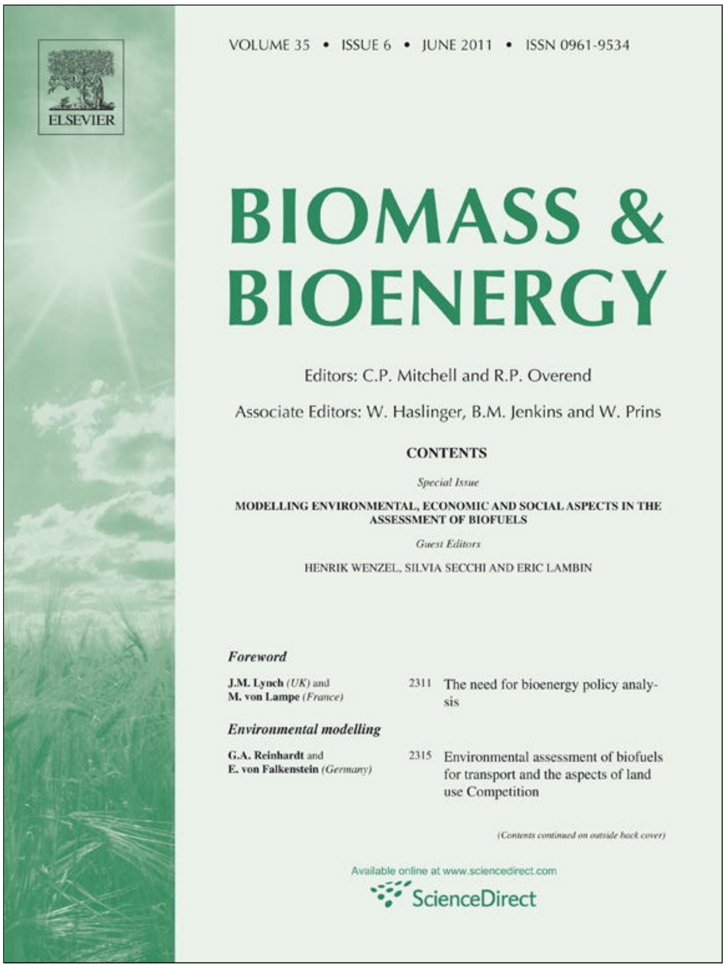
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Environmental assessment of biofuels for transport and the aspects of land use Competition

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ABSTRACT

Early comprehensive life cycle assessments (LCA's) that compared biofuels with fossil fuels already appeared in the beginning of the eighties. Since then the public, scientific and political interest in biofuels has continuously grown and the number of biofuels and assessed parameters has increased.At the same time, the methodology for this type of assessment has improved with certain aspects of the approach having come up by and by a process which still continues today. Several issues related to the land use currently stand in the centre of expert discussions.

1. Objective, scope and background

Early comprehensive life cycle assessments (LCA's) that compared biofuels with fossil fuels already appeared at the end of the 1980's. Since then the public, scientific and political interest in biofuels has continuously grown and the number of biofuels and assessed parameters has increased. At the same time, the methodology for this type of assessment has improved with certain aspects of the approach having come up by and by a process which still continues today.

Several issues related to the land use currently stand in the centre of expert discussions. Until recently, a so-called 'agricultural reference system' was included in the methodology; the findings from LCA studies on biofuels conducted within the past 15 years are based on the proceeding as it is described for example in [1] and exemplified in Fig. 1. First discussions regarding greenhouse gas emissions due to land use changes started as early as 1991 [2]. More recently, as the focus is moving from crops of the temperate climate zones to bioenergy plants cultivated in the tropics, new land use aspects have emerged as relevant which the former methodology does not give (sufficient) consideration to.

Concerning the main framework of life cycle assessments (LCA's), many of these studies have concluded that biofuels are more or less CO_2 neutral – the findings, however, vary considerably. It must also be noted that some environmental disadvantages are associated with biofuels as – in some cases – negative implications on acidification or eutrophication. These environmental implications vary greatly for the different biofuels, but also for the use of different raw materials.

In order to analyse the environmental advantages and disadvantages of different biofuels, this paper collates and compares international publications that provide scientifically reliable (in terms of being in line with the ISO standards) and comprehensive statements on biofuels. The considered publications mostly meet the requirements for life cycle

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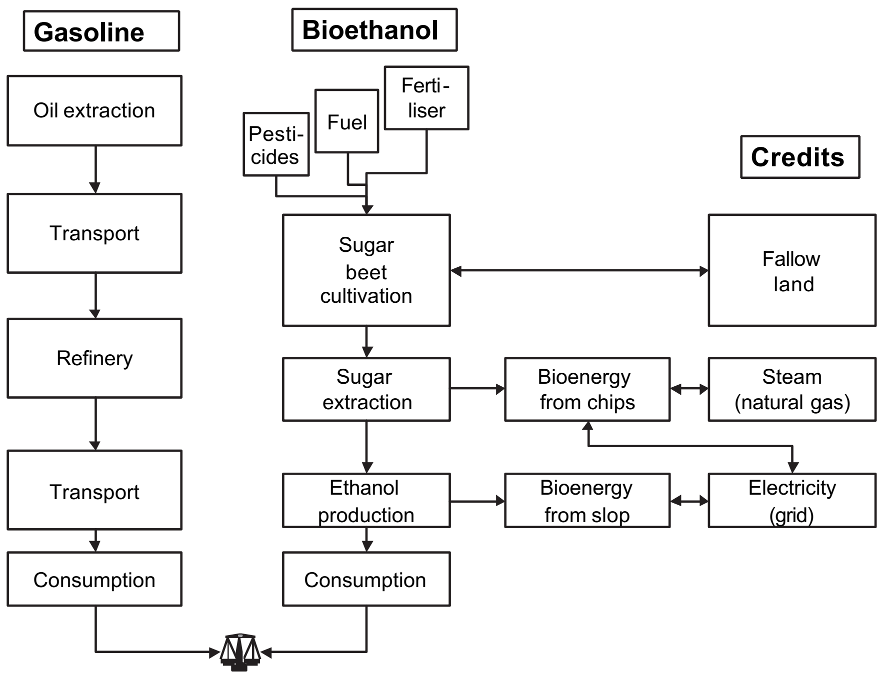

Fig. 1 – Schematic life cycle comparison "bioethanol from sugar beet versus gasoline".

analyses as defined by the respectively applicable standards ISO 14040–14043 [3] or ISO 14040 & 14044 [4]. This means not only the entire life cycle of a particular product is regarded in terms of environmental impacts, but also all by-products arising from its production. Under certain circumstances, the environmental effects of the by-products can outweigh those of the primary product, thus reversing the balance total's direction.

Most biofuels that are currently in use such as vegetable oil and biodiesel from rapeseed, bioethanol from sugar-cane and corn, etc. as well as biofuels that are currently not mass produced such as BTL and bio-hydrogen are considered. The advantages and disadvantages in respect to a range of environmental impacts (incl. greenhouse gas emissions, energy consumption, acidification, eutrophication, ozone depletion) are first demonstrated for biodiesel from rapeseed (RME) as an example. Afterwards the energy and greenhouse gas balance results are presented and interpreted for all considered biofuels. The investigated comparisons are shown in Table 1.

The basis for this analysis is a comprehensive IFEU study for the 'Research Association for Combustion Engines' [5] in which more than 800 studies were taken into account. Furthermore, several specific studies such as [6] for BTL, [7] for palm oil production as well as [8–11] have been used and additional research has been conducted.

2. Procedure

All regenerative fuels were balanced over their whole life cycles from cradle to grave, i.e. inputs from fertilisers and pesticides to the actual fuel consumption in a vehicle were taken into account. The same applies to the fossil fuels counterparts. Both options are finally compared against each other (see the example for bioethanol in Fig. 1).

Choices of agricultural reference systems have been taken into account and additives and co-products were also included. The latter were counted as credits. For further details and the underlying assumptions, see [12–16]. The evaluation is based on an inventory analysis and impact assessment.

For all processes, the respective energy and materials have been counted as inputs and emissions as outputs. More than 26 input (e.g. natural gas, brown coal, limestone) and output (e.g. CO_2, CH_4, SO_2, NO_x, HCl) parameters were examined quantitatively in the life cycle inventory (LCI) analysis. The comparison of all considered biofuels has a focus on the impact categories 'energy consumption' and 'greenhouse effect'. For the category 'energy consumption', the energy content of all non-renewable primary energy carriers were added up in order to obtain the CED (cumulated energy demand). Besides others, the following factors were used for the aggregation of CO_2 equivalents (greenhouse effect): CO_2: 1; CH_4: 21; N_2O: 310 – referring to CO_2 kg kg^{-1} of the respective substance ([17]). Similar procedures were followed for the assessment of acidification (SO_2 equivalents) [18] and eutrophication (PO_4 equivalents). Although no ozone depletion values exist for N_2O, it is undisputed that this gas has an impact on the ozone layer. Therefore, it was drawn on as an indicative parameter for the impact category of ozone depletion in the present investigation.

Fig. 2 shows the outcome of the comparison "biofuel versus fossil fuel" as described before for an example: biodiesel from rapeseed versus ordinary diesel fuel. The results for 'primary energy' and 'greenhouse effect' are in favour of RME while the other results are in favour of fossil diesel fuel. This means that

Table 1 – Biofuels considered in this paper and their fossil fuel counterparts; for explanation of abbreviations see Fig. 4.

Biofuels	Fossil fuel counterparts
Bioethanol	
Bioethanol from sugar-cane	Gasoline
Bioethanol from corn	Gasoline
Bioethanol from wheat	Gasoline
Bioethanol from sugar-beets	Gasoline
Bioethanol from lignocellulose	Gasoline
Bioethanol from potatoes	Gasoline
Bioethanol from molasses	Gasoline
ETBE	
ETBE from wheat	Fossil MTBE
ETBE from sugar-beets	Fossil MTBE
ETBE from lignocellulose	Fossil MTBE
ETBE from potatoes	Fossil MTBE
Biodiesel	
Biodiesel from rapeseed	Fossil diesel fuel
Biodiesel from sunflowers	Fossil diesel fuel
Biodiesel from soybeans	Fossil diesel fuel
Biodiesel from canola	Fossil diesel fuel
Biodiesel from coconut oil	Fossil diesel fuel
Biodiesel from palm oil	Fossil diesel fuel
Biodiesel from animal grease	Fossil diesel fuel
Biodiesel from used cooking grease	Fossil diesel fuel
Vegetable oil	
Vegetable oil from rapeseed	Fossil diesel fuel
Vegetable oil from sunflowers	Fossil diesel fuel
Biomethanol	
Biomethanol from lignocellulose	Gasoline/Methanol from natural gas
MTBE	
MTBE from lignocellulose	Fossil MTBE
DME	
DME from lignocellulose	Fossil diesel fuel
BTL	
BTL from agriculture	Fossil diesel fuel
BTL from residues	Fossil diesel fuel
Biogas	
Biogas from organic residues	Gasoline/Natural gas
Biogas from cultivated biomass	Gasoline/Natural gas
Hydrogen	
Gaseous Hydrogen from lignocellulose	Gasoline/Hydrogen from natural gas
Gaseous Hydrogen from organic residues	Gasoline/Hydrogen from natural gas
Liquid Hydrogen from lignocellulose	Gasoline/Hydrogen from natural gas

an objective decision in for either the biofuel or the fossil fuel is not possible. Therefore, a final conclusion must consider subjective value systems. If, for instance, the depletion of fossil resources and the greenhouse effect are ranked highest among the regarded environmental impact categories, an overall final assessment in favour of biofuels can be justified with these findings. This applies from a methodological perspective. Regarding content, it must furthermore be questioned, of course, whether the underlying system boundaries are adequate and complete and if the database is scientifically sound. This determines whether the results can be interpreted at all and must therefore always be clarified before any final conclusions are drawn.

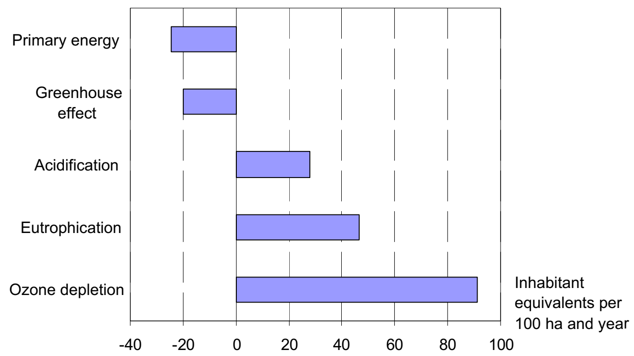

Fig. 2 – Exemplification of environmental impacts of RME compared to conventional diesel fuel (Source: Own calculations and updates based on [19])

3. Results: comparison of biofuels and fossil fuels

As has been mentioned above, a review of existing studies on the environmental implications of several biofuels is undertaken. The concluding assessment is discussed in the light of two issues: on the one hand with regard to the comparison "biofuels versus their fossil counterpart" and on the other hand with regard to the question how the different biofuels compare against each other. Thus the following comparisons can be identified:

(1) Biofuels from agriculture compared to fossil fuels and against each other
(2) Biofuels from residues compared to fossil fuels and against each other

3.1. *Biofuels from agriculture compared to fossil fuels and against each other*

As the abundance of area is the most restricting factor for producing biofuels from agriculture in Europe, all results are shown in relation to area (per hectare). Fig. 3 shows the results for the life cycle comparisons "biofuels from energy crops versus fossil fuels" for two environmental indicators chosen: energy consumption and greenhouse gases. The positive values indicate advantages for the fossil fuel and the negative ones advantages for the biofuels.

Most life cycle comparisons of 'primary energy' and 'greenhouse effect' are in favour of the biofuels. The only exception is biodiesel from palm oil if certain plantations (e.g. rubber) are converted to palm oil plantations. It must be noted in this context that the system assumptions may not be the same in all regarded studies. For example, most of them do not take into consideration land use effects such as carbon stock changes of soil and vegetation as well as indirect land use changes. These issues can, however, influence the outcomes and in some cases even cause a change in sign.

Concerning palm oil, it can be said that from an environmental perspective especially the optimisation of palm oil production as well as the establishment of new plantations on

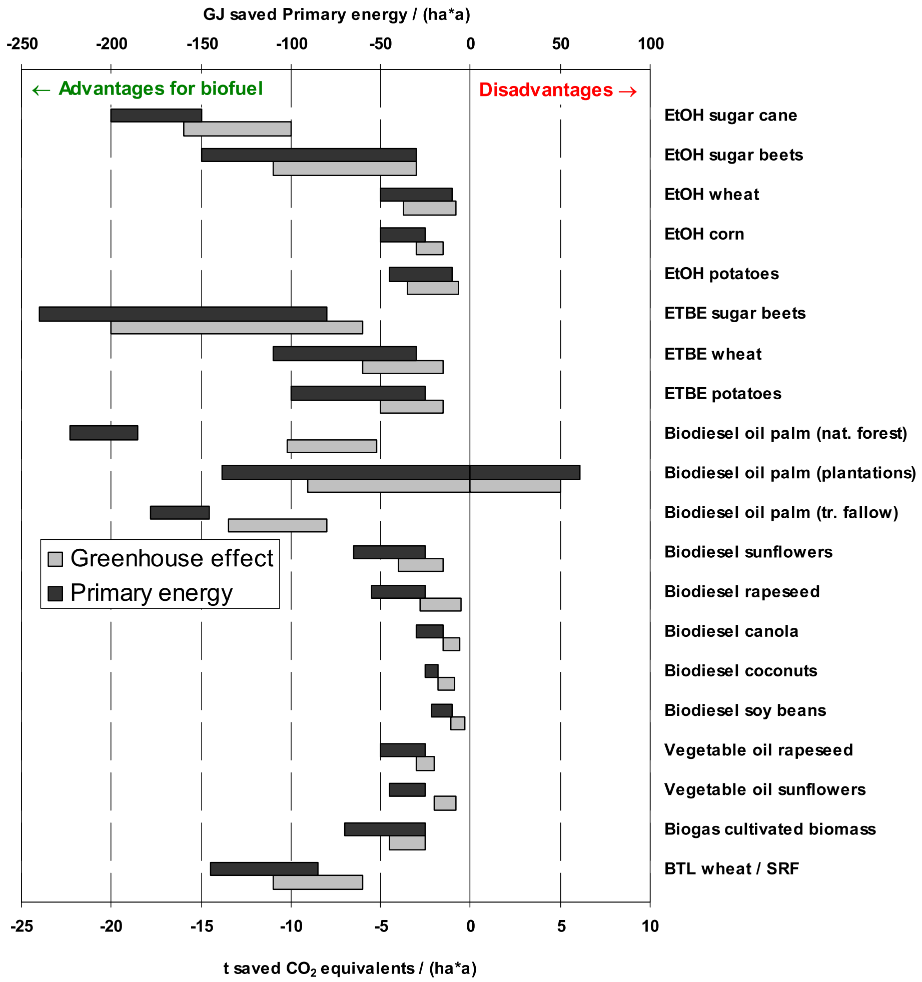

Fig. 3 – Advantages and disadvantages for greenhouse gases and primary energy for biofuels from agriculture compared to their fossil counterpart (Sources: [5], [6], [7]); for explanation of abbreviations see Fig. 4.

devastated ground which has previously been occupied by natural forest are the best options. Even better in energy savings is palm oil produced by cutting down tropical rain forests. But with this, the biodiversity of the tropical forest will be lost forever which is also an argument if talking about the sustainability of using palm oil for energy. Nevertheless, the results in [7] indicate that there is sufficient potential to use palm oil as an energy carrier also in the transport sector if the political and economic framework conditions are favourable.

BTL fuels have an ecological advantage over a range of other biofuels. There are, however, also options in the temperate as well as tropical climate which lead to better results than BTL fuels. BTL has a special ecological potential compared to other biofuels if it is produced from short rotation wood and not from cereals.

For more conclusions on all biofuels considered, the reader is asked to refer to chapter 5 (Conclusions and outlook).

3.2. *Biofuels from residues compared to fossil fuels and against each other*

For the comparison of different biofuels from residues, the amount of fuel in terms of energy (MJ) has been selected as the reference unit. Fig. 4 shows the results of the life cycle comparisons between 'biofuels from residues and fossil fuels'. Positive values indicate advantages for the fossil fuel, negative ones advantages for the biofuels.

The most important result is that the presented efficiencies only show small differences. In contrast to biofuels from energy crops, no ranking based on systematic advantages can be undertaken. Thus it is also irrelevant that the depicted bioenergy paths don't all have the same system boundaries. Other results can be obtained with a different analytical focus leading to the use of different relations, or under specific life cycle conditions – especially different system boundaries, other goal & scope questions, et cetera.

For more conclusions we refer to chapter 5 (Conclusions and outlook).

4. Results: land use aspects

In the past years, the number of studies assessing the environmental impacts of biofuels has increased rapidly and numerous expert conventions – including the LCA standards ISO 14040 & 14044 – have been achieved regarding the

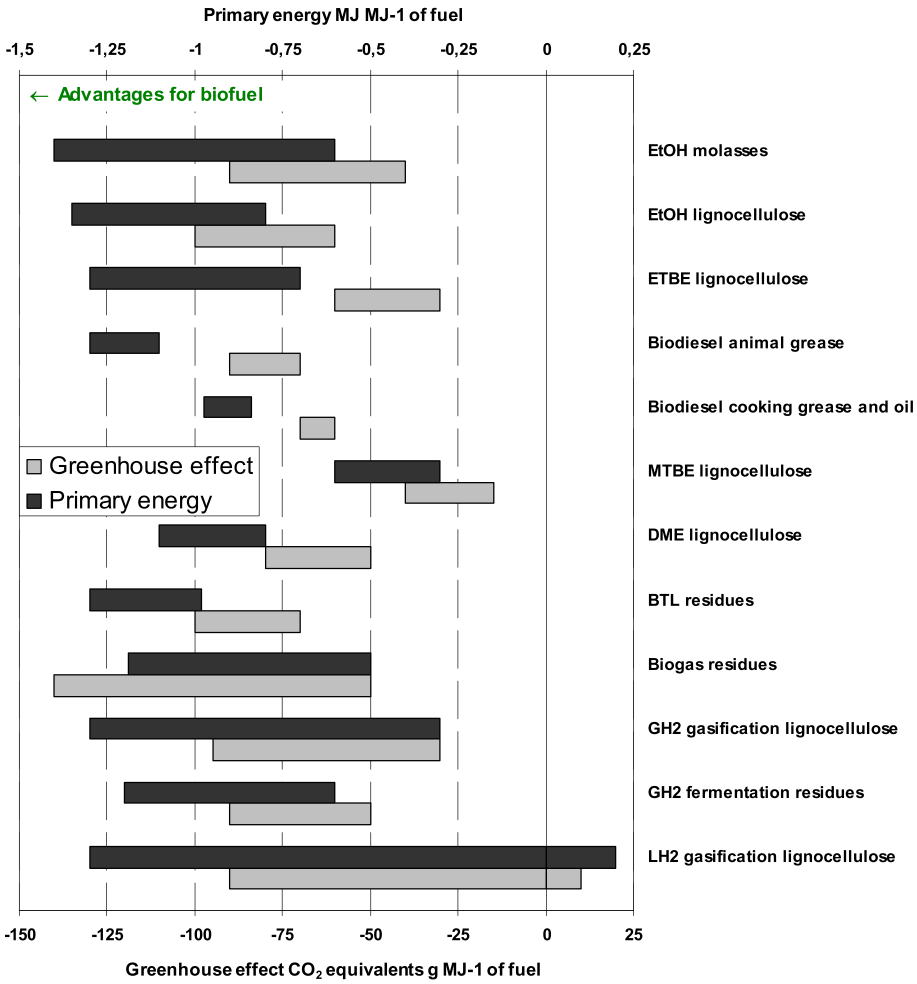

Fig. 4 – Greenhouse gas and primary energy savings for biofuels from residues compared to their fossil counterpart (Sources: [5], [6]) *Abbreviations*: EtOH – ethanol, ETBE – ethyl tertiary butyl ether, MTBE – methyl tertiary butyl ether, DME – dimethyl ether, BTL – biomass to liquid, GH2 – gaseous hydrogen, LH2 – liquid hydrogen.

methodology. Yet additional topics already discussed in the 1990's are now becoming more popular, for which a common approach has yet to be decided on. Currently, a major focus lies on aspects connected to the land use(s) of the area affected by the cultivation of the regarded energy crop. In spite of the fact that the system assumptions made in different studies are not necessarily the same, some basic conclusions can be drawn based on a comparison.

Besides the methodological challenges described in the following, an essential issue which concerns the concrete data used to determine the land quality (change) must be mentioned here: the generally available figures on several parameters are largely insufficient for precise calculations. Next to others, this concerns the carbon content of the above- and below-ground biomass as well as of the soil, a central parameter for greenhouse gas balances. Furthermore, very little is known about some N_2O emission factors which also play an important role in the greenhouse effect and beyond that in connection with the ozone depletion.

A central question regarding the research methodology investigates the so-called alternative land use: "What would a specific area of land be used for if not for the production of bioenergy?". In accordance with the approach described by [1], a permanent fallow or set-aside land was set as the alternative land use in most studies conducted since the middle of the 1990's – taking into account European conditions. In most cases, this proceeding did not make significant impacts on the outcome of the LCA. As more recent examinations have shown through more differentiated proceedings, however, the occurring land use change can be of great significance, not only regarding biodiversity issues but also for the greenhouse gas balance (e.g. [7]). This becomes most evident when the area's carbon stock is clearly affected; in some cases it can even lead to a quantitative reversal in the total outcome. Therefore, it is crucial to develop the methodology further accordingly.

One basic decision which must be made is which time frame is to be evaluated within the LCA, which raises the following two questions: How should the study account for (1) the land quality of the site at the moment the development into the energy crop cultivation area begins (this includes the land cover or vegetation and the type of soil) and (2) the type of vegetation and possible land uses beyond the end of the examination. It makes a difference, for example, if a piece of

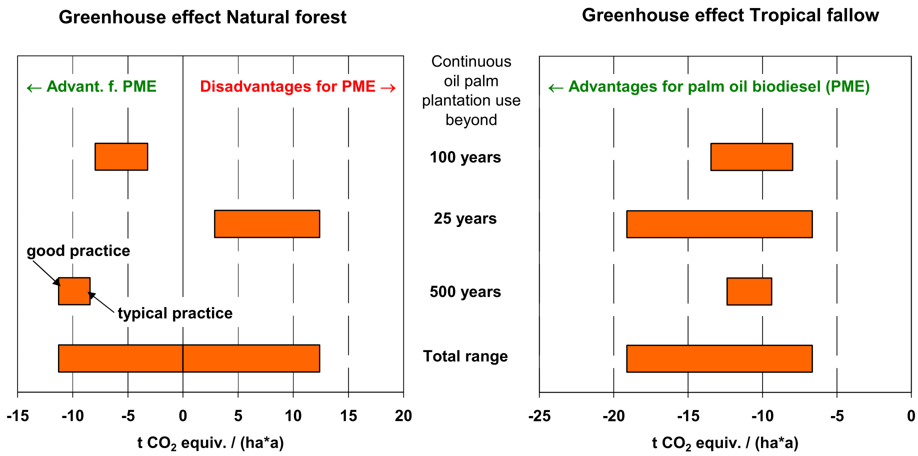

Fig. 5 – Ranges of greenhouse gas balance outcomes for palm oil biodiesel originating from plantations established on former natural forest and tropical fallow sites, respectively, assuming the cultivation of oil palms continues beyond the regarded (depreciation) period of 25, 100 or 500 years (Source: [7]).

tropical fallow land is developed into an oil palm plantation which is used continuously for more than say 100 years or if this plantation is established on a site which was cleared of natural forest and run for 100 years, after which the area is by and by covered by a secondary forest. These aspects can be of major relevance for the LCA results and study reports must therefore clearly state how they were dealt with.

The same applies for the definition of another crucial time span, which is directly connected to the issues described in the previous paragraph: (3) the depreciation period over which the respective increased or – in many cases – reduced carbon stock is calculated. Reference periods used in LCA's to date vary greatly and include absolute time spans ranging between 20 and 500 years, but also the (estimated) duration of a crop rotation period for the case-specific plantation type.

Fig. 5 illustrates the effect the regarded time span and the carbon may have on the greenhouse gas balance of a biofuel for two possible scenarios of palm oil production. The depicted results originate from the complete life cycle comparison between palm oil biodiesel and conventional diesel fuel. The ranges reflect the difference in outcomes between typical and good practice, i.e. optimised production methods. The findings show that (1) the balance total may turn out either positive or negative, depending on the chosen depreciation period and that (2) the quantitative values vary considerably in connection with the land use change. This example strikingly illustrates the great importance of including the consideration of land use aspects within environmental impact assessments.

Another process which is not sufficiently accounted for by the existing studies is the displacement of land uses which are being "forced into" other areas through the establishment of (new) energy crop plantations. For example, if palm oil from an existing oil palm plantation is used for bioenergy instead of for food, other sites will have to be developed for palm oil (or other native oils) to be produced for nutritional purposes – without a guarantee that environmental criteria will be given much consideration. While first studies already addressed this issue in the early 1990's e.g. [2], several studies have recently been dealing intensively with this topic under terminologies such as displacement issues or indirect land uses, e.g. [20]. Suggestions to use default values from risk adder assessment in order to account for this topic are currently being discussed [21].

5. Conclusions and outlook

The present assessment is based on the results of life cycle comparisons. These comparisons are made on numerous assumptions. Although it seems like scientifically reliable results can be derived, these results and the respective interpretations cannot be generalized because different goal and scope definitions, system boundaries, assumptions, etc. lead to different results. Therefore, these results must be explicitly discussed considering the underlying assumptions. Nevertheless, some basic conclusions can be drawn on the environmental implications of the regarded biofuels.

The main outcome for the comparison of biofuels and fossil fuels is that the energy and greenhouse gas balances of the regarded biofuels are – in most cases – more advantageous than those of their fossil equivalents, at least within the underlying system boundaries. Since most biofuels, however, also lead to disadvantages in other environmental impact categories (see exemplification for RME in Fig. 2), an objective decision in favour of one fuel or another can only be undertaken if energy savings of fossil resources as well as greenhouse gases are given the highest environmental priority. In this case, almost all reported results show the biofuels to be favourable compared to their fossil equivalents. However, the limitations and lackings in system boundary setting as described later, may change this outcome.

Recently, important findings have been made regarding the role of the land use in the broader sense; in connection with increased bioenergy crop production in tropical regions of the world, new aspects have arisen in the expert discussion. Generally, the outcomes of the greenhouse gas balances can be fundamentally determined by the change in carbon stock occurring through a land use change in connection with the establishment and management of the plantations. If, for example, tropical natural forest is initially cleared for oil palm cultivation and if the plantation site remains degraded after this cultivation is abandoned, the resulting long-term carbon loss will lead to clearly increased greenhouse gas emissions. This effect is even more detrimental if the sites in question are originally characterised by peat soils. The influence of such land use changes can even cause an otherwise positive outcome to be reversed into a disadvantageous greenhouse gas balance, i.e. the regarded palm oil-based biofuel will account for additional greenhouse gas emissions instead of helping to reduce them.

In connection specifically with the evaluation and consideration of land use changes, the definition of the time frame is also essential. Especially the depreciation period over which any carbon stock changes of the cultivation sites are to be "spread out" within the calculation of the greenhouse gas balance of a specific biofuel must be carefully determined – even if until now, no general agreements exist on the exact time spans which are most reasonable.

The following additional conclusions can be made from the presented results:

- High variability of the results – An examination of various studies in energy and greenhouse gas balances of biofuels shows a high level of variability in the findings. A direct comparison between the different biofuel options is not always possible. The high level of variability arises from the favourable or unfavourable assumptions made regarding system boundaries or specific conditions such as land use issues (including the cultivation), the biomass conversion and the utilisation of the co-products. In order to allow for a direct comparison among different biofuel options, the system boundaries must be determined very precisely.
- A ranking of biofuels can be undertaken for some examples:
  - Regarding the area-related consideration for biofuels from agriculture, ETBE shows advantages compared to all other biofuels.
  - In dependency of the resource basis, bioethanol scores better or less well than biodiesel and vegetable oil.
  - Biodiesel shows advantages compared to vegetable oil, when the same system boundaries are assumed.
  - Biodiesel from palm oil shows a very wide result range for the energy and greenhouse gas balances and can even lead to disadvantages compared to fossil fuel.
  - If regarded for area-related reference units, BTL shows greater advantages than biodiesel and wheat-, maize- and potato-based ethanol produced with conventional technologies. However, bioethanol shows advantageous results compared to BTL if produced from sugar cane.
- Specific geography-related advantages – The advantages of several biofuels do not apply in all parts of the world. The bioethanol production from sugar-cane, for example is limited to tropical climatic conditions while sugar beets can only be cultivated on particularly fertile soils within the temperate regions.

The technical potentials of biofuels are generally very high when all possibilities of biofuel production and currently unavailable technologies in the production of biofuels are considered. Whether and when these technologies will be available is not yet predictable with our present knowledge. A leading automobile manufacturer claims that the technology for the production of BTL should be available in the medium-term, and that the production of hydrogen should be possible in the long run.

5.1. *Competing land use*

The potentials of biofuels from cultivated biomass depends foremost on the available land area, while the production potentials from organic residues are independent of land area. The land area for the production of biofuels can compete with the area for foodstuff production and the area for natural conservation. [22] shows that for Germany, the technical potentials for biofuels are reduced considerably due to the importance given to natural conservation aspects (including surface water and soil conservation). Next to these aspects, which also include biodiversity, for example, one might have to take the following into account: under certain goal & scope definitions, transport fuels may compete with heat and power from bioenergy for cultivation area (land) and biomass. Transport fuels (and any other use of biomass) should thus be assessed in the light of inhibiting other uses of the land or biomass in question. This means that a certain data point on CO_2 equivalent reduction by a transport biofuel cannot be interpreted in isolation, as a long-term consequence may be an implicit equivalent extra demand for fossil fuels for heat and power. This additional demand should in turn be taken into account when judging on the environmental implications of the biofuel.

5.2. *Competing biomass usages*

[23] has shown that competing biomass usages greatly affect the production potentials of biofuels. In a scenario calculated here, the biofuel production in Germany in 2050 was reduced to one quarter of previous predictions based on the assumption that the biomass potentials would be used more in stationary facilities than in transport sector. No detailed estimations regarding the production potentials of biofuels exist that consider the competing biomass usages which are available for the remaining reference areas (EU and the world). While in many studies, it is assumed that the total available biomass will used in the fuel sector, single other examinations have regarded alternative (split-use) scenarios, for example the environmental impact assessments within [24].

Overall, there is a considerable need for further research on biofuels for transportation; a lack of data has been identified for numerous fields. For instance, in-depth examinations of the emissions from the combustion of biofuels such as BTL in the most modern motor concepts must be conducted. Also, environmental impacts other than greenhouse gases are ignored in many important individual studies. Another significant knowledge gap which has recently been increasingly addressed in the expert discussion is the lack of precise data on the carbon content of above- and below-ground biomass in bioenergy crop plantations and exact figures for some certain land use-related N_2O emission factors.

REFERENCES

[1] Jungk NC, Reinhardt GA. Landwirtschaftliche Referenzsysteme in ökologischen Bilanzierungen [agricultural reference systems in ecological balances]. Bonn: Federal Ministry for Agriculture, Food and Forestry; 2000. Report No.: FKZ 99 NR 009.

[2] DeLuchi MA. Emissions of greenhouse gases from the use of transportation fuels and Electricity. Volume 1. Argonne IL: Argonne National Laboratory - Center for transportation research; 1991 November. Report No.: ANL/ESD/TM-22153.

[3] Deutsches Institut für Normung e.V. (German Institute for Standardization). DIN EN ISO 14040 to 14043-Deutsche Normen (German and English versions). Berlin: Beuth Verlag; 1997–2000.

[4] Deutsches Institut für Normung e.V. (German Institute for Standardization). environmental management – Life cycle assessment – Requirements and Guidelines. ISO 14040: 2006(E) & ISO 14044:2006(E). Berlin: Beuth Verlag; 2006.

[5] Quirin M, Gärtner SO, Pehnt M, Reinhardt GA. CO2-neutrale Wege zukünftiger Mobilität durch Biokraftstoffe: Eine Bestandsaufnahme [CO2 Mitigation through Biofuels in the Transport Sector. Status and Perspectives]. Frankfurt a. m: Institute for Energy and Environmental Research (IFEU) for the Research Association Combustion Engines (FVV); 2004.

[6] Reinhardt GA, Gärtner SO, Patyk A, Rettenmaier N. Ökobilanzen zu BTL: Eine ökologische Einschätzung [LCA for Biomass-to-Liquid fuels. An overall Environmental Assessment]. Heidelberg: Institute for Energy and Environmental Research (IFEU) for the Agency of Renewable Resources (FNR); 2006.

[7] Gärtner SO, Reinhardt GA, Rettenmaier N. Environmental effects of palm oil production. Frankfurt: published in WWF Deutschland 2007-Rain Forest for Biodiesel? Ecological Effects of using Palm Oil as a Source of Energy; 2007.

[8] World Watch Institute (WWI) in cooperation with GTZ (Gesellschaft f. Techn. Zusammenarbeit) and FNR (Agency for Renewable Resources). Biofuels for transportation. Global potential and implications for Sustainable agriculture and energy in 21st Century. Washington, D.C: Federal Ministry of Food, Agriculture and Consumer Protection (BMELV), Germany; 2006.

[9] CONCAWE and EUCAR for the Joint Research Centre (JRC) of the European Commission. Well-to-Wheels analysis of Future Automotive fuels and Powertrains in the European context; 2006 May. Version 2b. Brussels.

[10] Netherlands Agency for Energy and the Environment (NOVEM) (coordinator) with 18 project partners. Shift Gear to biofuels. results and recommendations from the VIEWLS project. Utrecht: supported by the European Commission; 2006.

[11] CONCAWE, EUCAR & JRC. Well-to-Wheels analysis of future Automotive fuels and Powertrains in the European context; 2007. Brussels: WELL-to-WHEELS Report. Version 2c.

[12] Borken J, Patyk A, Reinhardt GA. Basisdaten für ökologische Bilanzierungen: Einsatz von Nutzfahrzeugen für Transporte, Landwirtschaft und Bergbau [Fundamental Data for LCAs: Use of Utility Vehicles in Transport, Agriculture and Mining]; 1999. Braunschweig/ Wiesbaden.

[13] Gärtner SO, Reinhardt GA. Ökologischer Vergleich von RME und Rapsöl [Environmental Comparison of RME and Rapeseed Oil]. Heidelberg: Institute for Energy and Environmental Research (IFEU) for the Agency of Renewable Resources (FNR); 2001.

[14] Bioenergy for Europe. which ones fit best? A comparative Analysis for the Community. Final report. CLM (NL), CRES (GR), CTI (I), FAT/FAL (CH), INRA (F), TUD (DK). Supported by the European Commission DG XII; 09/1998 – 08/2000. Heidelberg: Institute for Energy and Environmental Research (IFEU) (coordinator) with BLT (A); 2000.

[15] Kaltschmitt M, Reinhardt GA. Nachwachsende Energieträger: Grundlagen, Verfahren, ökologische Bilanzierung [Biofuels: Basics, processes, LCAs]; 1997. Braunschweig/ Wiesbaden.

[16] Patyk A, Höpfner U. Ökologischer Vergleich von Kraftfahrzeugen mit verschiedenen Antriebsenergien unter besonderer Berücksichtigung der Brenn-stoffzelle [Environmental Comparison of Motor Vehicles with different Types of Fuels and Drive Systems with special Focus on Fuel Cells]. Heidelberg: Institute for Energy and Environmental Research (IFEU) for the Office of Technology Assessment at the German Parliament (TAB); 1999.

[17] ntergovernmental Panel on Climate ChangeI. IPCC Third assessment Report – Climate change 2001. Cambridge; 2001. Working Group I: The Scientific Basis.

[18] Heijungs R, Guinée J, Huppes G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A, et al. Environmental life cycle assessment of products. Guide and Backgrounds. Leiden University. Centre of Environmental Science (CML); 1992 October. Report No. NOH 9267130.

[19] Gärtner SO, Reinhardt GA. Life cycle assessment of biodiesel: Update and new aspects. Heidelberg: Institute for Energy and Environmental Research (IFEU) for the Union for the Promotion of Oil and Protein Plants (UFOP); 2003.

[20] Delucchi MA. Documentation of a lifecycle emissions model (LEM): Lifecycle emissions from transportation fuels, motor vehicles, transportation Modes, Electricity use, heating and Cooking fuels, and materials. Main report: Delucchi, Mark A. ITS-Davis, California; 2003. Publication No. UCD-ITS-RR-03-17-MAIN REPORT.

[21] Fritsche U. GHG accounting for biofuels: considering CO2 from Leakage. Darmstadt, Germany: Öko-Institut; 2007.

[22] European Environment Agency. How much Bioenergy can Europe produce without harming the Environment?; 2006. Copenhagen: EEA Report 7/2006.

[23] Nitsch J, Krewitt W, Nast M, Viebahn P, Gärtner SO, Pehnt M, et al. Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland [Environmentally optimized Extension of utilising Renewable Energies in Germany]. Stuttgart/Heidelberg/Wuppertal: German Aerospace Center (DLR). Institute for Energy and Environmental Research (IFEU) and Wuppertal Institute (WI) for the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; 2004.

[24] Detzel A, Gärtner SO, Krüger M, Reinhardt GA, Rettenmaier N. Nachwachsende Rohstoffe für die chemische Industrie: Optionen und Potenziale für die Zukunft [Renewable Resources for the Chemical Industry: Options and Potentials for the Future]. Supported by the German Chemical Industry Association; 2007.