Considering the variability of farming practices improves the LCA of biodiesel from oilseed rape

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ABSTRACT

Nitrogen fertilization practices have a significant effect on the LCA results of biodiesel chains, which warrants reliable inventory data. In this study focused on the Lorraine region (eastern France), we established a typology of oilseed rape fields based on fertilization practices, and used the agro-ecosystem model CERES-EGC in lieu of generic emission factors to simulate the productivity and externalities associated with oilseed farming. The results were subsequently used to generate an LCA of biodiesel from oilseed rape. We also tested the effect of improved practices on the LCA results. In Lorraine, oilseed rape crops appeared to be frequently over fertilized compared to best management practices. Switching to improved practices with optimal fertilization has a potential to reduce the GWP of 1 megajoule of biodiesel by around 6 gr CO_2eq, against a total life-cycle of 43.9 gr CO_2eq.

Keywords: biodiesel, oilseed rape, farming practices, emissions modeling, LCA

1. Introduction

The development of the use of biofuels in the transportation sector in Europe is the consequence of policies aiming at enhancing energy security and mitigating climate change through the reduction of anthropogenic greenhouse gas (GHG) emissions. After the recognition of the unexpected effects of the development of first generation biofuels on agricultural prices and land-use, a set of sustainability criteria outlined in a directive dedicated to renewable energy must henceforth be respected (Ben Aoun et al. 2013). From 2016, the substitution of fossil fuels by biofuels should allow the saving of at least 50% of GHG emissions (European Commission 2009).

The standardized method of life cycle assessment (LCA) is currently widely recommended for evaluating the environmental balance of products. When applied to bioenergy chains, several factors may influence its outputs. Thence, LCA studies concerning the same biofuel type can lead to significantly different results (IPCC 2011). In addition to methodological choices such as system boundaries, functional unit and co-products handling, these variations are essentially due to differences in the life cycle inventory stage. Recent studies (Davis et al. 2013, Smeets et al. 2009) showed that data on the feedstock production stage account for most of this variability. According to the same studies, this arises from the fact that the larger the geographical scale of the LCA study (eg. a region or a country), the coarser the data that depend on local factors (soil type, climate conditions and farming practices). The latter include crop yields and GHG emissions, in particular nitrous oxide (N_2O). This translates into a high uncertainty band for the biofuels LCA results.

As a consequence, improving the quality of such LCAs requires a better consideration of local factors when estimating agronomic and environmental data. The use of agro-ecosystem modeling is one of the solutions proposed to avoid the use of generic, fixed emissions factors (EFs) with a worldwide scope as suggested in the Tier 1 methodology of IPCC guidelines (2006). Such an approach would make it possible to obtain site-specific and reliable values when estimating N_2O emissions from soils (Dufossé et al. 2013, Cherubini 2010).

The objective of this study was to reduce the uncertainty surrounding biofuels LCAs through the use of an agro-ecosystem model (CERES-EGC) to estimate the agricultural and environmental variables needed for establishing the life-cycle inventory. It was applied to biodiesel from oilseed rape, the main biofuel produced in Europe, in the context of the Lorraine region (eastern France). Given that organic and inorganic nitrogen fertilization is responsible for 90% of the life-cycle GHG emissions related to oilseed rape production in France (Cerrutti et al. 2013), the effect of improved fertilization practices on LCA results was explored.

2. Methods

2.1. Goal and scope

This study focused on improving the quality of the inventory phase for the LCA of biodiesel from oilseed rape, using agro-ecosystem modelling and farm surveys. Biodiesel LCA results were compared to those of LCA of fossil-based gasoline. The effects of improved fertilization practices on the initial biodiesel LCA results were also examined.

For reasons of data availability, this study only focused on biodiesel made from oilseed rape harvested during the year 2012 in the Lorraine region in France. A study on the whole France is currently in progress.

The evaluated system includes five main stages: oilseed rape production, delivery to a biorefinery, conversion to biodiesel, storage in the plant and distribution, i.e. well-to-wheel boundaries. One mega-joule of biodiesel is the functional unit retained for this study. Rape meal, acid oils and glycerin are co-produced during the biodiesel conversion stage. To share environmental burdens between biodiesel and its co-products, the energetic allocation was applied, as recommended in the renewable energy directive (European Commission 2009).

2.2. Life cycle inventories

2.2.1. Crop management and biomass conversion data

Information on farming practices were derived from survey data conducted on behalf of the French technical center of oilseeds and hemp (CETIOM). A typology of fields producing oilseed rape in Lorraine was established according to farmers' nitrogen fertilization practices. In this typology, we assumed that the amount of inorganic nitrogen fertilizers applied on oilseed rape depends on three key factors: whether organic fertilizers were regularly applied (i.e. at least once every four years) or not, whether organic fertilizers were applied before sowing, and whether a decision support tool was used or not. This allowed us to identify 10 different fertilization practices (Table 1).

Table 1. Typology of oilseed rape management in Lorraine

Fertilization practice type	Regular fertilization	Organic fertilization before sowing	Use of decision support tool	Percentage of occurrence in the region
1	No	No	No	13.4%
2	No	No	Yes, well-respected	1.1%
3	No	No	Yes, non-respected	22.9%
4	No	Yes	No	6.3%
5	No	Yes	Yes, non-respected	3.2%
6	Yes	No	No	5%
7	Yes	No	Yes, well-respected	0.6%
8	Yes	No	Yes, non-respected	13.4%
9	Yes	Yes	No	15%
10	Yes	Yes	Yes, non-respected	19.1%

The decision-support tool was developed by CETIOM and calculates the optimal amount of inorganic fertilizer N to be applied in spring, based on a balance-sheet method. Therefore its use allows to avoid situations of both under and over-fertilization, which can largely influence crop yields and emissions of reactive N (Nr).

Particular attention was given to the form of organic fertilizer applied, as it can have considerable effects on Nr emissions (Dambreville et al. 2008). Still, for the sake of simplification only the most commonly-used forms were retained. Therefore, we considered that cattle manure was the only form of organic fertilizer applied to oilseed rape in Lorraine.

Data on machinery and inputs production (i.e. fertilizers, pesticides, fuel, etc.) were taken from the French data base AGRIBALYSE, recently developed by the French Environment Agency (Koch and Salou 2013). Data on oilseed rape transport and its conversion to biodiesel were taken from the Ecoinvent data base (v2.0). Those concerning biodiesel distribution were taken from a recent study carried out by ADEME (Biois 2010). Table 2 summarizes the data sources used for the life cycle inventory of biodiesel from oilseed rape in Lorraine.

2.2.2. Crop simulations

The agro-ecosystem model CERES-EGC can simulate yields, soil carbon dynamics and reactive nitrogen emissions including N_2O, as detailed by Gabrielle et al. (2006). To make possible the use of the model on larger scales while taking into account the variability of local conditions, a GIS database containing geo-referenced informations on the administrative borders, land cover, soil properties and climatic conditions was built. The corresponding layers of spatial information were overlaid to delineate elementary spatial units. These units represent a unique combination of soil type and climatic conditions to be used in the CERES-EGC simulations (Dufossé et al. 2013, Gabrielle et al. 2014).

Table 2. Sources of data for life-cycle inventory of the pathway investigated.

Stage	Source
Feedstock production	
Crop management	CETIOM
Crop yield	CERES-EGC simulations
Machinery & inputs production	AGRIBALYSE
Direct N2O emissions	CERES-EGC simulations
Indirect N2O emissions	CERES-EGC & IPCC 2006 guidelines
Other Nr losses	CERES-EGC simulations
Soil c dynamics	CERES-EGC simulations
Transport	Ecoinvent database
Conversion to biodiesel	Ecoinvent database
Distribution	ADEME

For each practice, daily simulated fluxes of direct Nr emissions were accumulated from the harvest of the previous crop to the harvest of oilseed rape. Indirect emissions of N_2O due to nitrogen leaching were calculated following the 2006 IPCC guidelines as 0.75% of the nitrate losses and 1% of ammonia and nitric oxide emissions, as simulated by CERES-EGC.

To simplify the regional modeling, we assumed an uniform distribution of management practices (as detailed in the above typology) over the whole region, i.e. assuming the occurrence of fertilization practices in each CERES-EGC simulation unit was the same as that on a regional scale. Therefore yields and externalities related to each fertilization practice have been simulated for each simulation unit. Then, results obtained from these simulations make it possible to estimate a representative regional yield and nitrogen emissions by weighting the simulations results of each practice by its percentage in the region (via Equations 1 & 2).

$$\sum_{i=1}^{10} y_i * perc_i = Y_{Lorraine} \qquad \text{Eq.1}$$

$$\sum_{i=1}^{10} e_i * perc_i = E_{Lorraine} \qquad \text{Eq.2}$$

With :
i : fertilization practice n° i
y_i : yield of the fertilization practice n° i
e_i : emissions related to oilseed rape production via the fertilization practice n° i
$perc_i$: percentage of the fertilization practice n° i in the region
$Y_{Lorraine}$: regional oilseed rape yield
$E_{Lorraine}$: regional emissions due to oilseed rape farming

2.2.3. Impact characterization and interpretation

LCA was conducted for each fertilization practice using Sima-Pro software package (v7.2). The environmental impacts were characterized with the CML 2000 method at mid-point level. The following impacts categories were analyzed: global warming, eutrophication, acidification, depletion of abiotic resources, photochemical ozone formation. Results were subsequently aggregated on the regional scale

3. Results

3.1. Current fertilization practices may still be improved

We used the CETIOM survey data to determine the quantities of inorganic nitrogen currently applied on oilseed rape for each fertilization practice described above. We found that oilseed rape producers apply about 158 kg of inorganic nitrogen per hectare in Lorraine on average.

We also calculated the recommended amount of inorganic nitrogen to be applied for each fertilization practice using the nitrogen balance method. Results show that inorganic nitrogen rates currently applied exceed the recommended ones (Table 3). Indeed Lorraine farmers tend to over fertilize oilseed rape: only less than 2% of oilseed rape fields receive the recommended dose of inorganic nitrogen.

3.2. Field emissions of reactive N

Table 4 lists the regional yields and emissions of reactive nitrogen for the various oilseed rape fertilization practices obtained with the ecosystem model CERES-EGC.

Table 3. Differences between current and recommended fertilization practices (in kg N/ha)

Fertilization practice type	**Percentage in the region**	**Current inorganic Nr fertilization**(1)	**Recommended inorganic Nr fertilization**(2)	**Fertilization gap** (1-2)
1	13.40%	160.35	117.03	43.32
2	1.10%	170.00	166.05	3.95
3	22.90%	156.15	122.75	33.40
4	6.30%	158.88	100.30	58.58
5	3.20%	176.75	96.29	80.46
6	5.00%	175.89	94.37	81.52
7	0.60%	165.00	159.50	5.50
8	13.40%	148.83	86.43	62.40
9	15.00%	156.18	82.89	73.29
10	19.10%	158.14	91.11	67.03
Average	100.00%	158.17	102.12	56.05

Compared to yields reported in the CETIOM survey, predicted oilseed rape yields in 2012 for the various fertilization practices were over-estimated by around 15%. As the model does not take accidents such us crop diseases or weeds into account, and since the year 2012 was marked by a significant occurrence of this type of accident in Lorraine region, these simulated yields can be accepted and the risk of a systematic modeling bias may be considered low. Also, harvest losses are not included in the modelled yields and may amount to the 15% discrepancy observed.

According to CERES-EGC, the highest direct emissions of N_2O occurred with fertilization practices in which organic nitrogen is applied before sowing of oilseed rape in the fall (i.e. fertilization practices no 4,5,9 and 10). For the practices involving only inorganic fertilization, direct N_2O emissions were much lower. Here, one should mention that for the various fertilization practices, direct N_2O emissions simulated by CERES-EGC are 2 to 3 fold lower than would be estimated when using the Tier 1 IPCC guidelines. In contrast, calculated indirect N_2O emissions were higher than what could be found using the IPCC methodology. This is due to the high nitrate losses simulated by the model.

Regarding optimal fertilization practices, results show that both direct and indirect N_2O emissions and nitrate decreased by 10 to 15% when recommended practices were simulated in lieu of current ones, whereas crop yields were less sensitive to these changes (Table 5)

3.3. Life-cycle impacts of biodiesel from oilseed rape chain

Table 6 reports the environmental performance of biodiesel from oilseed rape for the various fertilization practices adopted by farmers during the feedstock production phase in Lorraine.

Our results show that all impact categories selected in this study are sensitive to nitrogen fertilization practices, except for the ozone formation and abiotic depletion categories which remained unchanged regardless of the fertilization practice. Thus, Nr emissions, in relation to N fertilization have a significant effect on biofuels LCA results, whether from direct field emissions or upstream inputs manufacturing. This is in line with findings by Gabrielle et al. (2014).

Table 4. Nitrogen losses and oilseed rape yields predicted by CERES-EGC with current practices

Fertilization practice type	Yield (Kg ha^{-1})	Direct N_2O (Kg $N\text{-}N_2O$ ha^{-1}	Nitrate (Kg N-NO_3 ha^{-1})	NH_3 (Kg N-NH_3 ha^{-1})	NO (Kg N-NO ha^{-1})	Indirect N_2O (Kg $N\text{-}N_2O$ ha^{-1})
1	3077	0.59	26.03	22.14	1.31	0.88
2	3037	0.66	26.44	20.57	1.30	0.88
3	3074	0.58	26.04	22.16	1.31	0.87
4	3410	1.36	64.15	53.45	2.39	2.16
5	3453	2.01	106.99	101.86	3.30	3.87
6	3041	0.68	26.61	14.67	1.13	0.82
7	3103	0.62	26.29	14.86	1.15	0.81
8	3051	0.58	26.00	18.69	1.29	0.85
9	3446	1.83	96.77	94.61	3.04	3.39
10	3446	1.82	95.68	95.01	3.04	3.37
Average	3229	1.09	54.95	50.04	2.01	1.90

Concerning the global warming potential (GWP), all fertilization practices currently adopted by Lorraine farmers allow the whole biodiesel chain to emit less GHG than fossil diesel if land use change effects are not considered. On a regional scale, the GHG intensity of 1 mega joule of biodiesel from oilseed rape in Lorraine is about 43.9 gr CO_2 eq. The European sustainability criteria are thus not met because the 50% abatement threshold for GHG emissions is not reached.

Table 5. Nitrogen losses and oilseed rape yields predicted by CERES-EGC with optimal practices

Fertilization practice type	Yield (Kg ha^{-1})	Direct N_2O (Kg $N\text{-}N_2O$ ha^{-1}	Nitrate (Kg N-NO_3 ha^{-1})	NH_3 (Kg N-NH_3 ha^{-1})	NO (Kg N-NO ha^{-1})	Indirect N_2O (Kg N-N2O ha^{-1})
1	2995	0.51	25.13	10.37	1.12	0.74
2	2954	0.55	25.11	23.06	1.20	0.87
3	2841	0.51	25.11	11.64	1.13	0.75
4	3344	1.25	59.09	37.63	2.18	1.87
5	3405	1.87	101.86	117.05	3.06	3.53
6	2850	0.50	25.33	3.90	0.97	0.68
7	3064	0.58	25.34	13.44	1.03	0.77
8	2857	0.48	25.33	4.50	1.06	0.68
9	3380	1.72	91.86	74,31	2.82	3.06
10	3388	1.73	91.79	75.63	3.83	3.07
Average	3090	1.01	52.48	36.18	1.81	1.63

Adopting best fertilization practices for oilseed rape production may significantly improve the environmental balance of biodiesel in Lorraine. Overall, the life-cycle GHG emissions of biodiesel may decrease from 43.9 to 37.6 g CO_2 eq per MJ of biofuel (Table 7). This translates as an abatement of 56% when substituting gasoline with oilseed rape biodiesel, and thus ensures compliance with European sustainability criteria.

Figure 1 compares the environmental performance of biodiesel from oilseed rape produced with current fertilization practices to biodiesel processed by rape produced with optimal fertilization practices. It shows that balancing the inorganic nitrogen fertilization to crop nitrogen needs could allow reducing GWP and eutrophication by 15%, while mitigating acidification by 35%.

Table 6. Environmental performances of 1 MJ of biodiesel from oilseed rape with current practices in Lorraine

Fertilization practice type	**GWP (100 years) (g CO_2 eq)**	**Acidification (kg SO_2 eq)**	**Eutrophication (kg PO_4 eq)**	**Ozone formation (kg CFC-11 eq)**	**Abiotic depletion (kg Sb eq)**
1	36.4	4,05E-04	2,03E-04	1,15E-09	9,94E-05
2	38.0	3,92E-04	2,02E-04	1,15E-09	9,94E-05
3	36.0	3,75E-04	1,96E-04	1,15E-09	9,94E-05
4	45.2	7,28E-04	3,63E-04	1,15E-09	9,94E-05
5	59.1	1,44E-03	6,24E-04	1,15E-09	9,94E-05
6	46.0	3,18E-04	1,86E-04	1,15E-09	9,94E-05
7	36.3	3,12E-04	1,82E-04	1,15E-09	9,94E-05
8	35.4	3,62E-04	1,94E-04	1,15E-09	9,94E-05
9	54.1	1,18E-03	5,43E-04	1,15E-09	9,94E-05
10	54.0	1,90E-03	5,42E-04	1,15E-09	9,94E-05
Regional average	43.9	8,42E-04	3,38E-04	1,15E-09	9,94E-05

Table 7. Environmental performance of 1 MJ of biodiesel from oilseed rape with optimal practices in Lorraine

Fertilization practice type	**GWP (100 years) (g CO_2 eq)**	**Acidification (kg SO_2 eq)**	**Eutrophication (kg PO_4 eq)**	**Ozone formation (kg CFC-11 eq)**	**Abiotic depletion (kg Sb eq)**
1	31.5	2,47E-04	1,66E-04	1,15E-09	9,94E-05
2	36.9	4,22E-04	2,05E-04	1,15E-09	9,94E-05
3	32.1	2,64E-04	1,70E-04	1,15E-09	9,94E-05
4	38.7	5,37E-04	3,09E-05	1,15E-09	9,94E-05
5	57.0	1,80E-03	5,56E-04	1,15E-09	9,94E-05
6	29.2	1,61E-04	1,49E-04	1,15E-09	9,94E-05
7	35.4	2,32E-04	1,76E-04	1,15E-09	9,94E-05
8	28.7	1,67E-04	1,50E-04	1,15E-09	9,94E-05
9	46.4	9,40E-04	4,78E-04	1,15E-09	9,94E-05
10	47.0	9,57E-04	4,82E-04	1,15E-09	9,94E-05
Regional average	37.6	5,44E-04	2,92E-04	1,15E-09	9,94E-05

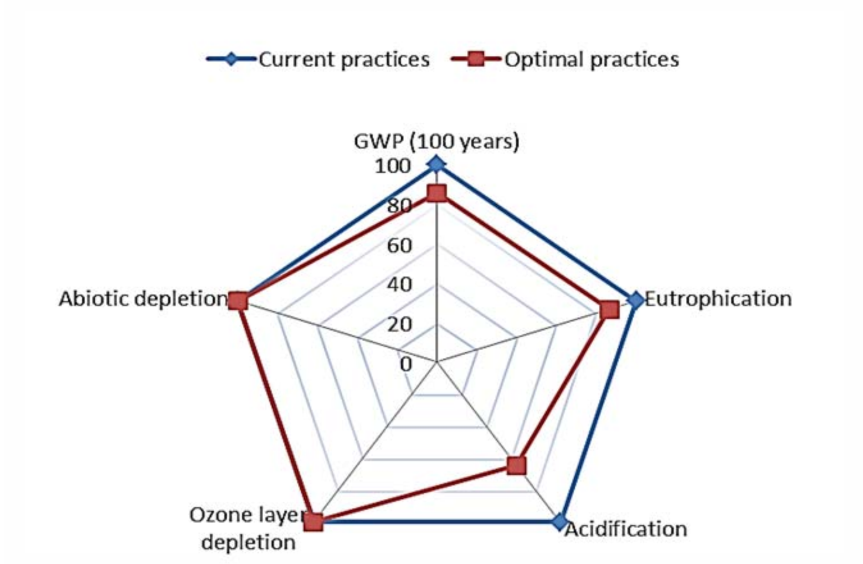

Figure 1. Impacts of fertilization practices improvement on LCA results of biodiesel from oilseed rape

4. Discussion

4.1. Reliability of simulated yields and nitrogen emissions

The modeling approach used here with CERES-EGC to estimate oilseed rape yields and Nr emissions related to its production takes into account the variability of local conditions and nitrogen fertilization practices adopted by farmers in the Lorraine region. However, since the model was run only for the year 2012 because of data availability, the effect of interannual climate variability was not tackled in this study. Thus, it would be desirable to run simulations for a longer duration and thus make it possible to place oilseed rape in a representative crop rotation of the region. This would probably significantly affect the modeled outputs.

In this study, we chose to accumulate simulated fluxes from the harvest of the previous crop to the harvest of oilseed rape because of lack of meteorological data availability. We thus attributed the emissions associated to the residue management of the previous crop. However some studies (eg, Gabrielle et al. 2014) opted for simulations from the sowing of the considered crop to the sowing of the following crop.

Direct N_2O emissions simulated by CERES-EGC were consistently lower than the estimates based on the Tier 1 IPCC guidelines. Regarding indirect N_2O emissions, the opposite trend was found. Thus, the total N_2O emissions simulated by CERES-EGC are quite similar to those obtainable with the IPCC methodology. By contrast, when comparing regional emissions related to current fertilization practices to those related to optimal practices, the difference between the two methodologies becomes significant. The decline in direct N_2O emissions after the adoption of optimal practices simulated with CERES-EGC is 5 fold lower than the decline calculated by using IPCC methodology. Thus, using IPCC guidelines would result a greater benefit of best management practices on the environmental balance of biodiesel from oilseed rape.

This study shows that practices based on organic fertilizers are causing significant emissions of N_2O compared to practices with only inorganic fertilizers. Because organic nitrogen remains available in the soil for the following crops and contribute to their yields, allocating part of the emissions occurring in the year following application to these following crops could be considered.

The simulated oilseed rape yields during the year 2012 were slightly overestimated. This could impact the environmental balance of biodiesel since using the observed yields instead would result in higher emissions per ton of grains harvested. However, the simulated yields were overall very similar to the oilseed rape yield recorded during the past five years, on average. They may thus be considered more representatives of yields for the area.

4.2. LCA outputs

With the current fertilization practices, the GWP intensity of biodiesel from oilseed rape obtained in this study is quite similar to that estimated by the European Commission for the whole Europe (i.e. 44 g CO_2 eq per MJ) , which used the same method of co-product handling. However, our estimated environmental performance of biodiesel from oilseed rape in Lorraine is most likely not representative of the whole France or Europe because of the specific characteristics of this region, in which yields are also usually below the national average.

In addition to the effect of yields and nitrogen emissions on the outputs of the LCA, the chosen allocation method has a key role in the environmental performance of biodiesel from oilseed rape. For example, the use of a mass-based allocation could reduce life-cycle GHG emissions of the biodiesel chain. The opposite could be observed if co-products were handled by system expansion. However when using this method, it should be borne in mind that some unrealistic assumptions which simplify market mechanisms are inevitable.

The modifications occurred in the inventory data related to feedstock production when we tested the effects of optimal fertilization practices are the source of the environmental balance of biodiesel improvement. Improving the environmental performance of the biorefinery would further reduce the LCA indicators of biodiesel.

5. Conclusion

The environmental impacts of biodiesel from oilseed rape were assessed in the French Lorraine region. The use of an agro-ecosystem model allowed considering local conditions and fertilization practices heterogeneity when estimating oilseed rape productivity and related reactive nitrogen emissions. LCA results showed that the GHG saving currently permitted by the substitution of fossil diesel is not consistent with the sustainability criteria to be respected at the European scale. Famers must opt for optimal nitrogen fertilization practices in order to mitigate the environmental impacts of the whole biodiesel chain. Such improvement in the crop management can lead to produce a more environmental friendly biodiesel, at least when land use change effects are neglected (both direct and indirect). However, these effects may be large and are currently coming in sharp focus from a policy and sustainability perspective.

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