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Biogenic greenhouse gas emissions linked to the life cycles of biodiesel derived from European rapeseed and Brazilian soybeans

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Abstract

Biogenic emissions of carbonaceous greenhouse gases and N_2O turn out to be important determinants of life cycle emissions of greenhouse gases linked to the life cycle of biodiesel from European rapeseed and Brazilian soybeans. For biodiesel from European rapeseed and for biodiesel from Brazilian soybeans grown for up to 25 years with no tillage on arable soil for which tropical rainforest or Cerrado (savannah) have been cleared, the life cycle emissions of greenhouse gases are estimated to be worse than for conventional diesel. Improving agricultural practices should be an important focus for cleaner production of biodiesel. These may include increasing soil carbon stocks by, e.g., conservation tillage and return of harvest residues and improving N-efficiency by precision agriculture and/or improved irrigation practices.

Keywords: Biogenic greenhouse gas emissions; Biodiesel; Rapeseed; Soybean

1. Introduction

Biodiesel, consisting of the methyl or ethyl ester of fatty acids, is rapidly developing into a significant fuel for automotive purposes [1–3]. The environmental impacts of substituting conventional diesel by biodiesel have been characterized as beneficial by some authors [1,3] and the characterization and quantification of these impacts attract increasing attention.

It has been reported that substitution of diesel by biodiesel reduces sulphur dioxide (SO_2) emissions, but tends to increase the emissions of nitrogen oxides (NO_x) from diesel engines and that, on substitution, the acute effects on respiratory organs apparently do not change significantly [1,4–7]. The impact on emissions of particulate matter is complex, with evidence that biodiesel substitution reduces the amount of particulate matter emitted, the size of emitted particles and mutagenicity, increases the soluble organic fraction, enhances oxidative reactivity and cytotoxicity and impacts the nanostructure of diesel soot [4,8,9]. The latter is a determinant of particle hazard [10]. The overall effects of the changes of emissions on the human health impacts of exposure are not clear and await further research [7]. Concerning impacts on ecosystems, Koh [11] has pointed out that a large expansion of biodiesel production may well lead to habitat and biodiversity losses. In this context he particularly mentions the possibility that expansion of soybean production may be detrimental to biodiversity hotspots in the tropics such as tropical rainforests and the Brazilian Cerrado, the latter being an often wooded and brush-like savannah.

Another important environmental aspect of biodiesel use concerns the life cycle (seed to wheel) emissions of greenhouse gases. There are already a considerable number of studies on the life cycle emissions of greenhouse gases associated with biodiesel. To the extent that these deal with biodiesel from virgin vegetable fatty acids, these have mainly focused on CO_2 emissions linked to fossil fuel inputs and to a lesser extent on N_2O emissions linked to crop growth [1,2,12–24]. Most studies considering fossil fuel inputs, and occasionally N_2O emissions, have concluded that substituting diesel by

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biodiesel leads to lower emissions of greenhouse gases [1,2,12–15,20–22,24], but some studies [e.g. 19] have drawn the opposite conclusion. One study has explicitly focused on the application of cleaner technology in the synthesis of biodiesel from vegetable oil. This study actually shows for all technologies studied higher emissions of greenhouse gases linked to the biodiesel life cycle, if compared with conventional diesel [23]. Assumptions regarding inputs and outputs (such as N_2O) of the biodiesel life cycle are important in determining the outcome of life cycle assessments for biodiesel based on virgin vegetable oils, and so is allocation of life cycle greenhouse gas emissions to vegetable oil and other outputs of cropping. Emissions may be allocated to vegetable oil only, to the marketable products involved (i.e. oil and meal) or to all harvested biomass. In the latter two cases allocation may be on the basis of prices, or physical units such as energy or weight. Choices made regarding allocation can lead to large differences in outcome [25].

One of the biodiesel studies available so far [17] has considered the combined biogenic life cycle emissions of N_2O and carbonaceous greenhouse gases such as CO_2. The latter are associated with changes in the carbon content of ecosystems. Kim and Dale [17] found net sequestration of carbon in arable soils in case of US soybean based biodiesel. Such sequestration was confirmed by Adler et al. [26]. On the other hand there have also been studies showing that biofuel production may be associated with carbon losses from ecosystems. Studies regarding bioethanol from European starch or sugar crops and regarding palm oil have shown that such losses may have a significant impact on the biofuel 'seed to wheel' emissions of greenhouse gases [27,28].

The aim of this paper is to estimate the emissions of biogenic carbonaceous gases such as CO_2 and of N_2O linked to the life cycle of biodiesel derived from European rapeseed, currently the dominant type of biodiesel [1,2], or from Brazilian soybeans, for which a large expansion of production is intended [3]. The global warming potentials of these gases used here are on the basis of a 100 years period. Apart from allocation between different crops, allocation based on prices is employed here in the life cycle evaluation of greenhouse gases. The prices used for this allocation are the prices in the decade up to 2007, before the major price rises of 2007. To focus on the quantitative importance of these estimates, we will compare the estimates for the combined emissions of biogenic greenhouse gases with the difference in the emission of fossil fuel derived greenhouse gases of conventional diesel and biodiesel.

2. Biogenic emissions, yields and allocation

2.1. Carbonaceous gases

In Brazil, soybean production concerns largely soils that have recently been taken into agricultural use. The expansion of Brazilian soybean production has been in the Cerrado region [3,29,30], and has also replaced tropical rainforest [31–33]. Here, we will separately consider direct replacement of rainforest and Cerrado by soybean production.

The aboveground biomass on arable fields is different from that in tropical forests or on the Cerrado. Based on a large data set, Fearnside [33] estimated the amount of aboveground biomass in tropical Brazilian forest to be on average 464 Mg ha^{-1} and the average aboveground biomass on farmland over a yearly period about 0.56 Mg ha^{-1}. Using an estimated carbon content of forest biomass of 50%, this reflects an estimated difference of 231 Mg C. As there may be trees extracted for wood production before burning to clear for arable land, it has been proposed to use a factor 0.72 to arrive at the amount of C that is emitted in gaseous form due to clearing for agriculture [33]. Burning used in clearing areas for agriculture will also involve loss of soil carbon. For Brazilian forests this amount can be estimated at about 8 Mg ha^{-1} [33,34]. Due to burning there will be the release of both CO_2 and non-CO_2 greenhouse gases. The latter add about 10–20% to the emission in terms of CO_2 equivalence [28,33]. All in all, it can be estimated that per hectare 703–767 Mg CO_2 equivalent will be emitted on the conversion from tropical rainforest to arable land. As it will be supposed here that corn and soybean will be grown in rotation on land that is cleared, half of this loss will be allocated to growing soybeans.

For the Cerrado region the difference in aboveground biomass between the original vegetation and crops is on average about 16.7 Mg C ha^{-1} [35]. There are no empirical data about the loss of C from Cerrado soil on clearing the savannah by burning. However, losses from soils on burning vegetation are known to vary between 2.7 and 10 Mg ha^{-1}[33,34,36]. Here the loss from Cerrado soil on clearance by burning is estimated to be 6 Mg C ha^{-1}.

Equal to burning of tropical forests, burning of Cerrado vegetation adds 10–20% in terms of CO_2 equivalence [28,33]. So, overall the emission of greenhouse gases on converting the original Cerrado to arable land amounts to an estimated 92–103 Mg CO_2 equivalent ha^{-1}. Again, half of this loss will be allocated to growing soybeans, as corn and soybeans will be grown in rotation.

To allocate emissions due to land clearing, assumptions have to be made as to the time that the land will remain in agricultural production. In Brazil agricultural lands are often abandoned when yields go down, to be replaced by higher yielding virgin lands [33,37]. Here we will consider two possibilities for the time that the land will remain in use. The first one, 10 years, reflects early abandonment, the other is substantially longer: 25 years. What happens after abandonment is here outside the system boundary of the analysis.

In cultivating soybeans, there may also be carbon loss from soils [35,36]. In the Cerrado region this C loss is estimated to be ~0.5 Mg ha^{-1} year^{-1} for continuous zero tillage and up to 1.5 Mg ha^{-1} year^{-1} for conventional tillage, when there is rotation of soybean and corn and there are two crops per year [35]. It is assumed here that half of the yearly soil C loss can be allocated to the soybean crop. Working on this assumption, per soybean harvest there is a loss of 0.92 Mg CO_2 ha^{-1} year^{-1} for zero tillage and 2.75 Mg CO_2 ha^{-1} year^{-1} for conventional tillage. For the Amazon region no direct measurements regarding soil carbon in soybean cultivation could be found. Estimates for soil carbon in agricultural soils used for soybean production vary widely, with some estimates suggesting large losses [38–40] and other estimates [31] some gains in soil carbon for soybean no-till systems. Here a range of changes in soil carbon levels will be considered, varying between a yearly loss of 0.75 Mg C ha^{-1} year^{-1}, similar to conventional tillage on Cerrado soil [35] and a net sequestration of 0.175 Mg soil carbon ha^{-1} per soybean harvest (half of the yearly average of the values given by Lal [41]). The latter corresponds with 0.64 Mg CO_2 ha^{-1} year^{-1}.

European arable soils are estimated to lose on average 0.84 Mg C ha^{-1} year^{-1}, which corresponds with 3.08 Mg CO_2 ha^{-1} year^{-1} [42] There is on such soils usually one crop per year. Allocation of C losses of soils to specific crops is questionable, as use of European arable soils tends to be subject to rotation to reduce pests. For instance, in Germany and the UK planting of rapeseed is for this reason restricted to once every 3–5 years to avoid club root and other Brassica diseases [2,43].

2.2. N_2O emissions associated with biodiesel crops

In the production of biodiesel, biogenic N_2O emissions are associated with the cropping of rapeseed or soybean when conversion by microorganisms of fixed N-compounds takes place. Fixed nitrogen is added to the agricultural fields by way of fertilizer, manure, harvest residue biological fixation and atmospheric deposition. The size of the biogenic N_2O emissions is subject to considerable debate. Mosier et al. [44] have presented data suggesting that direct N_2O emissions from agricultural fields associated with the cropping of European rapeseed and Brazilian soybeans may be about 1.25% of added fixed nitrogen. In addition, they argue that fixed nitrogen lost from agricultural fields may also be subject to microbial conversion to N_2O (estimated at 2.5% of fixed N lost). Crutzen et al. [45] have taken a different approach and present some evidence that the combined direct and indirect emission may amount to 3–5% of the fixed nitrogen added. Moreover there is uncertainty since local conditions may significantly affect local conversion rates [44].

In view of this, we will use a wide range of 1.5–5% of fixed nitrogen added to the agricultural fields for the N_2O emission. For biodiesel from rapeseed it is further assumed that – in line with German practice – on average 165 kg fixed N is added per hectare of harvested rapeseed [46]. For soybean production in Brazil the input of fixed N is estimated to be 170 kg ha^{-1} of harvested soybeans [29]. Assuming that climate forcing by 1 kg N_2O is as large as that of 296 kg CO_2 [25] and that N_2O emission from soils is 1.5–5% of the input of fixed N into cropping, this would mean that per hectare of rapeseed the emission of N_2O corresponds with 0.73–2.44 Mg CO_2 equivalent and per hectare soybeans to 0.76–2.52 Mg CO_2 equivalent.

2.3. Yields and allocation

In case of (Brazilian) soybeans the yearly yield is about 2.8 Mg ha^{-1} [47]. Somewhat less than 19% of this yield can be obtained as oil and 78.6% as meal [47–49]. Using average prices for Brazilian soybean oil and meal over the decade–2007 [47,50], ~45% of the biogenic emissions linked to soybean cropping should be allocated to oil and 55% to meal.

In case of European rapeseed, the yield is ~3 Mg ha^{-1} [48,50]. About 38.5% of this yield can be obtained as oil and ~54% as meal. Based on average prices in NW Europe during the decade–2007 [47,50] the allocation of biogenic emissions should be on a basis of ~72.5% for oil and ~27.5% for meal.

3. Fossil fuel related emissions

For the purpose of estimating cumulative energy demand, the study of Zah et al. [21] is used, based on the Ecoinvent database, which is of relatively high quality. Zah et al. [21] give data for the cumulative energy demand for conventional diesel and biodiesel based on European rapeseed and American soybeans with allocation based on prices. The cumulative energy demand for biodiesel based on European rapeseed is ~60% and for Brazilian soybean based biodiesel 70% of the cumulative energy demand for conventional diesel. Additionally, it is assumed that methanol used in biodiesel (estimated at 9% of biodiesel weight) is fossil fuel-based, that the heat of combustion of biodiesel is 17% lower, on a weight basis as determined according to ASTM method D 240, than the corresponding value for conventional diesel [51] and that the life cycle emission of greenhouse gases linked to a kilogram of conventional fossil diesel is ~3.57 kg CO_2 equivalent [2].

From these data it is estimated that, when the fossil fuel mix is assumed to be the same for the production of all types of diesel and when the requirement is not to perform worse than conventional diesel, the combined emission of biogenic greenhouse gases per kilogram biodiesel should not exceed 1.2 kg CO_2 equivalent for biodiesel from European rapeseed and 0.9 kg CO_2 equivalent for soybeans from Brazilian soybeans.

4. Results

First we will consider the emissions of biogenic greenhouse gases per hectare of arable soil, using different assumptions as to previous vegetation, time that the arable soil remains in use and tillage system. Fig. 1 shows the biogenic emissions in kg CO_2 equivalent ha^{-1} year^{-1} for soybean production in the Cerrado region. Fig. 2 shows such emissions for arable land previously covered by tropical rainforest. Initial carbon loss dominates the cumulative greenhouse gas emission score for soybean production in both the Cerrado region and tropical rainforests, except for the 25-year time horizon in the Cerrado region. Overall uncertainties in the

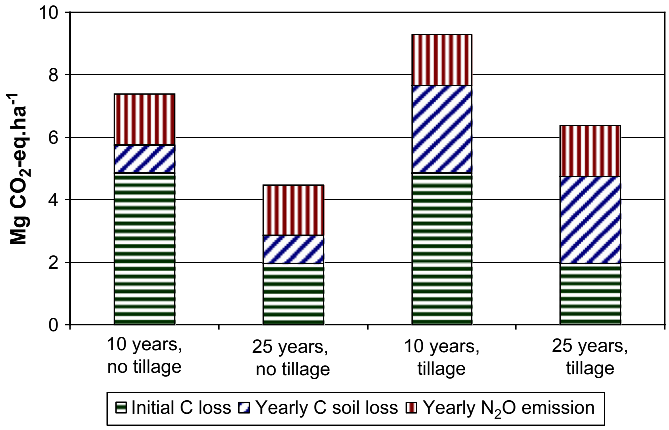

Fig. 1. Yearly typical CO_2 equivalent emission in Mg ha^{-1} from soybean agriculture in the Cerrado region caused by initial C loss, yearly C soil loss and yearly N_2O emission. Overall uncertainties in the figures are ±10–30%.

figures are ±10–30%, mainly caused by the uncertainty in N_2O emission estimates.

Table 1 shows the biogenic, fossil fuel related and total emissions in kg CO_2 equivalent kg^{-1} conventional diesel and biodiesel from European rapeseed, and soybeans grown on soils for which forest or Cerrado were recently cleared, when allocation is based on prices. Rapeseed based biodiesel performs worse than conventional diesel regarding the life cycle emission of greenhouse gases, as the biogenic emissions exceed the 1.2 kg CO_2 equivalent kg^{-1} biodiesel. For soybean derived biodiesel, Table 1 shows the values for biogenic carbonaceous gases and N_2O emissions on allocation to prices, when the arable land takes the place of tropical rainforest or Cerrado, and remains in use for 10 or 25 years, assuming zero tillage. Here the values exceed the 0.9 kg CO_2 equivalent kg^{-1} biodiesel that would allow soybean based biodiesel not to be worse than conventional fossil diesel.

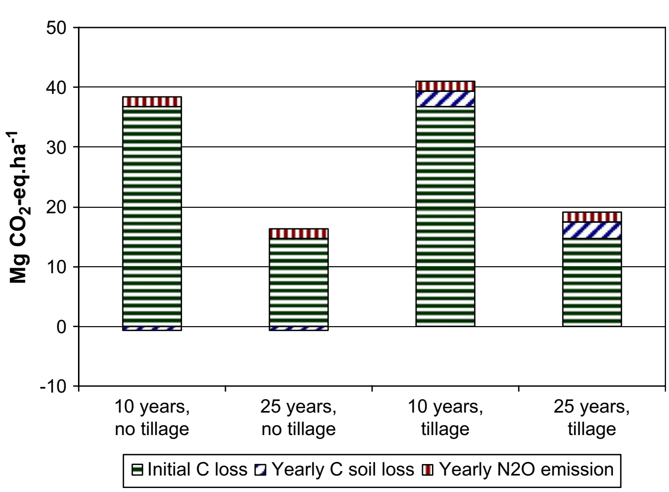

Fig. 2. Yearly typical CO_2 equivalent emission in Mg ha^{-1} from soybean agriculture caused by initial C loss, yearly C soil loss and yearly N_2O emission in area previously covered by tropical rainforest assuming carbon sequestration by no-till agriculture. Overall uncertainties in the total figures are ±10–20%.

Table 1
Life cycle CO_2 equivalent emissions kg^{-1} biodiesel due to the emission of carbonaceous greenhouse gases and N_2O linked to cropping, when allocation to vegetable oil is on the basis of prices

Fuel type	Emission in kg CO_2 equivalent kg^{-1} diesel		
	Biogenic	Fossil	Total
Biodiesel from European rapeseed	2.2–3.1	2.4	4.6–5.5
Biodiesel from Brazilian soybeans grown for 10 or 25 years instead of tropical rainforest	11.2–32.5	2.7	13.9–35.2
Biodiesel from Brazilian soybeans grown for 10 or 25 years instead of Cerrado	2.7–8.0	2.7	5.4–10.7
Conventional fossil diesel	–	3.6	3.6

5. Discussion

Clearly in case of growing soybean on deforested land, the loss of the aboveground C stock in converting tropical forest into arable land has a major impact on the life cycle greenhouse gas emissions of biodiesel estimated here. The loss assumed here is similar to losses reported for other tropical forests [28,52]. The conclusion as to growing soybeans for biodiesel production on deforested land does not have a favourable impact on the emission of greenhouse gases is similar to that of Righelato and Spracklen [53] who argued that saving forests is to be preferred over growing crops for biofuel production.

In arriving at the estimates of Table 1, however, assumptions have been made. First, it has been assumed that the average loss of carbon from European soils is applicable to rapeseed, in view of the fact that rapeseed is part of the crop rotation system. On the other hand, as rapeseed is a crop with relatively low yields, it may be argued that cropping rapeseed will be associated with relatively large losses of soil carbon because crops with higher residue yields tend to be more conducive to the sequestration of carbon in soils [54,55]. For instance the C inputs with residues in to soil (in Mg ha^{-1}) have been reported to be 4.61 for sugarbeet, 1.80 for potatoes, 1.95 for corn, 1.82 for wheat and 0.96 for rapeseed [54]. Moreover part of the land taken into use for rapeseed production was formerly out of production (set aside land) [2], and this would mean that losses of soil carbon linked to rapeseed cultivation would probably be larger than from agricultural land that remained in production [42,54,56]. Thus it would seem that the assumption used here, a yearly loss of 0.84 Mg C ha^{-1} year^{-1} from European agricultural soil [42] would be a conservative estimate in case of rapeseed cultivation.

Second, as to Brazilian soybeans, it is assumed here that they are grown in rotation with corn and that half of the yearly soil C loss can be allocated to the soybean crop. The latter assumption is conservative in the sense that like in case of rapeseed, soybean is, if compared with corn, a low yielding crop contributing relatively little to soil organic carbon sequestration [37,54,57]. The input of C into soil with residues associated with soybeans has been reported as 1.02 Mg ha^{-1}, whereas it is 1.95 Mg ha^{-1} for corn [54].

Third, as pointed out in Section 1, the estimates for fossil fuel related CO_2 emissions vary considerably. The values used here are based on the study of Zah et al. [21]. Other studies arrive at higher values [19,23], but there are also lower estimates. When it is for instance assumed that the cumulative energy demand of biodiesel is actually 30% of the cumulative energy demand for conventional diesel, then the values for biogenic emissions in Table 1 should not exceed 2.1 kg CO_2 equivalent kg^{-1} of biodiesel. Actually, these values in Table 1 are larger.

Fourth, the maximum period over which the annual effects of land use change are calculated is 25 years. One may argue that this period does not do justice to arable fields that remain in use for a longer time. On the other hand the 25-year period used here exceeds the 20-year period recommended for this purpose by the Intergovernmental Panel on Climate Change [58].

Fifth, only a limited number of environmental impacts of biodiesel production have been considered. Zah et al. [21] have considered a larger number of impacts. As to Brazilian soybeans the impacts for eutrophication, smog and ecotoxity are estimated to be larger than for conventional diesel, whereas for European rapeseed the impact for eutrophication estimated by Zah et al. [21] is larger than that of conventional diesel. These impacts are largely related to the growth of crops for biodiesel production.

All in all, it can be concluded that the seed to crop stage in biodiesel production has a large impact on the life cycle emissions associated with biodiesel production from European rapeseed and Brazilian soybeans. This has implications for cleaner production. Harding et al. [23] have shown that reductions in life cycle emissions of greenhouse gases up to about 4% are possible by the application of cleaner production to the synthesis of biodiesel from virgin vegetable oil. Changes in agricultural practices may allow for larger improvements [27,28,59–61]. Not cutting forests to generate arable land, but conserving soils so that they can be used productively for a much longer time helps to improve the environmental performance in Brazilian agriculture [33,37]. Using no-till practices instead of mechanical tillage, use of cover crops and maximizing the return of harvest residues to arable soils leads to higher soil carbon stocks and this lowers life cycle CO_2 emissions of biofuels [27]. Life cycle N_2O emissions of biofuels can be lowered by improving the N-efficiency of agriculture. Precision agriculture [60], higher soil carbon levels [41] and improved irrigation practices [61] may be conducive to improved N-efficiency.

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