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Report 379

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Summary

This report focuses on the effects of different allocation methods on three major sustainability aspects (fossil energy use, greenhouse gas emission and land use) of biodiesel production from oilseed rape produced in the Netherlands. It was assumed that oilseed rape replaces green fallow and indirect land use change was not taken into account.

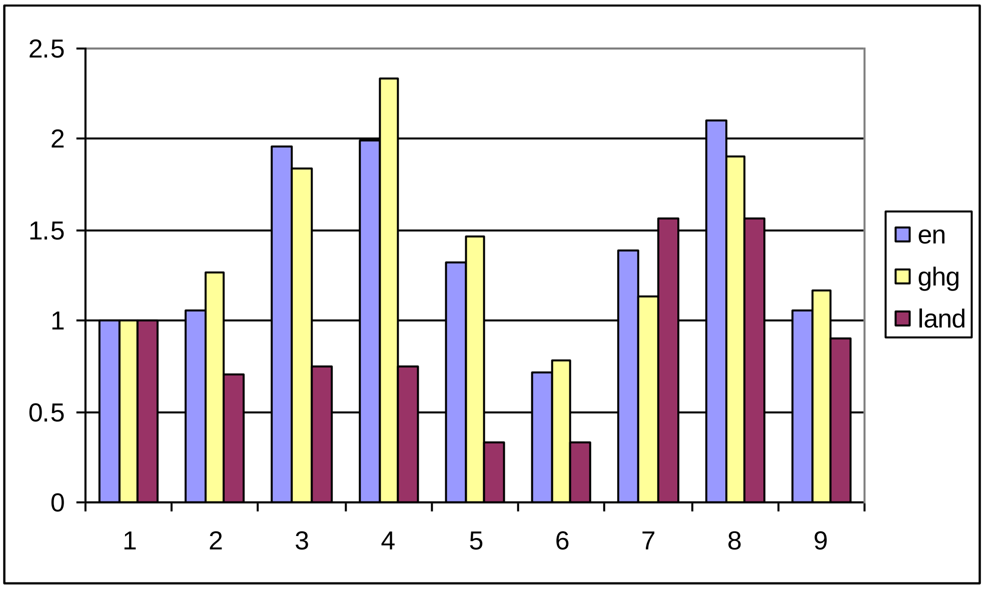
Allocation of environmental burdens over different products made from one commodity is a major problem in Life Cycle Assessment. LCA principles demand the use of system expansion as allocation method whenever possible. Only when system expansion is not possible, attributional allocation methods might be used, preferably methods with a physical basis, like energy content. A physical basis has the advantage of simple, constant ratios between co-products whereas an economical basis has the disadvantage of continuously changing price levels. For the evaluation of the sustainability of biofuels, the EC demands a calculation of the GHG emission from the production chain of the biofuels, using allocation on the basis of energy content. This is not in accordance with the LCA principles but this method was chosen for reasons of simplicity and for limiting administrative burdens.

Production of biodiesel from oilseed rape delivers three co-products: straw, left when the seeds are harvested, meal, left when the oil is extracted from the seeds, and glycerin, a co-product from esterification of the oil. Straw is mainly left in the field but is also used as bedding in stables and it could be used for energy production. Meal is used as a protein rich animal feed component and might also be used as an energy source. Glycerin can be purified and used in food, feed and cosmetics, replacing glycerin produced from mineral oil, and is also used as an energy source since the market for purified glycerin is saturated.

In this study different scenarios with different allocation methods combined with options for the use of co-products were established and evaluated for their effects on energy yield, GHG emission reduction and land use, compared with the use of fossil based diesel. As basic scenario (scenario 1), the EU Directive on the promotion of Renewable Energy (RED) was followed: using attribution on the basis of energy content as allocation method while straw and glycerin are not supposed to be valuable co-products, only meal is involved in allocation in this scenario. In alternative scenarios straw and glycerin were also involved in attribution, based on energy content (scenario 2) or on economic value (scenario 9), or different variants of system expansion were evaluated. Meal was used as feed, replacing soy meal, in scenarios 3, 4, 5 and 6 or used for the production of energy in scenarios 7 and 8. Glycerin was replacing synthetic glycerin in scenarios 3, 4 and 5 and used for the production of energy in scenarios 6, 7 and 8. Straw was used for the production of energy in scenario 8.

As shown in the figure below (Figure 3 from chapter 3), the results of the scenarios concerning net energy yield, net GHG emission reduction and allocated land use can be very different.
The high values of net energy yield and net GHG emission reduction in scenarios 3, 4 and 5 are based on the replacement of synthetic glycerin by glycerin from the esterification process, the low values for allocated land use in scenarios 3, 4, 5 and 6 are based on the use of rape meal in animal feed, with replacing import of soy beans showing a lower value compared with replacing import of soy meal. The high values of net energy yield and net GHG emission reduction in scenarios 7 and 8 are based on the use of rape meal and straw (only scenario 8) for the production of energy. In these scenarios no other agricultural (co-)product is replaced and hence, the value for allocated land use is high. Apparently a high efficiency in net energy yield and net GHG emission reduction has a clear trade off in a large allocated land use.

The currently most probable scenarios are scenario 4 or 5, as long as the market has a demand for purified glycerin, and scenario 6 when the market for glycerin is saturated and for all new production. This last scenario has a relatively poor net energy yield and net GHG emission reduction, on the other hand its allocated land use is small. The efficiency in energy yield and GHG reduction could be improved without a trade off in larger allocated land use by harvesting the straw for the production of energy. This improvement, however, has a trade off in a lower soil carbon storage.



Summary of results, relative to scenario 1 with a net energy yield (en) of 39 GJ ha^{-1}*, a net GHG emission reduction (ghg) of 2.0 tonne* CO_2*-eq ha*$^{-1}$ *and an allocated land use (land) of 0.64 ha ha*$^{-1}$*.*

The EC Directive gives threshold values for the efficiency of GHG emission reduction being considered acceptable of 35% for now up to 60% from the year 2018 for new production. Since the least efficient scenario still shows an efficiency of 46%, all scenarios can be accepted by the EC with the current threshold. For the future, only scenarios with system expansion with replacement of synthetic glycerin or energy production from straw do have a sufficient efficiency, but these scenarios do not comply with the allocation methods prescribed in the RED. Because replacement of synthetic glycerin is not considered an option for new production, the only option to reach the thresholds in the future seems to be harvesting the straw for energy production, however at the cost of soil carbon storage.

Conclusions

Allocation by means of system expansion gives the opportunity to account for real effects of the use of co-products and is therefore to be preferred over allocation on the basis of attribution.

System expansion involves often arbitrary choices which can have large effects on the values of sustainability indicators. This introduces a high uncertainty level in allocation by means of system expansion and necessitates once more the importance of drawing realistic scenarios.

Since a high net energy yield and a high net GHG emission reduction function as a trade-off for allocated land use, focusing on GHG emission reduction efficiency only, without taking the land use into account, gives a too narrow view of the sustainability of biofuel production.

The reduction in land requirement due to the use of co-products as animal feed can be very high, but is also uncertain, due to the dependence on the yield levels of the different crops. Because of its magnitude in reduction the use of co-products as animal feed can play a significant role and should be part of a sustainability assessment of biofuel production.

Harvesting straw without accounting for its effect on soil carbon significantly overestimates the net reduction in GHG emission and changes in soil carbon should therefore be added to the balance calculations. In areas with low soil organic matter it can also affect negatively the crop production possibilities.

1. Introduction

The production of biofuels from agricultural crops involves a number of (biophysical) sustainability aspects: fossil energy use, greenhouse gas (GHG) emission, (in)direct land use, water, fertilizers and biocides use. In this report the focus is on the first three aspects which are of major global concern. Use of biofuels can certainly improve the sustainability of our energy use by decreasing the depletion rate of fossil fuels and possibly reducing GHG emission, although its quantitative potential is debated. On the other hand it is clear that substantial production of biofuels involves extensive areas of land, with increasing risks for food, feed and other land related products and biodiversity as a result. If natural lands such as forests and grasslands are used to cultivate crops for biofuels, the net GHG emission may even be increased instead of reduced during the coming decades. Therefore, it is important to evaluate the sustainability of biofuel production from agricultural crops on the three aspects mentioned above in an integrated way.

Production of biofuels from agricultural crops normally involves the production of marketable co-products. In order to make a fair energy- and GHG-balance, it is necessary to allocate a part of the energy use and GHG emission caused by the production of the biofuels to these co-products. Also for land use it is reasonable to allocate it partly to the production of co-products. For the current calculation of the GHG-balance of biofuels according to the European Union Renewable Energy Directive (RED) it is required to perform this allocation by means of an attribution on the basis of the energy contents of the co-products (EC 2009). This allocation method, attribution, however, is not in accordance with the principles of Life Cycle Assessment (LCA, ECS 2006-a; ECS 2006-b). Attribution does not take into account the real effects of the production of the co-products and is therefore rather an administrative in stead of a realistic calculation method (Corré & Conijn 2008, Conijn & Corré 2009). Attribution is as ‘Attributional LCA’ certainly a recognized method of allocation, but only when system expansion is not possible, like in existing production systems where the energy used or GHG emitted is divided between different products (e.g. between milk and meat in dairy farming; Casey & Holden 2005). ‘Attributional LCA’ is not meant to be used for new production that will replace other production, as in the case of biofuels. For new production it is in principal possible to investigate what changes this production will cause in the production of other products. In that case ‘Consequential LCA’ can be used, a method that uses system expansion (Thomassen *et al.*, 2007). System expansion involves investigating the consequences of replacing existing products by co-products of biofuel production. Energy use, GHG emissions and land use related to products, that are replaced by co-products of biofuel crops are allocated to these newly produced co-products. In this way all consequences of the production of biofuels in relation to energy, GHG emission and land use become fully exposed.

In practice system expansion implicates besides an analysis of replacing fuels of fossil origin also an analysis of the replacement of existing products by the co-products of the biofuel production. Co-products of biofuel production will often replace other (agricultural) co-products and therefore normally a (very) complex analysis is necessary (e.g. Kim & Dale, 2002). This is the main reason that mostly a simpler calculation method with attribution on the basis of energy content or eventually on the basis of mass or economic value is chosen. This implicates, however, that the actual consequences of biofuel production remain out of sight and the calculated result has an increased uncertainty level. An example of not recognized effects are the consequences for land use. Biofuel production has on first sight an easy to quantify effect on land use: the land on which the crop is produced. However, when co-products can replace other agricultural products this land use could be compensated (partly) by decreased land use elsewhere. In methods of attributional allocation it is possible to allocate land use to the co-products, analogue to e.g. energy use, but in this case the actual use of the co-products is also not taken into account. This use can vary from replacing agricultural products with a real land use to replacing synthetic products to which no land use can be allocated. Furthermore, system expansion can indicate in which way co-products can be used to reach an optimal sustainability of biofuel production.

Critical in system expansion is the choice of products which will be replaced by the co-products of biofuel production. In many cases this will be co-products of other agricultural crops, with as a result also consequences for the other products of these agricultural crops. For this reason the system to analyse can increase quickly and possibly become unmanageable. To prevent this it is necessary to keep the system to describe limited but still realistic.

In this study system expansion as method of allocation is applied and compared to attributional allocation methods. Results of calculations will be shown for the energy balance, the GHG balance and land use for the production of biodiesel from rapeseed (rape methyl ester, RME) produced in the Netherlands with green fallow as replaced land use. Co-products are straw, rape meal and glycerin. The straw is used as bedding in stables and with a low market price a part is left on the land. Rape meal is used as animal feed and crude glycerin can be used after purification in personal care products, food products and animal feed. Since the market for purified glycerin is saturated, raw glycerin is currently also used for low value purposes. Co-fermentation with manure or other substrates to biogas gives good results (Amon *et al.*, 2006) and addition of larger quantities as energy source to animal feed seems also possible (Boekhoff *et al.*, 2008). The results will be compared with the results of calculations with a method of attribution on the basis of energy contents and a method of system expansion in which all co-products are converted to energy. This latter method is in accordance with the principles of consequential LCA, but it does not reflect the (probable) actual use of the co-products. As additional illustration also the results of an attribution on the basis of economic values is shown. This type of attribution has as advantage that more is allocated to co-products with higher economic values. Disadvantage, however, is the sensitivity to changes in price levels, causing strongly fluctuating results. This makes this method less suitable for the calculation of sustainability indicators. Macro-economic studies can estimate the ‘real’ replacement of products by the co-products of biofuel production based on commodity prices. E.g. rape meal may replace soy meal but also animal feed ingredients from other crops or from residues of food chains. The study described in this report has not investigated these market changes, but systems of replaced products were selected to illustrate the effects, without considering the effects of price development on the actual replacement of alternative products.

Using different allocation methods can have large effects on the environmental impact of the production of biodiesel from oilseed rape (Bernesson *et al.*, 2004). However, the system expansion in that study was limited to the replacement of synthetic glycerin by purified glycerin from esterification and by replacement of soy meal by rape meal and did not include use of straw, alternative use of glycerine and consequences for land use. Moreover, no background data on the calculations of the effects of replacing products are shown and thus the results can not be used to in other calculations.

Opportunities for calculations using system expansion will be added to the calculation tool E-CROP, developed in recent years for the evaluation of sustainability and optimization of the production of different energy crops – biofuel chains (Corré & Conijn 2008, Corré & Langeveld 2008, Conijn & Corré 2009). E-CROP already offers the possibilities of calculating (1) attribution on the basis of energy content and (2) system expansion with conversion of co-products to energy (Conijn & Corré 2009). With new methods of system expansion in E-CROP it would be possible to analyse current practices concerning the use of co-products and to give a better evaluation of some sustainability aspects of biofuel production. Furthermore these calculations will be used in the EC-FP7 project ‘Ecodiesel’ (Grant Agreement 219040) for the evaluation of the sustainability of the biodiesel production based on oilseed crops produced in Europe. This project aims at investigating possibilities for improvement of the biodiesel production in Europe, where besides optimisation of crop production the use of co-products is an important issue.

2. Methodology

2.1 Basic system

As basic starting point we used the report 'Sustainability aspects of production and processing of energy crops in South-East Netherlands' (Conijn & Corré 2009, in Dutch). In Figure 1 the quantities of end, intermediate and co-products for the average production level of winter oilseed rape in South-East Netherlands are shown (Conijn & Corré 2009).

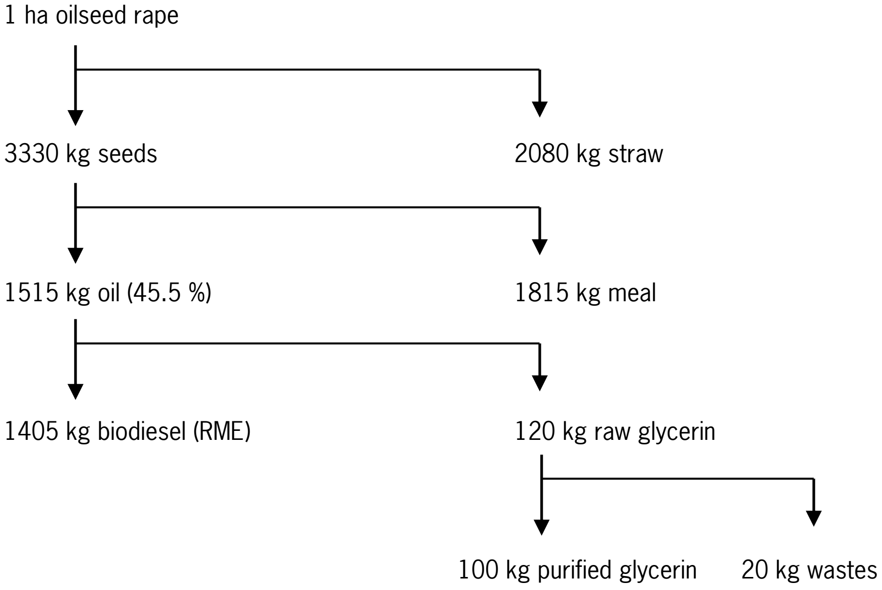


Figure 1. Flow chart of the production of biodiesel and co-products from oilseed rape. All values are expressed in dry matter. Fresh weight of seeds, straw, meal and glycerine are respectively 3700 kg (10% moisture), 2500 kg (17% moisture), 2100 kg (13.5% moisture) and 140 kg (15% moisture); energy content of these (co-)products are respectively 27.6, 17, 17 and 16 MJ per kg dry matter.

2.2 Calculation methods

Calculations with the model E-CROP from Conijn & Corré (2009) result in a positive net energy yield and a positive net GHG emission reduction per hectare oilseed rape for the production of biodiesel. The results of these calculations are affected by the way of allocation of energy use and GHG emission to co-products or by the way of using co-products. In order to show the effects of different choices, a number of scenarios was established for the study described in this report, among these two that are comparable with the two basic scenarios as described in Conijn & Corré (2009).

The model E-CROP has been developed at Plant Research International in recent years to assess a number of sustainability aspects of biomass-bioenergy chains. E-CROP consists of two parts, one for the calculation of crop growth, soil dynamics and input-output relations in agriculture, and the other one for processing biomass to bioenergy. In this study, only part two was used and agricultural input data from Conijn & Corré (2009) were used. Part two is principally a tool for the calculation of energy use and production and GHG emissions in all parts of the chain and in the reference systems by means of LCA principles. The calculation allows for different methods of allocation.

Besides effects on energy use and GHG emission, the choices made in the scenarios also have effects on land use. At a defined production level the land used for the production of 1 unit biofuel is in principle fixed, part of it, however, can be allocated to the production of co-products, analogue to the allocation of energy use or GHG emission, or, in case of replacing other products, compensated by a decreased production of other crops.

Definitions

- **Gross energy yield** is the amount of fossil energy replaced by the energy produced from the harvested biomass. Besides its combustion energy it includes the energy needed to make the fossil energy available in usable forms.
- **Energy use** comprises all primary energy used over the whole chain for the production of the bioenergy. It includes direct energy and indirect energy; i.e. energy used to make direct energy available or energy used to produce agricultural and industrial inputs and machinery.
- **Net energy yield** is the gross energy yield minus the energy use.
- **Energy efficiency** is the net energy yield divided by the gross energy yield.
- **Gross GHG emission reduction** is the amount of GHG emission avoided by replacement of fossil energy by the energy produced from the biomass.
- **GHG emission** includes all emissions resulting from the production of bioenergy. The most important emissions are CO_2 emission as result of energy use and N_2O emission resulting from nitrogen inputs in agriculture.
- **Net GHG emission reduction** is the gross GHG emission reduction minus the GHG emission.
- **GHG emission reduction efficiency** is the net GHG emission reduction divided by the gross GHG emission reduction.
- **Allocated land use** is ‘gross’ land use (in E-CROP always defined as 1 hectare) minus the land that is attributed to the production of co-products or avoided in case co-products replace other crop’s land use. Allocated land use thus refers to land use allocated to biofuel/bioenergy.

In E-CROP the gross energy yield includes the energy yield from co-products, whereas in most biofuel GHG balance calculation tools gross energy yield is defined as the energy yield from the biofuel only and the energy yield from co-products is subtracted from the energy use. The net energy yield is not affected by this different definition but the energy efficiency becomes higher, with an increasing difference when the energy production from co-products increases relative to the biofuel production. The same differences are applicable for calculations of the GHG emission reduction. In the results of chapter 3 these differences will be presented by the energy and GHG emission reduction efficiency of *bio-energy* (see definitions above) and of *biodiesel* (definitions as in most balance calculation tools).

2.3 Options for allocation to co-products

Allocation of energy use, GHG emission and land use is calculated according to methods with attribution and with system expansion. In both methods different variants were used. In allocation methods using attribution, allocation can be calculated on the basis of energy content (scenarios 1 and 2) and on the basis of economic value (scenario 9) of the different products and co-products. Scenario 1 conforms to the EU Directive (EC 2009), which allows only allocation to the meal and not to the straw and the glycerin. Scenario 2 is conform the scenario ‘Attribution’ from Conijn & Corré (2009), in which allocation to straw, meal and glycerin was applied based on energy content. In allocation methods using system expansion for the different co-products (i.e. meal, glycerin and eventually straw) firstly system expansion must be defined. The different possibilities were combined to the scenarios 3, 4, 5, 6, 7 and 8, based on a number of choices related to the products replaced by straw, meal and glycerine.

Straw

Rape straw will most probably be used as bedding in stables and replace straw from cereals. Straw from cereals is a co-product from cereal production and a decrease in cereal production is not likely as a result of the production of rape straw. Depending on the price level, always a smaller or larger part of straw of cereals is left on the land and therefore it seems realistic to assume that the wheat straw that is replaced by the rape straw will still be produced, but will be left on the land. To wheat straw left on the land no energy use, GHG emission and land use can be allocated, so when this straw is replaced by rape straw no allocation can be made to the rape straw (scenarios 3, 4, 5, 6 and 7). Another option is to use the straw for the production of energy, or eventually use replaced wheat straw to produce energy. In scenario 8 rape straw is harvested and burnt in a biomass plant for the production of electricity conforms to the calculations in the scenario 'Energy' in Conijn & Corré (2009). The straw will now replace the fossil energy that would be needed to produce an equivalent amount of electricity. Recently, techniques are becoming more and more mature to use straw (and comparable biomass such as woodchips) for the production of biofuels. This option has not been elaborated in this report.

Meal

Rape meal is a protein rich component of animal feed and as such best comparable with soy meal. Soy meal contains 15% more protein and has a 15% higher feeding value on fresh product basis, according to CVB (2008). Hence, 2100 kg of rape meal can replace 1790 kg of soy meal (scenarios 3, 4, 5 and 6). This replacement ratio, however, is a simplification. The efficiencies of protein uptake and energy uptake are different for various animal species (ruminants, pigs, or poultry) and are on average better for soy meal protein in comparison with rape meal protein (Lywood *et al.*, 2009). Hence, when rape meal replaces soy meal, the digestible protein to digestible energy ratio of the feed becomes slightly lower and in order to keep this ratio balanced, rape meal should replace a combination of soy meal and a small quantity of a protein poor product, like barley or wheat (Dalgaard *et al.*, 2008; Lywood *et al.*, 2009). The part of cereal needed depends on the type of animal to be fed and so does the replacement ratio. For reason of simplicity, however, the system expansion in this study is restricted to replacing only soy meal. This replacement can take place by a decrease of the import of soy meal (scenarios 3 & 4) or by a decrease of the import of soy beans (scenarios 5 & 6).

In the case of soy meal, an allocation of energy use, GHG emission and land use of soy cultivation over oil and meal is necessary. Such an allocation was made in the data of Reinhardt & Jungk (2001, used in scenario 3) and the data of Blonk *et al.* (2008, used in scenario 4), but the method of allocation was not described in these publications. Dalgaard *et al.* (2008) made a GHG calculation for soy meal with a system expansion with results very comparable to Blonk *et al.* (2008), on the condition that the soy oil would be replaced by palm oil. When the soy oil would be replaced with rapeseed oil, the calculation of the GHG emission allocated to soy meal was much lower (Dalgaard *et al.*, 2008). Replacement of soy oil with palm oil due to a decreased demand for soy meal is more likely than replacement with rapeseed oil since palm oil currently functions as the marginal oil on the world market (Dalgaard *et al.*, 2008: Reinhardt & Zah, 2009). Land use allocation of soy meal was slightly higher with palm oil as replacing oil (Table 1) due to the higher oil yield of palm compared with oilseed rape (Dalgaard *et al.*, 2008). Dalgaard *et al.* (2009) and BioGrace (2010) did not publish data for energy use and therefore the data from Blonk *et al.* were used in scenario 4.

In the case of soy beans, a complete crop is imported and replacing 1790 kg of soy meal implicates also the replacement of 403 kg of soy oil (18.4 %) while the net oil production decreases from 1515 kg to 1112 kg ha^{-1}. The net biodiesel production decreases to 1031 kg and the net production of raw glycerin to 103 kg. For soy beans data from Blonk et al (2008) were used in the scenarios 5 and 6. Data for soy beans from Dalgaard *et al.* (2009) were very comparable with the data used. Soy meal could also be used for the production of energy by means of anaerobic fermentation to biogas and subsequent production of electricity, and will than replace fossil fuels (scenarios 7 and 8). Due to its high value as animal feed component, this option for using soy meal is less probable with the current market prices of animal feed. Literature data on energy use, GHG emission and land use for the production of soy meal and soy beans are summarised in Table 1.

Glycerin

The raw glycerin produced as co-product of biodiesel can be purified and used in e.g. food or animal feed. At first, this glycerin will replace synthetic glycerin, produced on the basis of mineral oil. However, the market for synthetic glycerin has been practically taken over by glycerin from biodiesel production and nowadays synthetic glycerin is only used for application where very pure glycerin is needed. This means that increase of the glycerin production can not longer lead to replacement of synthetic glycerin but only to replacement of lower valued components in animal feed or to replacement of fossil energy by fermenting it into biogas. Since it is not clear which components in animal feed can be replaced by glycerin (Boekhoff *et al.*, 2008) only calculations for replacement of synthetic glycerin (data from Reinhardt & Jungk 2001 in scenarios 3, 4 en 5, see Table 1) and for fermentation to biogas (conform to the scenario 'Energy' from Conijn & Corré 2009 in scenarios 6, 7 en 8) were made.

Table 1. Literature data used for replaced products.

Product	Source	Energy use	GHG emission	Land use
soy meal		MJ kg^{-1} biodiesel*	kg CO$_2$-eq kg^{-1} biodiesel*	
	1	6.49	0.48	–
		MJ kg^{-1} meal	kg CO$_2$-eq kg^{-1} meal	ha ton^{-1} meal
	1	5.10	0.377	–
	2	5.73	0.761	0.29
	3 RSO**	–	0.344	0.30
	3 PO***	–	0.721	0.36
soy beans		MJ kg^{-1} beans	kg CO$_2$-eq kg^{-1} beans	ha ton^{-1} beans
	2	2.76	0.652	0.36
	3	–	0.642	0.33
	4	–	0.600	0.36
synthetic glycerine		MJ kg^{-1} biodiesel*	kg CO$_2$-eq kg^{-1} biodiesel*	
	1	23.78	1.39	0

1 *Reinhardt & Jungk (2001).*
2 *Blonk et al. (2008).*
3 *Dalgaard et al. (2008).*
4 *BioGrace (2010)*
* *expressed per kg biodiesel produced from rapeseed.*
** *soy oil is assumed to replace rapeseed oil.*
*** *soy oil is assumed to replace palm oil.*

2.4 Description of the scenarios

1. Basic scenario: allocation to co-product meal by means of attribution on the basis of energy content and no allocation to straw and glycerine conform to the guidelines for the calculation of the reduction of the GHG emission from the EU Directive on the promotion of the use of renewable energy (RED, EC 2009).
2. As scenario 1, with attribution to straw and glycerin on the basis of energy content. In this scenario it is assumed that straw is harvested and sold outside the system boundaries, conform to the scenario 'Attribution' from Conijn & Corré (2009).
3. System expansion conform to Reinhardt & Jungk (2001). No allocation to straw, the meal replaces imported soy meal and the glycerin replaces synthetic glycerin. Due to the co-production of soy oil with soy meal, this scenario describes only a partial system expansion where the effects on replaced soy oil are not taken into account.
4. As scenario 3, but conform to data for the replacement of soy meal from Blonk *et al.* (2008).
5. System expansion including the use of soy oil. In this scenario the meal also replaces soy meal, but now from imported soy beans. The corresponding soy oil yield is distracted from the rapeseed oil yield. Energy use, GHG

emission and land use for soy beans are conform to Blonk *et al.* (2008). Allocation to glycerin conforms to scenario 3. Due to the replacement of a complete agricultural crop this scenario can be considered to be a complete system expansion.

6. As scenario 5, with production of energy from glycerin. The glycerin does not longer replace synthetic glycerin but is fermented to biogas which is converted to electricity. The surplus co-generated heat is assumed not to be utilised.
7. As scenario 6, with production of energy from the meal. The meal does not longer replace soy meal but is fermented to biogas analogue to the glycerin.
8. As scenario 7, with production of energy from the straw. In this scenario the straw is harvested and used for the production of electricity by burning it in a biomass plant. The surplus co-generated heat is assumed not to be utilised. In this scenario all co-products are used for the production of energy, conform to the scenario 'Energy' from Conijn & Corré (2009), and only replace fossil energy. This scenario can also be considered to be a complete system expansion.
9. As scenario 2, with allocation to co-products by means of attribution on the basis of economic value conform to the method used by Horne *et al.* (2003). As economic values the average price levels from the period 1997-2000 in the UK were used. These price levels are shown in Table 3.

The system boundaries for the scenarios 3 and 4 on one side and the scenarios 5 and 6 on the other are shown in Figure 2. This figure illustrates the difference between the partial system expansion of the scenarios 3 and 4 and the complete system expansion of the scenarios 5 and 6. The allocation methods used are shown for each scenario and each co-product separated in Table 2.

Most realistic for the *currently existing* biodiesel production seems to be replacement of cereal straw (with no allocation), soy meal from imported soy beans (conform scenarios 5 and 6) and a combination of synthetic glycerin, eventually lower value component in animal feed and fossil energy. Quantification of the partitioning between the three possible replacements for glycerine in current practice, however, is not possible within this study. Hence, for the existing production a combination of scenarios 5 and 6 seems realistic but the most probable partitioning between the two scenarios is not clear. For *new* production the use of glycerin for energy production seems most likely, conform to scenario 6.

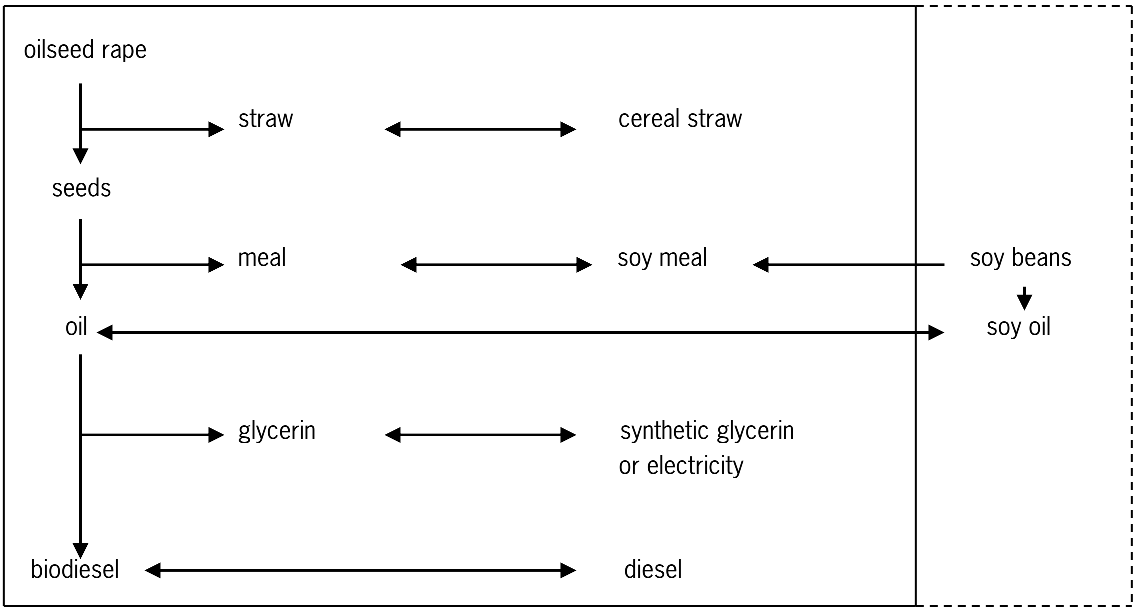


Figure 2. System boundaries for scenarios 3/4 (——) and scenarios 5/6 (- - -).

Table 2. Summary of the allocation methods used in the different scenarios.

Scenario	1	2	3	4	5	6	7	8	9
allocation method	attr	attr	sys	sys	sys	sys	sys	sys	attr
straw	–	enc	–	–	–	–	–	elec	ecv
meal	enc	enc	soym	soym	soyb	soyb	elec	elec	ecv
glycerin	–	enc	syng	syng	syng	elec	elec	elec	ecv

attr: *attribution.*
enc: *on the basis of energy content.*
ecv: *on the basis of economic value*
sys: *system expansion.*
soym: *with replacement of soy meal.*
soyb: *with replacement of soy beans.*
syng: *with replacement of synthetic glycerin.*
elec: *with production of electricity.*
--: *no allocation.*

Table 3. Ratio's for allocation with attribution on the basis of economic values (scenario 9).

	Mass ratio[1]	Prices[2]	Economic value ratio (%)
seed to straw	3917/2310	152/25	91/9
seed to straw[3]		230/40[3]	91/9
oil to meal	1515/2105	323/84	73/27
biodiesel to glycerin	1405/140	268/388	87/13

[1] *mass ratio from Figure 1 adapted to moisture contents used by Horne et al. (2003).*

[2] *prices according to Horne et al. (2003).*

[3] *prices according to KWIN (2006).*

3. Results

The results of the calculations are summarised in Table 4 (per ha) and Table 5 (per kg biodiesel produced). The final results for net energy yield, net GHG emission reduction and allocated land use per ha oilseed rape grown in the Netherlands are show in Figure 3. The results are expressed as relative figures over scenario 1, the scenario according the regulations of the EU Directive on renewable energy (EC 2009).

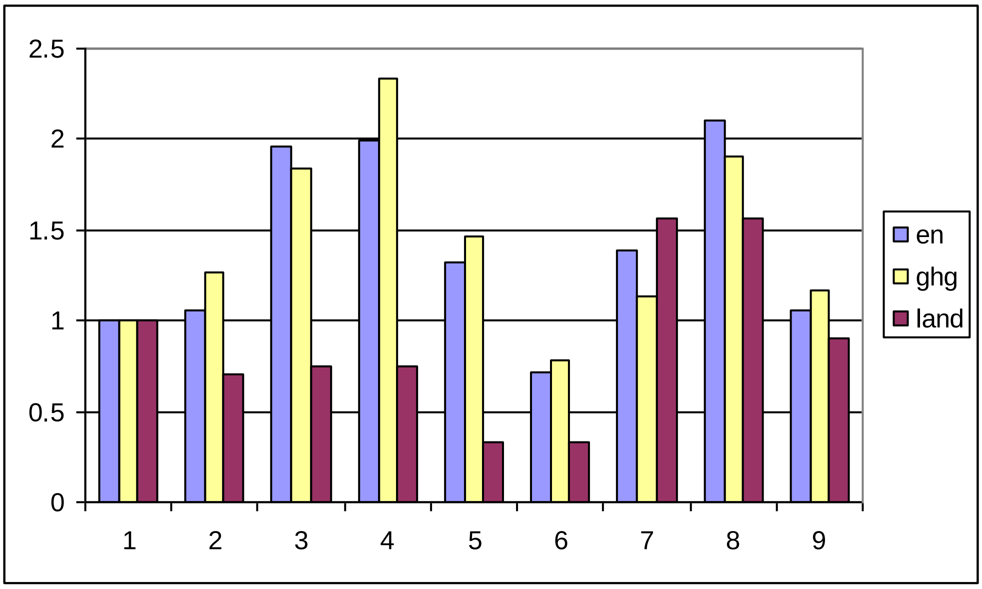


Figure 3. Summary of results, relative to scenario 1 (en: net energy yield in GJ ha^{-1}*, ghg: net GHG emission reduction in kg* CO_2*-eq ha*$^{-1}$*, land: allocated land use in ha ha*$^{-1}$*).*

In the basic scenario (1) the biodiesel produced has, according to the calculations with E-CROP with allocation on the basis of energy content to meal only, a net energy yield of 39 GJ per ha crop, a net emission reduction of circa 2000 kg CO_2-eq per ha crop and an allocated land use of 0.64 ha per ha crop. The energy efficiency equals 67% and the GHG emission reduction efficiency is 46%, which is very close to the RED typical value of 45% (see for definitions section 2.2 of this report).

Additional allocation to straw and glycerin (scenario 2) increases the net energy yield with 2.4 GJ per ha, resulting in an energy efficiency increase to 72%. The effects on the GHG emission and land use are larger, the GHG emission reduction efficiency increases to 59% and the allocated land use decreases to 0.45 ha per ha. These effects are larger because the allocation to straw is relatively larger for GHG emission and land use than it is for energy use. In the part of the production chain before the separation of seeds and straw, the energy use is small while an important part of the GHG emission (N_2O) takes place. The allocation of land use is calculated based on total crop land use (by definition 1 ha) and the energy contents of all selected (co-) products.

Attribution on the basis of economic value (scenario 9 compared to scenario 2) shows a smaller allocation to straw and meal and a much larger allocation to glycerine, with as end result an only negligible lower allocation to biodiesel. As a result the energy efficiency remains almost at the same level (71%) and the GHG emission reduction efficiency shows a small decrease to 54%. The allocated land use shows an appreciable increase to 0.58 ha per ha as result of the smaller allocation to straw. For the attribution on the basis of economic value price levels from the period 1997-2000 were used (Horne *et al.*, 2003). More recent general data were only found for seeds and straw (KWIN 2008). The price ratio of seed to straw, however, remained almost the same and differences in results would be

Table 4. Results of calculation for different scenarios, expressed per ha oilseed rape.

Scenario		1	2	3	4	5	6	7	8	9
Biodiesel	kg	1405	1405	1405	1405	1031	1031	1405	1405	1405
	GJ	52.36	52.36	52.36	52.36	38.43	38.43	52.36	52.36	52.36
Replaced diesel energy	GJ	58.12	58.12	58.12	58.12	42.65	42.65	58.12	58.12	58.12
Replaced other energy	GJ	-	-	-	-	-	1.29	20.87	48.66	-
Replaced energy, total	GJ	58.12	58.12	58.12	58.12	42.65	43.94	78.99	106.78	58.12
Energy use, total	GJ	24.08	24.08	24.08	24.08	21.72	21.84	24.87	25.16	24.08
- allocated to straw	GJ	0	2.73	0	0	0	0	0	-	0.95
- allocated to meal	GJ	5.14	4.18	9.12	10.25	-	-	-	-	3.86
- allocated to repl. soy beans	GJ	-	-	-	-	6.07	6.07	-	-	-
- allocated to glycerin	GJ	0	0.62	33.24	33.24	24.39	-	-	-	2.36
- allocated to bio-energy	GJ	18.94	16.55	-18.28	-19.41	-8.74	15.77	24.87	25.16	16.91
Net energy yield	GJ	39.18	41.57	76.40	77.53	51.39	28.17	54.12	81.62	41.21
Efficiency biodiesel	%	67	72	131	133	120	66	93	140	71
Efficiency bio-energy	%	-	-	-	-	-	64	69	76	-
Avoided emission diesel	kg CO_2-eq.	4346	4346	4346	4346	3189	3189	4346	4346	4346
Avoided emission other energy	kg CO_2-eq.						76	1234	2889	-
Avoided emission, total	kg CO_2-eq.	346	4346	4346	4346	3189	3265	5580	7235	4346
Emission, total	kg CO_2-eq.	3274	3180	3274	3274	3117	3126	3305	3402	3274
- allocated to straw	kg CO_2-eq.	0	634	0	0	0	0	0	-	210
- allocated to meal	kg CO_2-eq.	941	686	674	1360	-	-	-	-	655
- allocated to repl. soy beans	kg CO_2-eq.	-	-	-	-	1434	1434	-	-	-
- allocated to glycerin	kg CO_2-eq.	0	68	1954	1954	1434	-	-	-	300
- allocated to bio-energy	kg CO_2-eq.	2333	1792	646	-40	249	1692	3305	3402	2009
Net emission reduction	kg CO_2-eq.	2013	2554	3700	4386	2940	1573	2275	3833	2337
Efficiency biodiesel	%	46	59	85	101	92	49	52	88	54
Efficiency bio-energy	%	-	-	-	-	-	48	41	53	-
Allocated land use for biodiesel	ha	0.64	0.45	0.48	0.48	0.21	0.21	1	1	0.58

Table 5. Results of calculation for different scenarios, expressed per kg biodiesel.

Scenario		1	2	3	4	5	6	7	8	9
Replaced diesel energy	GJ	41.4	41.4	41.4	41.4	41.4	41.4	41.4	41.4	41.4
Replaced other energy	GJ	0	0	0	0	0	1.3	14.9	34.6	-
Replaced energy, total	GJ	41.4	41.4	41.4	41.4	41.4	42.7	56.1	76.0	41.4
Energy use, total	GJ	17.1	17.1	17.1	17.1	21.1	21.2	17.7	17.9	17.1
- allocated to straw	GFJ	0	1.9	0	0	0	0	0	-	0.7
- allocated to meal	GJ	3.6	2.9	6.5	7.3	-	-	-	-	2.7
- allocated to repl. soy beans	GJ	-	-	-	-	5. 9	5.9	-	-	-
- allocated to glycerin	GJ	0	0.5	23.7	23.7	23.7	-	-	-	1.7
- allocated to bio-energy	GJ	13.5	12.8	-13.1	-13.9	-8.5	15.3	17.7	17.9	12.0
Net energy yield	GJ	27.9	28.6	54.5	55.3	49.9	27.4	38.4	58.1	29.4
Avoided emission diesel	kg CO_2-eq.	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09
Avoided emission other energy	kg CO_2-eq.	0	0	0	0	0	0.07	0.88	2.06	0
Avoided emission, total	kg CO_2-eq.	3.09	3.09	3.09	3.09	3.09	3.16	3.97	5.15	3.09
Emission, total	kg CO_2-eq.	2.33	2.26	2.33	2.33	3.02	3.03	2.35	2.42	2.33
- allocated to straw	kg CO_2-eq.	0	0.45	0	0	0	0	0	-	0.15
- allocated to meal	kg CO_2-eq.	0.67	0.49	0.48	0.97	-	-	-	-	0.54
- allocated to repl. soy beans	kg CO_2-eq.	-	-	-	-	1.39	1.39	-	-	-
- allocated to glycerin	kg CO_2-eq.	0	0.07	1.39	1.39	1.39	-	-	-	0.28
- allocated to bio-energy	kg CO_2-eq.	1.66	1.28	0.46	-0.03	0.24	1.64	2.35	2.42	1.43
Net emission reduction	kg CO_2-eq.	1.43	1.82	2.63	3.12	2.85	1.53	1.62	2.73	1.66
Allocated land use										
- per kg biodiesel	m^2	4.6	3.2	3.4	3.4	2.0	2.0	7.1	7.1	4.1
- per GJ net energy yield	m^2	166	110	64	63	41	76	188	124	143
- per kg net emission reduction	m^2	3.2	1.8	1.3	1.1	0.7	1.3	4.4	2.6	2.5

negligible. A decrease in the price of glycerin, which is to be expected since the price of glycerin was higher than the price of biodiesel in the data used, would probably have larger effects. However, also this effect will still be limited since the amount involved is relatively small: 1 kg of raw glycerin on 10 kg of biodiesel.

The results of the scenarios with system expansion show more variation. System expansion with replacement of soy meal and synthetic glycerin (scenarios 3 and 4) shows large effects compared to scenario 1, partly due to the replacement of soy meal and partly due to accounting for glycerin and the replacement of synthetic glycerin. The net energy yield is nearly twice as high and comparable in both scenarios. The larger part of the increase, however, was caused by the replacement of synthetic glycerin, for which only one figure was available, which was used in both scenarios. Also the net GHG emission reduction is increased, but substantially more in scenario 4 than in scenario 3. This is caused by a much larger allocation of GHG emission per unit allocated energy to soy meal by Blonk *et al.* (2008) compared to Reinhardt & Jungk (2001). The backgrounds of calculation of these literature data were not published. Also for the allocation of land use only one value was available, using this value results in a decrease of the land use allocated to the production of biodiesel from 0.64 in scenario 1 to 0.48 ha per ha in both scenarios 3 and 4. This decrease is fully a result of the replacement of soy meal, the production of synthetic glycerin involves no land use at all and land use related to soy oil has not been taken into account in scenarios 3 and 4.

Replacing soy beans instead of soy meal (scenario 5 compared to scenario 4) results in a lower biodiesel production as result of the replacement of soy oil. This causes an appreciable decrease of the net energy yield and the net GHG emission reduction per ha but per kg biodiesel produced the decrease is only small. The allocated land use becomes much smaller because of a much lower yield of soy oil per ha compared to rapeseed oil. Replacement of soy beans is to be preferred over the replacement of soy meal because the latter neglects that with the replacement of meal the corresponding amount of soy oil which is no longer produced needs to be compensated as well in the balance calculations.

Energy production from glycerin (scenario 6) results in a sharp decrease of the net energy yield and the net GHG emission reduction compared to the replacement of synthetic glycerin (as in scenario 5). The production of synthetic glycerin needs a large amount of energy relative to its combustion energy content. No effect on land use is calculated because both ways of treating glycerin do not involve any land use. Energy production from rape meal (scenario 7) compared to the replacement of soy beans (scenario 6) results in a large increase of the net energy yield and the net GHG emission reduction but also in a large increase of the allocated land use. This is caused by the trade-off of the replacement of a crop (involving land use) for energy production. Harvesting rape straw (scenario 8) for the production of energy compared to leaving the straw in the field results in a clear increase of the net energy yield and the net GHG emission reduction while the allocated land use remains unchanged.

Summarising we can conclude that differences between scenarios can be very large, as is shown in Figure 3. Differences involve all three investigated aspects, i.e. net energy yield, net GHG emission reduction and allocated land use, and sometimes in opposite directions. Hence, system expansion is not only principally to be preferred over attribution but can also show clearly different results. Attribution (scenarios 1, 2 and 9) as calculation method is used for administrative purposes and is not reflecting a real-life situation. Regarding the scenarios with system expansion (3 to 8), scenarios 3 and 4 are not complete (neglecting the effects of soy oil in their calculations), leaving only scenarios 5 to 8 as being more or less realistic. Obviously, the three calculated indicators of sustainability cannot be optimised in one scenario. The net energy yield is optimal in scenario 8, the net GHG emission reduction in scenario 4 and the land use in scenarios 5 and 6. Seven out of eight alternative scenarios perform better on net energy yield and net GHG emission reduction compared to the basic scenario calculations conform to the EC Directive. The only one performing worse with respect to net energy and net GHG emission reduction (scenario 6), is probably the most realistic scenario for new biodiesel production. However, regarding allocated land use it performs much better than scenario 1 and regarding the efficiency of the GHG emission reduction (kg CO_2-eq kg^{-1} biodiesel) it also performs a little better. Scenario 8 should be used for achieving maximum energy production of oilseed rape cultivation with the negative consequence of having the highest allocated land use.

4. Discussion and conclusions

4.1 Discussion

It was shown that, in the case of oilseed rape, calculations based on system expansion can yield very different results when compared to attributional allocation methods. These differences occur for three main reasons. First is the presence of a high value co-product, the glycerin, for which alternative production (synthetic glycerin) involves a large energy use. This results especially in positive effects on net energy yield and net GHG emission reduction. Second is the presence of a co-product with good qualities as animal feed component, the meal. Depending on the animal feed components that actually can be replaced, this can result especially in a large effect on allocated land use. Finally, both meal and straw if used for energy production can replace an amount of fossil energy almost equal to the amount replaced by the produced biodiesel from oilseed rape. This results in large positive effects on both net energy and net GHG emission reduction but also in a larger allocated land use.

The results also stress the necessity to use realistic scenarios; potential pathways show results that strongly differ from practical possibilities or current practices. Potential alternative system expansions can show the sustainability of these alternatives but as long as these alternatives are no current practice, they do not show the sustainability of the actual production. An example is the saturated glycerin market. This new situation involves changes in the system expansion concerning the use of glycerin. Drawing realistic scenarios is also important when using attributional methods. An illustration of a problem of this kind is the allocation to straw. The simple existence of a market for rape straw while it most probably only displaces other straw from the market does not justify any allocation to rape straw.

In the production of biodiesel from oilseed rape in the Netherlands the following options seem to be the most realistic for the coming decade:

- The straw is left in the field or replaces other straw which will be left in the field in stead; no allocation to straw should be made. A future option can be the use of straw for the production of energy or biofuel.
- The meal replaces soy meal, imported as soy meal or as soy beans.
- The glycerin may replace synthetic glycerin as far as the market has a demand for it and the surplus glycerin is used for the production of energy. In the future replacing lower valued components of animal feed could be an option.

These options are best described in the scenarios 5 and 6. The current production is best described by a combination of these two and new production is best described by scenario 6. For the future, a combination with scenario 8 (energy production from glycerin and straw but not from meal) seems realistic. Furthermore other applications of glycerin seem possible but it is not yet clear which other products could be replaced and a realistic scenario for this option can not yet be made.

A common problem in system expansion is the replacement of co-products by co-products of other agricultural crops (e.g. Kim & Dale 2002). These cases easily lead to complicated system descriptions, often resulting in the introduction of new attributions. For the production of biodiesel from oilseed rape this problem is relatively small. The co-product with potential complications, the meal, can be replaced by a co-product from one other crop, soy, which is comparable with oilseed rape in terms of feeding quality, although for a complete match rapeseed meal should be compared with a combination of soy meal and a cereal. The matching ratio of soy meal and cereal depends on the animal species to be fed but the major part of the products to be replaced will be soy meal (Lywood *et al.*, 2009). For our study a relatively simple system expansion, as is illustrated in Figure 2, was supposed to be sufficient. Moreover, the quantitative consequences of this system expansion are well known, they are also important in the calculation of effects on energy use, GHG emission and land use of soy meal used as animal feed (Blonk *et al.*, 2008, Dalgaard *et al.*, 2008). System expansion with soy meal only or with the complete production of soy beans, including oil, leads to very different results (compare scenarios 4 and 5). This large difference is probably caused by the attribution between soy meal and soy oil and the exclusion of soy oil from the described system as is applied in the data used in scenario 4. In this case scenario 5 with its more complete system expansion would describe the system more realistically. In the case of soy meal import, a further system expansion is possible by involving soy oil production abroad (not done in scenario 3 & 4). However, soy oil production and further use in the Netherlands or abroad is likely to result only in minor differences in effects on energy use, GHG emission or land use relative to scenario 5. According to Dalgaard *et al.* (2008) and Reinhardt & Zah (2009) the place where soy oil is extracted or used has a minor effect but the type of oil with which the soy oil is compared has a large effect on the allocation that could be made to soy oil. Scenario 5 is based on the replacement of soy oil by rapeseed oil and this means that, while the allocation to soy beans is correct, the further system expansion concerning the soy oil could well be not the most likely option.

Different results could be found when the soy oil was assumed to be replaced by palm oil and the production of biodiesel from rapeseed oil would be left unchanged. However, for quantification of differences data on energy use, GHG emission and land use of the production of palm oil are needed and only for land use estimates were found. FAO (2004) reports yields of palm oil of approximately 8 times the yield of soy oil. Substitution of soy oil by palm oil in scenario 5 and 6 would lead to an appreciably larger land use allocated to rapeseed production (0.31 vs. 0.21 ha ha^{-1}) but only to a small increase of allocated land use per kg biodiesel produced (2.2 vs. 2.0 m^2) since now all rapeseed oil would be converted to biodiesel. However, replacing soy oil by rapeseed oil or by palm oil may not result in much difference in allocated land use; it involves land use in different climate zones and could have very different effects.

All scenarios described involve production in the Netherlands with green fallow as replaced land use. When other crops, e.g. wheat, are replaced, a further system expansion should be made to quantify the effects of replacing the production of that crop to another place (e.g. wheat grown in France). Eventually, all production of energy crops will lead to a decrease in non-agricultural land use (Reinhardt & Jungk 2001). Depending on the crop and the location this decrease can take place in different parts of the world and can be smaller or larger, and also the effects on e.g. soil carbon storage and biodiversity will be different (so-called indirect land use change).

On the other hand, agricultural land requirement can be reduced if other agricultural (co-)products are replaced by the co-products of an energy crop, as is the case if they can be used as animal feed or as component for the production of animal feed. For production of oilseed rape in the Netherlands this reduction in land requirement can be very substantial, i.e. almost 80% of the ‘original land’ used by the oil crop in a system expansion where import of soy beans is replaced (scenarios 5 and 6). In our calculations, one ha of oilseed rape in the Netherlands is correlated to a land requirement reduction of 0.8 ha of soy dominantly grown in South America. When in the future more glycerin might be processed into animal feed, this reduction could be even somewhat larger, however due to the small amount of glycerin relative to meal; this effect will be limited for oilseed rape. In scenarios where all co-products are used for the production of energy no reduction for land requirement can occur, in these cases land use functions as a trade off for energy production which can be considerably increased by this alternative use of co-products. Also crops without marketable co-products, like Miscanthus and sugar cane, do have a high energy yield but do not have any reduction for land requirement. When energy crops are compared on efficiency of energy production or GHG emission reduction it is necessary to evaluate also their land use.

The consequences of compensation of land use for the sustainability of production systems are hard to quantify, especially when compensation takes place on other continents. It is, however, of extreme importance to quantify these effects, since they have large effects on sustainability and a quantification is indispensable for comparing scenarios with a substantial replacement of agricultural products (scenarios 5 and 6) with scenarios with a substantial extra energy production from co-products (scenarios 7 and 8). This is especially important when production of palm oil is involved; much palm oil is still produced with large GHG emissions from production on peat soils and disposal of wastes (Reijnders & Huijbrechts, 2008).

Scenario 8 with production of energy from straw showed a much higher net energy yield and net reduction in GHG emission compared to scenarios where the straw is left in the field. Not considered in this scenario is the effect of harvesting the straw on soil organic matter contents. Harvesting of straw will result in lower soil carbon content. Until a new and lower equilibrium content has been reached, the net GHG emission reduction will be smaller and a decrease to an unsustainably low soil organic matter content is possible. Conijn & Corré 2009 calculated for sandy soils in the Netherlands a decrease in equilibrium soil carbon content of approximately 5.25 ton C per ha when removing the annual straw input conform scenario 8. Using a twenty year period for accounting this difference on a GHG balance, as prescribed in the EU Directive (EC 2009), this results in an annual additional emission of 960 kg CO_2 per ha. Hence, harvesting the straw for energy production would still result in a reduction of the GHG emission but the total net GHG emission reduction would decrease from 3833 to 2873 kg CO_2-eq per ha per year and the efficiency would decrease from 88 to 66% (for biofuel) or from 53 to 40% (total bioenergy). Probably this loss can be partly compensated by growing a green manure crop after the oilseed rape is harvested. The decrease in soil carbon content of 5.25 ton C per ha is not likely to cause problems regarding the organic matter conditions of the soil in most parts of the Netherlands, even more so because this loss will be spread over a larger area because oilseed rape must be grown in a rotation with other crops.

The EU Directive gives threshold values for the efficiency of GHG emission reduction being considered acceptable. These values, referring to the whole chain from seeding to distribution of the biofuel, are 35% for current biofuel production and increase to 50% for new biofuel plants in 2017 and 60% in 2018. Hence, according to our calculations current biofuel production are above the threshold values of 35% (all scenarios) but most of them fall below 60%. An efficiency of 50 or 60% was only reached in scenarios with replacement of synthetic glycerin or using straw for energy production. Because system expansion with replacement of synthetic glycerin is not adequate for new production the only option to reach the thresholds in the future for oilseed rape seems to be harvesting and using the straw for energy production.

4.2 Conclusions

Allocation by means of system expansion gives the opportunity to account for real effects of the use of co-products and is therefore to be preferred over allocation on the basis of attribution.

System expansion involves often arbitrary choices which can have large effects on the values of sustainability indicators. This introduces a high uncertainty level in allocation by means of system expansion and necessitates once more the importance of drawing realistic scenarios.

Since a high net energy yield and a high net GHG emission reduction function as a trade-off for allocated land use, focusing on GHG emission reduction efficiency only, without taking the land use into account, gives a too narrow view of the sustainability of biofuel production.

The reduction in land requirement due to the use of co-products as animal feed can be very high, but is also uncertain, due to the dependence on the yield levels of the different crops. Because of its magnitude in reduction the use of co-products as animal feed can play a significant role and should be part of a sustainability assessment of biofuel production.

Harvesting straw without accounting for its effect on soil carbon significantly overestimates the net reduction in GHG emission and changes in soil carbon should therefore be added to the balance calculations. In areas with low soil organic matter it can also affect negatively the crop production possibilities.

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