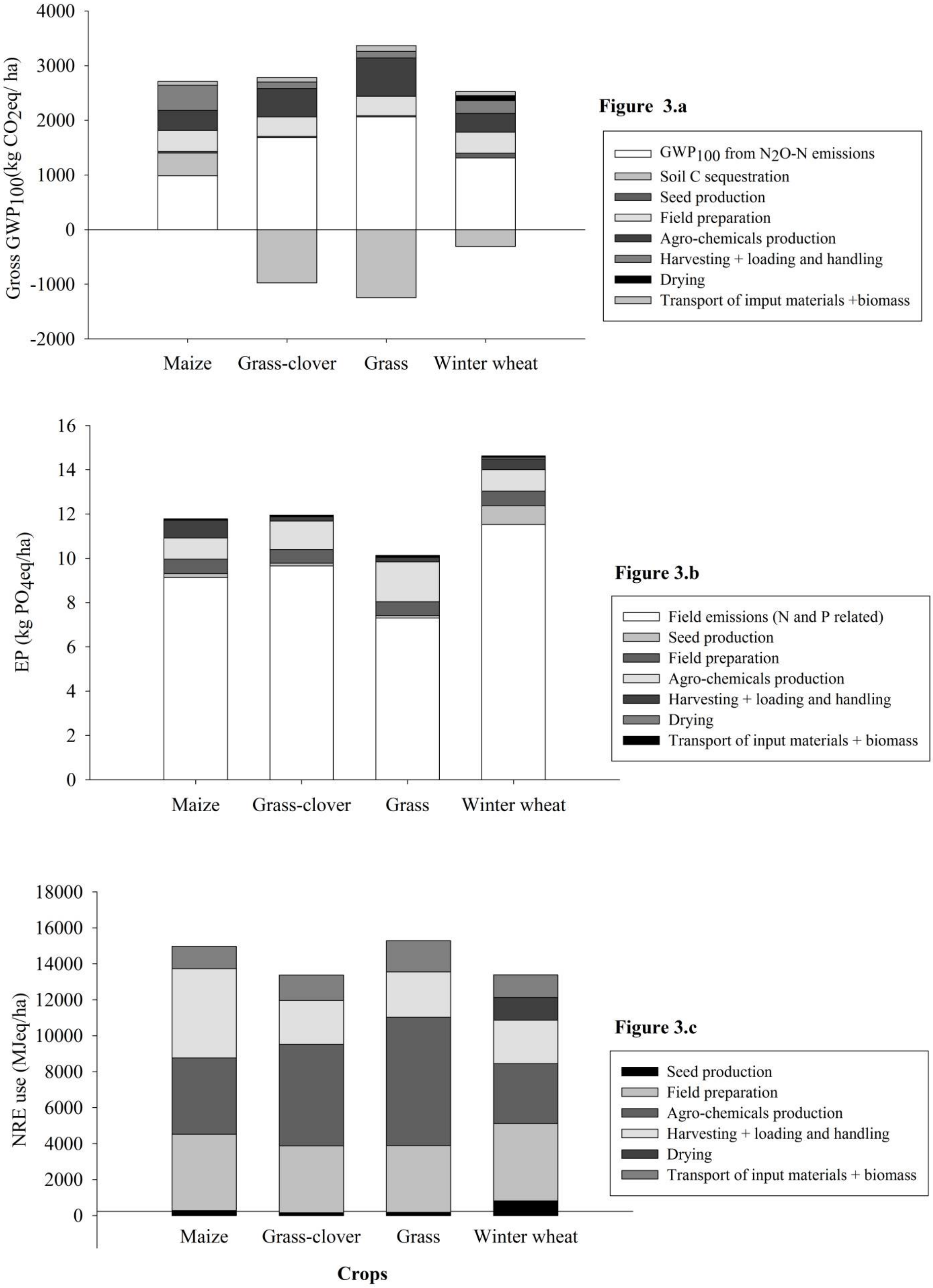


Figure 3: Environmental impacts in related value chains of crop production.