What is the most sustainable biomass supply mix for bioethanol production? Example of the Burgundy region in France

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ABSTRACT

Large uncertainties in the life-cycle greenhouse gas (GHG) emissions of biofuels could offset their potential savings. These arise from the difficulty in taking into consideration land use change effects and N_2O emissions, which are strongly dependent on local pedoclimatic conditions and technological options for feedstock cultivation. Here, we used an crop model (CERES-EGC) to simulate crop growth and C-N dynamics in the cultivation fields at the regional scale for a wide range of lignocellulosic feedstocks. Bioethanol made from cereal straw achieved the largest GHG reduction compared with fossil fuels (at 74%). Among the dedicated energy crops investigated, Miscanthus had the highest GHG abatement potential, ranging from 63 to 72% depending on crop management. A combination of feedstock sources (straw, Miscanthus and triticale) stroke the best compromise to fulfill sustainability criteria, secure the supply and limit the pressure on land and competition with food.

Keywords: lignocellulosic biomass, 2[nd] generation (2G) bioethanol, emission modeling, Miscanthus, greenhouse gas (GHG)

1. Introduction

Following its ratification of the Kyoto protocol, the European Commission set up directives to promote the development of biofuels in the transport sector, with a 10% target for the share of renewable fuels by 2020. Sustainability criteria were also introduced for conversion units coming onto the market after 2017, to ensure a minimum greenhouse gas (GHG) abatement of 60% compared to fossil equivalents (European Parliament 2009a; European Parliament 2009b). Biofuels are currently produced from agricultural sources. The agricultural sector, however, represents 15% of French GHG emissions, and 89% of N_2O emissions (CITEPA 2013). N_2O shows a high global warming potential (GWP), 298 higher than CO_2 (IPCC 2007). It is thus essential to accurately estimate GHG emissions from biomass crops to supply bioethanol conversion units.

Life cycle assessment (LCA) is an objective and holistic tool, commonly used to estimate the environmental impacts of biofuels. Whereas the uncertainty band in the GHG balance of fossil fuels typically amounts to 4 g CO_2 eq MJ^{-1}, it can be 2.5 to 10 times higher for first generation (1G) biofuels (10 to 40 g CO_2 eq MJ^{-1}) (Edwards et al. 2011) and not estimated for second generation (2G) biofuels due to the lack of data. Even if guidelines have been proposed (ADEME 2010), the methodology for GHG accounting lacks consensus on two crucial aspects: N_2O emissions and land use change (LUC) effects. Both of them could offset the conclusions on GHG savings (Searchinger et al. 2008; Hoefnagels et al. 2010; Cherubini and Strømman 2011; Smith and Searchinger 2012). In most cases, LUC is ignored or minimized, but recent studies encourage the integration of this factor within the biofuel sustainability criterion (ADEME 2012; De Cara et al. 2012; European Parliament 2012). N_2O emissions are mostly calculated from IPCC generic factors without considering any local pedoclimatic variations, which generates large uncertainties (Hoefnagels et al. 2010; Smith and Searchinger 2012).

As shown in recent publications (Dufossé et al. 2013), crop modelling can overcome these problems by a better consideration of local soil and climate variations and their effects on yield and GHG emissions. Combined with scenarios of bioenergy crop establishment, crop modelling makes it possible to define multi-sources feedstock supply scenarios and minimize GHG emissions from biofuel feedstocks. Whereas it is now obvious that the GHG abatement potential of 1G biofuels is limited (ADEME 2010; ADEME 2012; Humpenöder et al. 2013), 2G biofuels are still under technological development and their feedstock (lignocellulosic biomass) remains to be fully evaluated. In particular, different types of feedstock have to be compared to define the most reliable and sustainable mix for a given conversion unit.

The aim of this paper is thus to evaluate feedstock supply scenarios, through a LCA, for a unit of production of 2G bioethanol, considering field emissions, agricultural operations, agricultural input (fertilizers, pesticides, herbicides) manufacturing, as well as input and biomass transportation.

2. Methods

2.1. Crop modeling

Regional modeling was based on the crop model CERES-EGC (Gabrielle et al. 2002). The model requires meteorological and management data as forcing variables, as well as soil and vegetation data as input factors and runs at a daily time step. CERES-EGC comprises a physical sub-model which simulates the transfer of heat, water and nitrate down the soil profile, as well as soil evaporation, plant water uptake and transpiration in relation to climatic demand (Gabrielle et al. 2002). A biological sub-model simulates the growth and phenology of the crops and a microbiological sub-model simulates the turnover of organic matter in the ploughed layer. Direct field emissions of CO_2, N_2O, NO and NH_3 into the atmosphere are simulated with different trace gas modules (Lehuger et al. 2009; Lehuger et al. 2010). The nitrous oxide emission module simulates the production of N_2O in soils through both the nitrification and denitrification pathways. N_2O emissions resulting from both processes are soil-specific and are proportions of total denitrification and nitrification (Lehuger et al. 2009). CO_2 exchanges between the soil-plant system and the atmosphere are modeled from net photosynthesis and soil organic carbon (SOC) mineralization (Lehuger et al. 2010).

Soil input factors include physical properties, soil texture characteristics and biological parameters for nitrification and denitrification processes. At regional scales, these inputs are inferred from the 1:1 000 000 soil map of the European soil map, in which the twenty soil classes occurring in France were reduced to fourteen main soil types after an aggregation based on their characteristics (Dufossé et al., 2013). The model was run on simulation units (SU) defined by overlaying the soil map with geo-referenced databases on meteorology, land cover, administrative borders and crop management, as detailed in Dufossé et al. (2013). The area of the SU varied from 2.5 ha to 30 000 ha, with a median value of 1 210 ha. Administrative borders of regions and departments were given by IGN-GEOFLA and InfoSIG Cartographie (2010) and were used to determine crop management by deriving regional statistics (Agreste 2008). Corine Land Cover dataset (European Environment Agency 2006) provided the detailed area of utilizable agricultural land (UAL) within each SU, broken down into arable lands, fragmented lands and grassland areas. Meteorological datasets were provided on a 8km-mesh (SAFRAN grid, (Pagé et al. 2009)), each SU being associated to the closest grid point. The results presented in this paper at regional supply-area levels resulted from the weighted means of individual results from the SU involved.

2.2. Study domain and system boundaries

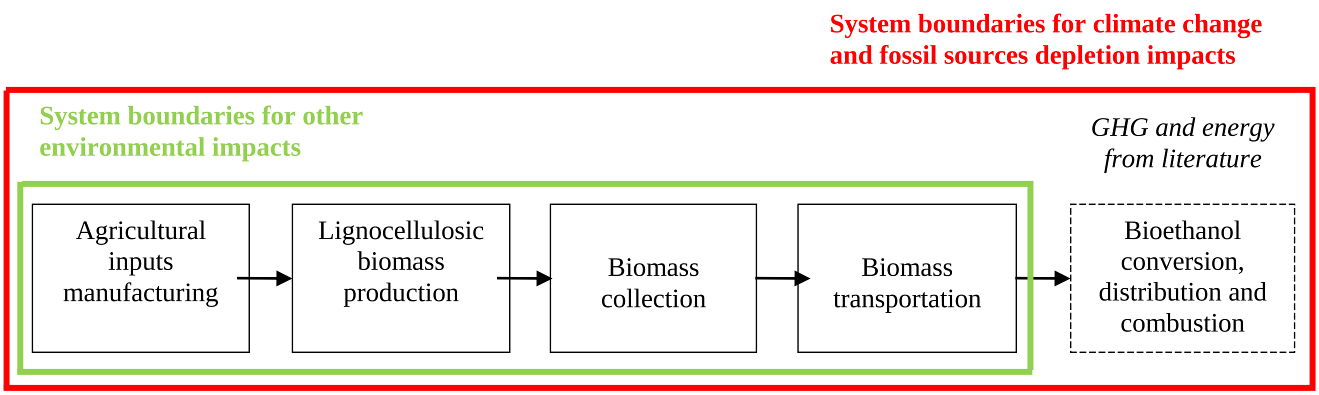

Figure 1: System description and boundaries for climate change and fossil resources depletion impacts (red) and other environmental impacts (green)

The LCA methodology applied in this study followed the ISO 14044 standard requirements. The biomass supplied to the bioethanol conversion unit represents the downstream boundary (green boundaries, Figure 1). The system was extended to the production of bioethanol to allow a comparison with a reference fossil fuel, in terms of GHG and energy balances. Data of the biomass conversion process were extracted for the theoretical unit presented by the National Renewable Energy Laboratory (Aden et al. 2002), for which emissions and consumptions were evaluated by a later study (Edwards et al. 2013) (Figure 1).

This unit can produce 600 t ethanol d^{-1} [annual production of 219 000 t ethanol], from a biomass supply of 730 000 t DM yr^{-1} [i.e. with a process mass efficiency of 30% kg EtOH kg $biomass^{-1}$]. These estimations were based on a single biomass source of woody short rotation coppice (SRC). Because of the lack of adequate data in the literature, we assumed this conversion efficiency to be independent of the type of input biomass.

The Burgundy region (Northeastern France) was thus selected as representative of the agricultural situation of France, presenting in particular a supply area large enough to supply the bioethanol conversion unit. Besides, a simulation period of 20 years appeared to be a minimum to capture inter-annual climatic variations and take into account a whole life-cycle of perennial crops. For these reasons, the 2010-2030 time slice was selected for the climate data. All results presented in this paper are thus annual means from the whole 20-year life cycle. Several biomass sources were studied: crop residues (cereal straw) and dedicated crops, either annual (sorghum and triticale) or perennial (Miscanthus). A feedstock composed from a mix of biomass sources, based on wheat straw, Miscanthus and triticale, was also examined.

2.3. Life cycle assessment (LCA)

2.3.1. Methodological aspects

Table 1 sums up the methodological choices made for the LCA study. N_2O emissions estimates LUC effects are more detailed within the life cycle inventory section below. As infrastructures represent a t

Table 1. Summary of methodological choices for the LCA

Methodology aspect	Choice	Reference
Functional unit	Feedstock supply at the conversion unit entrance (730 kt DM yr^{-1}) and 1 MJ of producted and used biofuel for GHG and energy comparison	(European Parliament 2009a)
LCA software and database	Simapro 7.3.3 and Ecoinvent 2.2	(Frischknecht et al. 2007; PRé Consultants et al. 2010)
Allocation rules between products and byproducts	Energetic prorate applied in the NREL process calculations, from biomass to bioethanol No byproducts were considered in the biomass production	(European Parliament 2009a)
GHG emissions calculations: - Biogenic carbon - Emissions factors - N_2O emissions	- GWP (biogenic CO_2) = 0 and GWP (fossil CO_2) = 1 - IPCC 2007 GWP considered for 100 years - Direct N_2O emissions from CERES-EGC model outputs - Indirect N_2O emissions from CERES-EGC model outputs (NH_3, NOx and NO_3^-) combined with IPCC 2006 equations	(IPCC 2006; IPCC 2007)
Land use changes (LUC)	Both direct and indirect LUC were considered: - Direct LUC estimated from CERES-EGC model outputs and scenarios - Indirect LUC from literature	(European Parliament 2009a; ADEME 2012; De Cara et al. 2012; European Parliament 2012)
Infrastructures consideration	Infrastructures were neglected (roads, buildings)	(European Parliament 2009a; ADEME 2010)

2.3.2. Life cycle impact assessment (LCIA)

The IMPACT 2002+ (Jolliet et al. 2003) method was selected, since it allows to evaluate midpoint and end-point impacts and also since it is based on the IMPACT 2002 model (Pennington et al. 2005), the Ecoindicateur 99 method (Goedkoop and Spriensma 1999) and the CML method (Guinée et al. 2002). As midpoint impacts are estimated from substance equivalences, they present fewer uncertainties than end-point impacts, based on models and strong hypotheses. The results presented in this study are therefore derived mainly from mid-point impacts.

A particular effort was carried on GHG balance and climate change impact to evaluate the sustainability of biofuels. The time horizon in IMPACT 2002+ is set to 500 years to consider long term impacts, especially for CO_2 that contributes to climate change for such a period. However, a time horizon of 100 years for the substances impacting the greenhouse effect is usually considered into the other methods, even if it does not reflect the whole impacts caused by these substances. We chose a time horizon of 100 years in this study.

In order to consider the energy efficiency of produced biofuels, the non-renewable energy consumption has to be estimated. Finally, since these fuels are based on biomass production, impacts specifically linked with agricultural production and affecting the ecosystems were considered, such as terrestrial and aquatic acidification, ecotoxicity, aquatic eutrophication and land occupation.

GHG balance uncertainties were estimated from modelling outputs (yield, N_2O, NO_x, NH_3 and NO_3^-) as N_2O emissions have the highest weights in biofuel GHG balance (Cherubini and Strømman 2011), excluding uncertainties from biomass conversion to bioethanol. They were calculated for individual SU from standard error of the annual results on a 20-year period (2010-2030), and then aggregated to region scale weighted by area.

2.4. Life cycle inventory (LCI)

2.4.1. Cropping management

- Agricultural residues

A reference crop succession was determined in Burgundy from statistical data and experts' knowledge, as follows: winter barley – oil seed rape – winter wheat (Agreste 2008; Lesur 2012). The cropping management of reference crops was determined through regional studies (Agreste 2008) with a unique level of fertilization for the whole region. Straw exportation rates varied from 33% (one removal every three years) to 50% and were determined for each soil type and crop succession to maintain soil C stocks (FRCA Picardie et al. 2009), by assuming that the rates determined in Picardy were applicable in Burgundy. Wheat straw was favored due to its high yield, and sometimes, completed by barley straw. Livestock requirements, estimated from literature (FCBA and PNRB 2009), were first subtracted to the straw thus produced, before assessing the amounts of straw available for bioenergy.

- Dedicated annual and perennial crops

As sorghum and triticale are annual crops, they can easily be inserted in crop succession, and thus be grown on any arable area within the region. Barley was thus substituted by the annual energy crops within the succession. Sorghum and triticale crops were silage-harvested (with a biomass at 70 and 60% of moisture respectively) while both early (autumn) and late (spring) harvests were simulated for Miscanthus (RMT Biomasse 2013). An organic variant for the management of this crop, without chemical inputs, was also implemented ("Misc.-0input", Table 2). In order to minimize the inputs, crop management was adapted to estimate crop yields and the resulting nutrient export rates (Table 2) (Cadoux et al. 2012; Béjot 2013). Early harvests ("Misc.-early") lead to higher yields with higher moisture content (around 60%), whereas late harvests ("Misc.-late") increase nutrient recycling within the rhizomes, while decreasing fertilizer requirements (Table 2) and the moisture content of harvested biomass (15%). As no data was available on the removal phase of Miscanthus, experimental measurements were used to apply the LCA on GHG emissions and measurement uncertainties were added in the miscanthus GHG balance (Dufossé et al. 2014).

- Mix of biomass sources

To provide an alternative perspective, a feedstock supply mix composed of three biomass sources in equal proportions (243 kt DM yr^{-1}) was assessed. It comprised cereal straw, triticale (which came out as the best annual energy crop in this study) and Miscanthus. In order to approach real establishment of energy crops, hypotheses on area restriction were carried Miscanthus and triticale. No hypothesis on area restriction was carried for straw. Miscanthus was assumed to be planted exclusively on marginal lands, as set aside land, to avoid competition with food crops. Protected areas were excluded. A late harvest and adapted fertilization rates were applied to Miscanthus ("Mix-Misc.", Table 2). Triticale was assumed to be on the less productive arable lands to minimize competition with food crops ("Mix-triti.").

Table 2. Mean fertilization rates applied to the crops for simulations. Mean annual rates, weighted by arable area within the SU. Three management for Miscanthus were simulated: early harvest with fertilization ("Misc.-early"), a late harvest with fertilization ("Misc.-late") and a late harvest without fertilization ("Misc.-0input"). Two annual crops were also simulated ("Sorghum" and "Triticale"), as well as a mix of biomass composed of a third of Miscanthus with fertilization and late harvest on set aside lands ("Mix-Misc.") and a third of triticale on low productive land ("Mix-triti.").

	Misc.-0input	**Misc.-late**	**Misc.-early**	**Sorghum**	**Triticale**	**Mix-Misc.**	**Mix-triti.**
N fertilization (kg N ha^{-1})	0	54	120	144	145	49	110
P fertilization (kg P ha^{-1})	0	7	14	24	25	6	18
K fertilization (kg K ha^{-1})	0	83	160	200	140	78	106

2.4.2. Direct and indirect emissions

Emissions of nitrogen compounds (N_2O, NOx, NH_3 and NO_3^-) in soil, water or atmosphere were simulated from the CERES-EGC model (Table 3). Indirect N_2O emissions were estimated from IPCC emission factors applied on simulated emissions of NOx, NH_3 and NO_3^- (IPCC 2006). Heavy metals inputs related to fertilization, and their transfer to soils were estimated from fertilization rates and emission factors proposed by Nemecek and Kägi (2007). Because of the lack of reliable data on heavy metals inputs through pesticides and exports by biomass, these fluxes were ignored.

Table 3. Main outputs of the CERES-EGC simulations, as inputs of the LCA. Mean annual rates, weighted by arable area within the SU.

	Misc.-0input	**Misc.-late**	**Misc.-early**	**Sorghum**	**Triticale**	**Mix-Misc.**	**Mix-triti.**
Yield (t DM ha^{-1})	16.13	16.69	22.56	13.46	13.73	15.6	9.0
Direct N_2O (kg N ha^{-1})	0.27	0.43	0.55	1.57	0.97	0.45	0.17
NO_3^- (kg N ha^{-1})	12.55	11.46	15.18	45.90	40.42	13.15	78.70
NH_3 (kg N ha^{-1})	-0.14	0.12	3.15	3.44	0.99	-0.01	0.16
NOx (kg N ha^{-1})	0.59	0.58	0.81	0.76	0.64	0.54	0.61
Net soil C variation (t C ha^{-1})	0.54	0.57	0.65	-1.11	0.19	0.91	0.07

2.4.3. Transportation

Because the lack of information on transportation, especially for the Burgundy region, the following hypotheses for distances were applied: 25 km between the farm and the regional storage where agricultural inputs (seeds, fertilizers, pesticides, fungicides and herbicides) are stored, and 100 km between fields and the region where the biomass is stored for the conversion unit supply, as in the JRC/EUCAR/CONCAWE study for European biomass (Edwards et al. 2013). All vehicles were selected among the most efficient vehicles in the Ecoinvent database (complying with the EURO5 standard, Frischknecht et al. (2007)).

2.4.4. Land use changes

Direct and indirect LUC (dLUC and iLUC, respectively) were considered separately, in a second part of the study. Firstly, dLUC from land conversion were estimated from variations in soil C stocks caused by the integration of bioenergy crops within the crop succession. These soil C stock variations were estimated from modeling outputs. Then, variations in soil C stock from the reference crop succession were withdrawn to obtain net stock differences (Table 3). These differences were transformed into CO_2 emissions according to the IPCC equations (IPCC 2006). For cereal straw, the dLUC was neglected since the exportation rates applied for modeling allowed to maintain soil C stocks (FRCA Picardie et al. 2009). To estimate the dLUC effects of converting set aside to cropland, the soil C variations of the reference crop succession were replaced by those estimated by simulating a set aside land with CERES-EGC before been subtracted to the soil C variations of energy crop succession.

Indirect LUC effects were mostly related to the displacement of food crops, because of the implantation of bioenergy crops. They were estimated at global scale, based on a recent meta-analysis (De Cara et al. 2012). For annual crops (sorghum and triticale), the CO_2 emissions due to iLUC were assessed at 37 g CO_2 eq MJ^{-1} (Al-Riffai et al. 2010; De Cara et al. 2012), whereas they were assessed at 27 g CO_2 eq MJ^{-1} for Miscanthus. These values correspond to the top of the range of values for every type of biomass from the meta-analysis. In scenarios where crops were established on set aside lands, no CO_2 emissions from iLUC were considered.

2.4.5. Biomass conversion into bioethanol

Emissions for the conversion of lignocellulose to ethanol were taken from the 2G bioethanol conversion unit described in the JRC/EUCAR/CONCAWE study ('WW/WFET1' scenario), as 15.6 g CO_2 eq MJ^{-1} including also conditioning and bioethanol distribution (Edwards et al. 2013).

This 2G bioethanol conversion unit also consumes 1.97 MJ of energy to produce 1 MJ of bioethanol (1.97 MJ $MJ(EtOH)^{-1}$). This consumption was split into multiple sources: non-renewable energy sources (0.28 MJ $MJ(EtOH)^{-1}$), nuclear power (0.01 MJ $MJ(EtOH)^{-1}$), biomass itself and heat recycling within the process (Edwards et al. 2013). In this study, for an equivalent conversion process, the energy consumption related to feedstock supply (poplar SRC) was estimated at 0.11 MJ $MJ(EtOH)^{-1}$. As non-renewable energy consumptions were not detailed according to bioethanol production steps, we assumed that the energy used in the agricultural phase was only non-renewable energy. For the bioethanol conversion phase, the non-renewable energy consumption was thus assumed at 0.18 MJ $MJ(EtOH)^{-1}$.

3. Results and discussion

3.1. GHG balance of bioethanol production

3.1.1. Global GHG balance

Figure 2 shows the GHG balance of bioethanol production from different lignocellulosic biomass sources. Thanks to the integration of local pedoclimatic variations in modeling crop production, the uncertainties on biofuel LCA results decreased from 1 to 4 g CO_2 eq MJ^{-1} for biomass production, excluding uncertainties from biomass conversion to bioethanol. The uncertainties were thus reduced ten-fold compared to recent studies (Edwards et al. 2011), improving the accuracy of estimates of GHG savings for 2G biofuels.

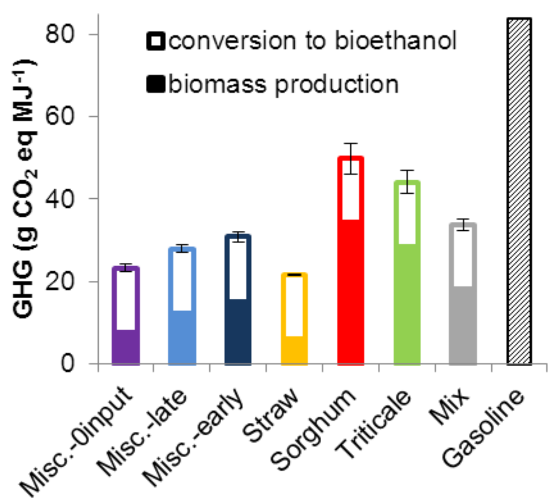

Figure 2. GHG balance of bioethanol produced from crop residues (straw), annual crops (sorghum and triticale), perennial crops (Miscanthus) and the mix of three biomass sources (straw, triticale and Miscanthus). GHG emissions of gasoline is also presented as the fossil reference. Error bars show the standard deviation of errors due to spatial and temporal variability within the region.

In terms of feedstock, Miscanthus (whatever its management) or cereal straw achieved larger GHG savings than annual crops, both reaching the 60% GHG threshold set by the RED Directive for 2017 (European Parliament 2009a).

The production of Miscanthus without fertilizer inputs (Misc.-0input) emitted 7.7 g CO_2 eq MJ^{-1}, which is similar to the 7.2 g CO_2 eq MJ^{-1} estimated as GHG emissions for poplar SRC cropping (with 25 kg N ha^{-1}) within JRC/EUCAR/CONCAWE study (Edwards et al. 2013). Both other Miscanthus management (Misc.-late and Misc.-early) received fertilization and emitted twice GHG than the one without inputs (12.4 and 15.2 g CO_2 eq MJ^{-1}). However, the required amount of area converted to Miscanthus (2.5% of UAL) seems unrealistic to supply the conversion unit with Miscanthus as a unique source of 2G bioethanol in the near future.

Since straw was considered as a crop residue, all impacts from wheat growing were attributed to grain production. Therefore, only impacts for biomass collection were attributed to straw, which minimized its GHG balance. In the JRC/EUCAR/CONCAWE study ('STET1' scenario), GHG emissions from straw were estimated to 3.8 g CO_2 eq MJ^{-1}, which is in the same order of magnitude as our findings (6.0 g CO_2 eq. MJ^{-1}). Since the study did not consider livestock in the estimation of available straw, yield per unit area should have been higher (in our study: 0.8 t DM ha^{-1} yr^{-1}) and therefore emissions due to collection, lower. Besides, due to these high livestock requirements (748 kt DM yr^{-1}), the amount of available straw could only supply 50% of the biomass required by the conversion unit (372 kt DM yr^{-1} produced for 730 kt DM yr^{-1} required).

Annual crops showed mediocre results when combining their high fertilizer requirements, high GHG emissions and moderate yields (around 12.5 t DM ha^{-1} yr^{-1}) in Burgundy. However, their introduction into crop successions could suffice to fulfill the biomass requirements of the conversion unit. A mix of biomass sources (residues, annual and perennial) is likely to be an interesting compromise to supply the conversion unit by ensuring feedstock supply while maximizing GHG savings (60% of GHG reduction for fossil reference, Figure 3).

Field N_2O emissions were the main contributor to GHG emissions for all biomass sources excluding Misc-0input, followed by emissions due to biomass transportation and fertilizer production (data not shown). Therefore, changes in land use have to be carefully thought to optimize biomass performances, by selecting fields which produce high yields and minimize N_2O emissions while located close to the conversion unit. Selecting annual crop variety with low input requirements is also a worthy option for improving biomass GHG balance, as also recommended by Smith and Searchinger (2012).

3.1.2. Effects of land-use changes (LUC) on GHG balance

The results presented above did not consider the effect of LUC on the GHG balance of feedstocks and bioethanol. Direct LUC effects were positive for Miscanthus (Figure 3b), as Miscanthus stored large amounts of C in soils. GHG savings from Miscanthus-based ethanol were between 63 and 72% without LUC effects and between 79 and 90% with them. However, due to significant and negative dLUC effects, sorghum GHG savings became negative (-4%), which means that, in Burgundy, producing and using bioethanol from sorghum results in higher GHG emissions compared to the reference fossil fuel.

When considering dLUC and iLUC, only straw biomass ensured biofuel GHG savings larger than 60% (Figure 3c). Miscanthus managed without inputs and the mix of biomass presented interesting results (58 and 57% of GHG savings respectively). Misc-0input had an overall acceptable GHG balance thanks to low N_2O emissions and the absence of fertilizer inputs. The mix of biomass sources compensated the poor GHG performances of triticale (11% of GHG savings) by the excellent ones of straw (74% of savings) and the advantageous ones of Miscanthus: no inputs (minimizing GHG emissions), high soil C storage (positive dLUC effects) and implantation on set aside lands (no iLUC effects).

The iLUC values used in this study came from the literature. They were generic and taken in their upper range. Due to the weight of the iLUC effects, further studies would be necessary to yield conservative estimates of GHG savings from 2G biofuels. Marginal lands showed reliable potentials for bioenergy cropping since the biomass produced would not compete with food production, and generate little iLUC effect.

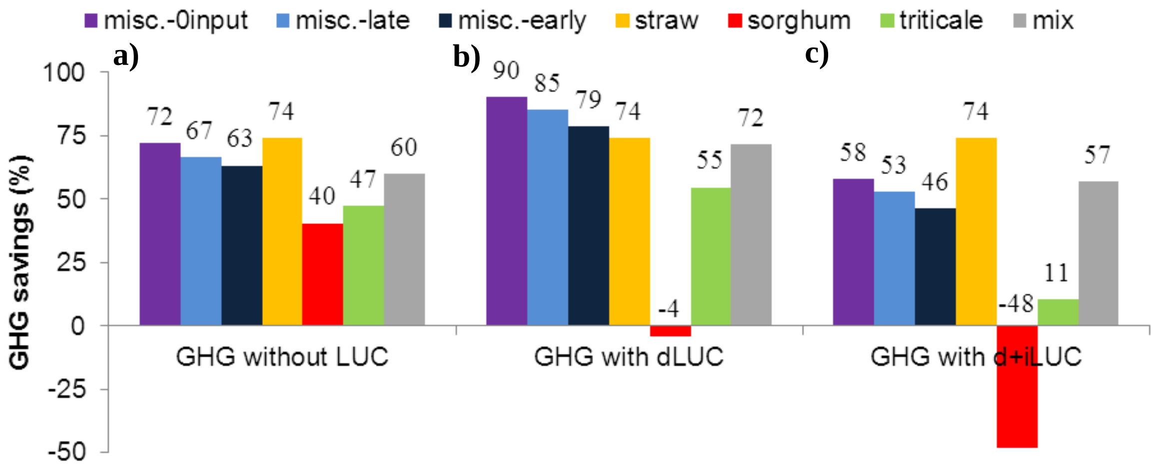

Figure 3. GHG balance of biofuels produced from different biomass sources, without considering LUC effects (a), with the integration of direct (dLUC, b) and indirect LUC (d+iLUC, c) effects in Burgundy.

3.2. Energy balance

Figure 4 showed the non-renewable energy consumptions for bioethanol production from different lignocellulosic biomass sources. Compared to the fossil reference, energy savings ranged from 65% for sorghum to 78% for Miscanthus without chemical inputs. These savings were highly dependent of the amount of cropping operations and chemical inputs. Biomass yields also played a role for these estimates as straw required few field operations but also produced low mean yields per hectare. Even if the conversion process was assumed to be similar for all studied biomass sources, the energy efficiency of 2G bioethanol was high in all cases and likely to increase as industrial processes are improved.

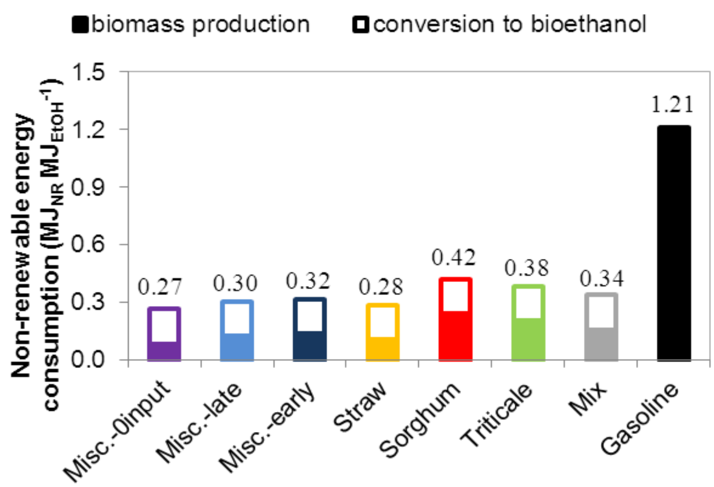

Figure 4. Non-renewable energy consumptions of 2G bioethanol produced from different biomass sources in Burgundy and comparison with fossil reference.

3.3. Other environmental impacts

Since few details were available on the conversion process for 2G bioethanol, the assessment of other environmental impacts focused exclusively on the biomass production to compare the various feedstocks. Crop receiving higher chemical inputs (herbicides, fungicides, fertilizers and associated heavy metal inputs) showed larger impacts on the ecosystem (scores of 63 to 100% of maximum impacts for eutrophication, aquatic and terrestrial acidification and ecotoxicity). Land occupation was directly related to crop yields. Sorghum and triticale were thus more harmful for the ecosystem (Figure 5). Compared to its other management, Miscanthus with early harvest turned out to affect notably the ecosystem, even if land occupation impact was lessened (Figure 5) thanks to high yields (averaging 23 t DM ha^{-1} yr^{-1}, Table 3).

Within the unique score assessed with the IMPACT2002+ method, damages on ecosystem had the bigger share compared to all endpoint impacts (data not shown). Since these impacts are strongly related to fertilizer input rates and in order to reduce the environmental impacts of bioethanol, it is crucial to select biomass sources that require the lowest chemical inputs, such as Miscanthus or agricultural residues. It is also possible to mitigate impacts if choosing a feedstock supply composed from a mix of biomass sources with straw, Miscanthus and triticale in equal shares. The considerable impacts of the last one (scores between 63 to 100% of maximum impacts) were mitigated by the limited impacts of Miscanthus and mainly straw to moderate impacts (scores of 35 to 79%).

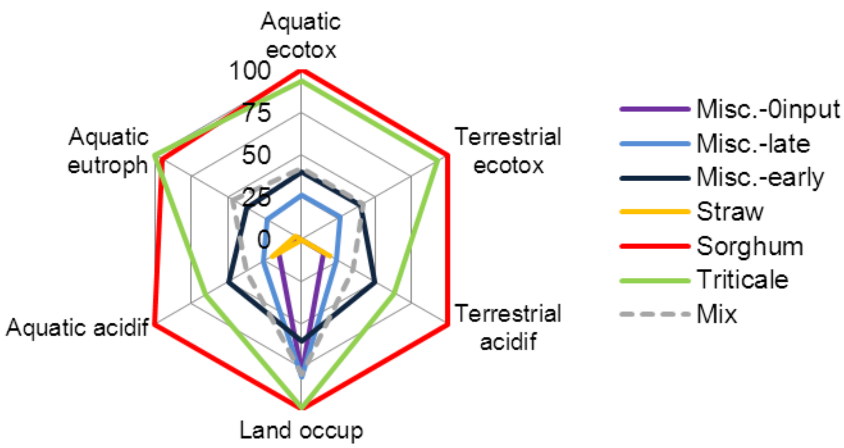

Figure 5. Results of midpoint impact assessment, of the damages on ecosystem endpoint impact, for different biomass production in Burgundy. Impacts are presented as a proportion of the highest score in the midpoint impact category.

4. Conclusion

Using a crop model to integrate the local pedoclimatic variability within a supply area made it possible to provide more accurately GHG balances for a conversion unit of 2G bioethanol from different sources of biomass. The estimated GHG savings, obtained with the LCA thus produced, could help for biomass selection and ensure the potential GHG reduction of 2G bioethanol from agricultural residues and Miscanthus. These bioethanol chains could fulfill the sustainability criteria set by the European Parliament. Sorghum and triticale, used as unique feedstock source, showed the lowest GHG savings. Nonetheless, if they are integrated in a feedstock mix with straw and Miscanthus, they can contribute to ensure the biomass requirements and limit biomass storage at the conversion unit, while their mediocre environmental performances could be mitigated by the other sources of biomass.

As shown by the previous results, the integration of LUC effects (direct or indirect) could offset the conclusions on GHG savings. When dLUC and iLUC were included in the GHG balance, only straw could ensure GHG savings higher than 60%. Since amounts of cereal straws are limited in the studied area, other biomass sources have to be considered. It is thus essential to accurately evaluate emissions, especially due to iLUC, and guide the establishment of energy crops towards zones that minimize emissions, such as set aside or marginal lands with low productivity in food cropping. However, these low productive lands may also show mediocre environmental and yield performances for energy crops, especially for cereals such as triticale.

Bioethanol from all energy crops presented in this study showed non-renewable energy consumptions reductions higher than 65% compared to fossil fuels. Best performances were obtained by straw and Miscanthus. The main environmental impacts of these crops on ecosystems were directly linked to the use of chemical inputs (fertilizers or herbicides). Biomass sources requiring the lowest chemical inputs rates should be favored in order to limit environmental impacts.

The study of innovative energy crops, such as Miscanthus, switchgrass or SRC, is likely to be critical to the optimization of biomass feedstock. Before widening the portfolio of biomass feedstocks for 2G bioethanol, we suggest using a mix of biomass sources for feedstock supply, made up of highly performing crops (Miscanthus), residues (straw) and commonly produced agricultural crops (triticale). Also, a particular interest should be paid to crop establishment patterns, and to the location of the biofuel conversion unit. Maps of potential yields, N_2O emissions and soil C sequestration rates, such as generated here with the ecosystem model, would be very useful and practical tools to guide public and private stakeholders in this direction.

5. Acknowledgments

This study was funded by BPIFRANCE as part of the FUTUROL project. The authors are grateful to Fabien Ferchaud, Stéphane Cadoux, Hubert Boizard and Claire Lesur for their data on crop successions and management as well as Nathalie Gagnaire for her support.

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This paper is from:

Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector

LCA Food 2014

8-10 October 2014 - San Francisco

Rita Schenck and Douglas Huizenga, Editors
American Center for Life Cycle Assessment

The full proceedings document can be found here:
http://lcacenter.org/lcafood2014/proceedings/LCA_Food_2014_Proceedings.pdf

It should be cited as:

Schenck, R., Huizenga, D. (Eds.), 2014. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014), 8-10 October 2014, San Francisco, USA. ACLCA, Vashon, WA, USA.

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ISBN: 978-0-9882145-7-6