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# WP 6

# Deliverable 6.3:

# *Report on environmental assessment*

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# SWEETFUEL:

## Sweet Sorghum: an alternative energy crop

## Deliverable 6.3:
## Report on environmental assessment

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# Executive summary

Increasing world market prices for fossil fuels, driven by limited reserves, growing demand and instability in producing regions make renewable fuels such as bioethanol or biogas economically more attractive. Bioethanol is one of the most prevalent biofuels in the world and represents an actual alternative fuel for the transport sector. Worldwide, the main source of bioethanol is sugar cane. However, the cultivation of this crop cannot be realised in water-limited regions. On this **background**, sweet sorghum (*Sorghum bicolor* (L.) Moench) has several advantages due to its efficiency in both water use and nutrient uptake. Another variant of this plant, termed biomass sorghum, is adapted to high biomass yields especially in temperate regions. It is a promising alternative feedstock for biogas production. The project "SWEETFUEL: Sweet Sorghum: an alternative energy crop" funded by the European Commission mainly aims at developing sweet sorghum cultivars for tropical and semi-arid regions and biomass sorghum cultivars for temperate environments. The production of these variants and the use of their products such as bioethanol or biogas may represent a sustainable alternative to meet future energy needs.

An **environmental sustainability assessment** is performed as part of the SWEETFUEL project. It primarily analyses whether a mature and large-scale cultivation and use of sweet and biomass sorghum in 2020 can live up to the expectations regarding environmental benefits primarily compared to the use of fossil fuels. This environmental assessment applies a generic and scenario-based comparison of whole life cycles from cradle to grave. To obtain a comprehensive picture of the environmental implications associated with sweet and biomass sorghum production and use, two approaches are applied in this study to cover global and regional as well as local environmental impacts: a life cycle assessment (LCA) and a life cycle environmental impact assessment (LC-EIA). The LCA addresses global and regional environmental impacts (e.g. use of energy resources and environmental consequences of emissions). LC-EIA is a newly developed methodology that applies elements of environmental impact assessment (EIA) to whole life cycles of products instead of to concrete projects. It complements LCA by a qualitative assessment of local environmental impacts, which cannot be reliably quantified yet.

Within the SWEETFUEL project, several **scenarios regarding the production and use of sweet and biomass sorghum** were defined. For sweet sorghum cultivation and use, these are: cane fallow, grain to food and syrup production. In all of these scenarios, the main product is ethanol. In the cane fallow scenario, sweet sorghum is cultivated on fallows between cycles of sugarcane with a focus on ethanol production from both the sugar juice and the grains. The grain to food scenario focuses on the cultivation of sweet sorghum instead of grain sorghum. Grains are not processed to ethanol but used as food to still guarantee food security. In the syrup production scenario, sugar juice is first concentrated into syrup at village level. The syrup is then processed in a central ethanol plant. The main biomass sorghum scenarios involve cultivation that aims at high biomass yields for biogas production. Alternatively, the combustion of the biomass and the production of second generation fuels is

analysed (second generation ethanol via fermentation and synthetic Fischer-Tropsch fuels via gasification).

Results of the LCA show that the production and use of sweet and biomass sorghum can cause a wide spectrum of potential global and regional impacts ranging from significant environmental benefits to distinctly detrimental environmental impacts. Most scenarios achieve a **mitigation of climate change and savings of non-renewable energy resources**. However, all scenarios lead to **additional environmental burdens** mainly caused by agriculture including e.g. acidification of soils or excess nutrient inputs into ecosystems. This pattern of environmental advantages and disadvantages is common for most biofuels from annually cultivated biomass. Nevertheless, advantages can be increased and disadvantages can be decreased by optimisation: Responsible for the individual outcome are factors such as the use of by-products (for sweet sorghum scenarios) and the choice and configuration of the conversion process (for all scenarios). Additionally, there are external factors that affect the environmental impacts like the type of land sweet sorghum is cultivated on.

For **local environmental impacts**, results of the comparison between the SWEETFUEL scenarios and conventional reference systems vary depending on the life cycle stage. In general, the local environmental effects are especially dominated by the life cycle step biomass production. The biomass conversion part, in contrast, plays only a subordinate role.

With regard to raw materials provision, biomass tends to be advantageous compared to fossil reference products (e.g. gasoline), as long as the biomass in question is produced sustainably. To which extent this is true, depends on the land sweet sorghum is cultivated on. As long as sweet sorghum is grown on idle land, the consequences of biomass production are neutral to negative but – at least to some extent – reversible. Partly irreversible, however, are consequences if sweet sorghum is cultivated on land that has a high ecological value (e.g. forests or grasslands). A conversion of these areas into cropland should therefore be avoided.

With regard to the conversion of raw materials, the differences between conversion units for sweet and biomass sorghum and for fossil raw materials (e.g. crude oil refineries) are negligible in terms of impacts resulting from construction phase or related to buildings, infrastructure and installations. Actual differences are rather associated with operation-related impacts. In this context, biomass conversion units show both advantages and disadvantages. Thus, the outcome depends on the chosen pathway but differences to conventional fossil-based products are mostly small.

The observed variability of results leads to concrete recommendations under which conditions and, if so, how sweet and biomass sorghum cultivation and use should be implemented: From an environmental point of view, one generalising **recommendation to optimise sweet and biomass sorghum cultivation** is the support of further research programmes that focus on breeding improved crop cultivars leading to both higher yields and a lower nutrient content (especially nitrogen) in the harvested biomass. These measures help to increase the output per hectare and decrease the input of applied mineral fertilisers; hence they lead to a better overall result. Another recommendation in this context is to support further research programmes to optimise the agronomic production principles of existing sorghum cultivars by all means of techniques such as variations in crop rotation cycles or indi-

vidual crop durations. For sweet sorghum production and use, it is recommended that the by-product leaves should be used for bioenergy production. The by-products grains and surplus bagasse (not required for process energy provision) should only be used for bioenergy production if grains are not needed as food and the use of surplus bagasse as feed is not needed to relieve pressure on regional land availability, respectively. In case of biogas production from biomass sorghum, digestate storage tanks should be covered and closed gas-tight and the digestate should be incorporated into the soil within one hour.

This study shows that the combination of LCA and LC-EIA represents a **viable approach to comprehensively assess all environmental impacts** throughout the life cycle of a product. Nevertheless, environmental impacts are only one aspect of sustainability and social and economic aspects have to be analysed and taken into account, too, for political decisions. Furthermore, observed variability makes it necessary to individually assess all concretely planned major projects for sweet and biomass sorghum cultivation and use. On that basis, sweet and biomass sorghum can be sustainably integrated into strategies for land and biomass use.

**In summary**, the production and use of sweet and biomass sorghum in the SWEETFUEL project carries the potential for a distinct reduction of greenhouse gas emissions and the use of non-renewable energy resources whilst local environmental impacts are negligible to advantageous compared to conventional fossil-based (reference) products as long as the biomass in question is produced sustainably. Specific options for the realisation of this potential have been identified and are detailed in this report.

# 1 Introduction, goal and scope

Bioethanol contributes to the increasing use of biofuels. Worldwide, sugar cane is the main source of bioethanol. However, the cultivation of this crop cannot be realised in water-limited regions. On this background, sweet sorghum (*Sorghum bicolor* (L.) Moench) has several advantages due to its efficiency in both water use and nutrient uptake. Furthermore, the production of food, feed and fuel can be combined in one crop. This is an important asset on the background of the currently increasing discussion on fuel production and food security. Another variant of this plant, termed biomass sorghum, is adapted to high biomass yields especially in temperate regions. Drought tolerance and resistance against specific pests make it a promising alternative feedstock for biogas production.

As a more widespread use of sweet and biomass sorghum for bioethanol and biogas production is primarily limited by the lack of variants specifically bred for this purpose, a project funded by the European Commission with the title “SWEETFUEL: Sweet Sorghum: an alternative energy crop” was launched (Grant agreement no. 227422). The SWEETFUEL project aims at developing sweet sorghum cultivars for tropical and semi-arid regions and biomass sorghum cultivars for temperate environments. The focus lies on tolerance to cold, drought and acidic soil as well as on a high production of stalk sugars, easily digestible biomass or grains – depending on the climatic region the crop shall be cultivated in and depending on the purpose it shall be used for. Properties and cultivation conditions of sweet sorghum are described in the energy sorghum handbook /Khawaja et al. 2014/. The project was split in seven work packages (WPs). WPs 1-5 focused on breeding aspects as well as cultivation and harvest practices. Based on the results of WPs 1-5, WP 6 performed a sustainability assessment while WP 7 transferred project results to the stakeholders.

WP 6 “Integrated assessment” of the SWEETFUEL project provided a multi-criteria evaluation of several sorghum production and use pathways taking into account technological, environmental, economic and social aspects. The outcome of the integrated assessment specifies a set of optimised, sustainable sorghum production and use systems.

This report is the outcome of Task 6.2 “Environmental assessment” as part of WP 6 “Integrated assessment” of the SWEETFUEL project. It was composed by IFEU with contributions from all SWEETFUEL partners, namely ARC, CIRAD, EMBRAPA, ICRISAT, KWS, UANL, UCSC, UNIBO and WIP. It delivers results of a life cycle assessment (LCA) of all sweet sorghum and biomass sorghum scenarios based on definitions and settings outlined in D 6.2 “Report on technological assessment” /Braconnier et al. 2013/. Additionally, site-specific environmental issues linked to feedstock production and transformation are presented using a life cycle related approach of an environmental impact assessment, the so called life cycle environmental impact assessment (LC-EIA).

The report on environmental assessment provides answers to the following core question:

- Which are the best options to use **sweet and biomass sorghum as energy crops** from an environmental point of view?

To address the core question, the following issues were assessed:

- What are the advantages and disadvantages of the different sweet and biomass sorghum **cultivation systems** investigated in this project?
- What are the main influencing life cycle steps and where are the main optimisation potentials?
- How do different usage pathways of the **by-products** affect the overall results? Which usage should be preferred from an environmental point of view?

The following chapter of the report describes all definitions, general specifications and settings as well as the methodology of the life cycle assessment and of the life cycle environmental impact assessment (chapter 2). In chapter 3, short descriptions of sweet and biomass sorghum scenarios are presented. The results from the life cycle assessment are described in chapter 4, those from the life cycle environmental impact assessment in chapter 5. The results are recapitulated in chapter 6 and recommendations are given. Chapter 7 lists references and in the annex (chapter 8), supplementary material can be found. Chapter 9 contains the glossary and abbreviations.

# 2 Methodology

This chapter defines general specifications and settings (subchapter 2.1) as well as the methodology of the life cycle assessment (subchapter 2.2) and of the life cycle environmental impact assessment (subchapter 2.3).

## 2.1 General specifications, definitions and settings

For the analysis of the investigated scenarios, general definitions and settings are necessary. They are used to assess environmental, economic and social implications and guarantee their consistency. The general settings have been described within the report for task 6.1 ('Report on technological assessment') /Braconnier et al. 2013/ and are quoted below.

**Definition of sorghum variants**

Sorghum is a crop which has quite a large diversity in phenotypic variability and composition. In the SWEETFUEL project the following terminologies are used:

**Sweet sorghum**: Sorghum cultivars with juicy stems and high juice sugar content in their stalks; potentially used as an energy and / or food crop.

**Biomass sorghum**: Sorghum cultivars with high lignocellulosic biomass yield, potentially used as energy crop.

**Energy sorghum**: Sweet and biomass sorghum cultivars used in this project.

**Grain sorghum**: Sorghum cultivars with high grain yield established as food and feed crop.

**Fibre sorghum**: Sorghum cultivars with a high content of fibre; potentially used as fibre or energy crop.

This project mainly focuses on sweet and biomass sorghum, whereas grain sorghum is treated as reference system. Fibre sorghum is not investigated in this project.

**Time frame**

In this project the use of sweet and biomass sorghum for both 1$^{st}$ generation and 2$^{nd}$ generation fuel technologies is assessed. The former, i. e. the production of bioethanol, is already well-established. In contrast, second generation technologies such as the production of ethanol from lignocellulose or the biomass gasification for so-called BtL (Biomass-to-Liquid) fuels are not yet commercially available, however, pilot and demonstration plants are operated in some countries (e.g. Europe, USA, Brazil, China, India). In this project prospective conditions given in the year 2020 are considered as main scenario since it is expected that the technology described will be mature then and thus comparable with other 1$^{st}$ generation ethanol production technologies. Additionally, the situation in 2015 is described for some

scenarios since this reflects the state of the art at the end of the project which is currently existent in Brazil for instance.

#### Geographical coverage

**Sweet sorghum:** In general, sweet sorghum is a manifold plant which can be cultivated in many parts of the world. Due to its high efficiency in water use and light exploitation it is particularly suitable for semi-arid and subtropical areas. Additionally, however, it is also thoroughly suitable for tropical regions. Thus, the following definitions are set for sweet sorghum cultivation:

- Subtropical / semi-arid climate with around 700 mm rainfall
- Tropical climate with around 1,200 mm rainfall per year

**Biomass sorghum:** In future, biomass sorghum will be mainly cultivated to obtain high biomass yields for biogas production. This requires protruding growing conditions. Coming along with the recent discussion on fuel versus food as well as political regulations, biomass sorghum has a high potential to be cultivated especially in temperate regions. Thus, for this investigation biomass sorghum scenarios are only settled in those areas.

Within the regions investigated in this project, there might be great variations due to differences in environmental conditions as well as due to varying production practices and conditions in different countries. These differences are captured by sub-scenarios and sensitivity analyses taking into account various yields, uses of the products and by-products or production costs etc. It is outside the scope of the project to analyse every single country where sweet or biomass sorghum could be produced.

#### Functional unit

The functional unit has to be chosen depending on the questions to be answered. As the project aims at increasing the output of the crop by developing improved cultivars and since land usually is the limiting factor, the use of sorghum cultivars from 1 hectare of land in 1 year is assessed.

#### Alternative land use options

The alternative land use defines how the land would be used if energy sorghum was not cultivated. It also comprises any change in land cover induced by the cultivation of energy sorghum. As agricultural land is becoming increasingly scarce, more and more natural land (e.g. forests or grass land) is transformed into arable land. Such land use and land cover changes may have considerable influences on the outcomes of the environmental assessment since e.g. the area’s carbon stock or biodiversity are influenced. For example, a decline in above-ground and below-ground carbon stocks leads to greenhouse gas emissions, which have to be included in the greenhouse gas balance. Beside direct land use changes also indirect changes can occur. This is the case if for example the cultivation of sweet sorghum displaces the production of a food crop to other areas. Depending on use and / or land cover of that area, the displacement can cause different environmental effects.

In this project, the standard scenario refers to reference systems where the difference in carbon stock between initial vegetation and energy sorghum cultivation is close to zero. This includes reference systems such as degraded soils, degraded pastures or land that becomes free due to the intensification of existing land use. Furthermore, also idle land can be used to cultivate energy sorghum. In the further course of the report all these land use options are referred to as **“idle land”**.

In order to derive a bandwidth of different vegetation types for the alternative land use, two reference systems are identified, which are captured by sensitivity analyses:

- Dense thickets / sparse forests (carbon loss around 60 t carbon / hectare)
- Wooded grassland / planted pastures / (carbon loss around 15 t carbon / hectare)

This classification is mainly oriented at the carbon difference which occurs if reference vegetation is replaced by energy sorghum cultivation. The carbon loss given here serves the purpose to characterise the reference systems. It does not reflect real carbon contents but serves as an indicative differentiation between the different reference systems defined.

Since the alternative land use differs among scenarios, more detailed descriptions are specified within respective scenario descriptions (see subchapters 3.1 and 3.2).

**Technical reference**

The technical reference describes the technology to be assessed in terms of plant capacity and development status / maturity. As the investigated scenarios cover both “central” and “decentralised production at village level” two main technical references were defined:

- 25,000 – 120,000 t ethanol per year production capacity in the case of centralised production
- 3 t syrup per day in the case of decentralised production
- For all plant capacities, mature, full-scale industrial plants are assessed

## 2.2 Life cycle assessment (LCA)

In the following paragraphs a general introduction of the methodology of a life cycle assessment (LCA) is given (subchapter 2.2.1) and the settings for a life cycle impact assessment (LCIA) are described (subchapter 2.2.2). Moreover, system boundaries (subchapter 2.2.3), further methodological issues (subchapter 2.2.4) and the origin of the data are considered (subchapter 2.2.5).

### 2.2.1 Introduction to LCA methodology

Life cycle assessment addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of emissions) throughout a product’s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. The approach is therefore often called cradle-to-

grave, well-to-wheel (biofuels) or farm-to-fork (food). The objective of carrying out an LCA in in this project is to identify the most promising SWEETFUEL pathways in environmental terms, to identify optimisation potentials and to compare the SWEETFUEL concepts to conventional production chains.

LCA methodology is laid down in important regulatory frameworks: two ISO standards and the ILCD Handbook, which are described in the following paragraphs.

### The ISO standards 14040 and 14044

Life cycle assessment (LCA) is a comprehensive approach that is structured and internationally standardised through ISO standards 14040:2006 and 14044:2006 /ISO 2006/. It can among others assist in:

- identifying opportunities to improve the environmental performance of products at various points in their life cycle and
- informing decision-makers in industry, government or non-government organisations (e.g. for the purpose of strategic planning, priority setting, product or process design).

The life cycle analyses (LCA) in this study are carried out largely following the above mentioned ISO standards on product life cycle assessment /ISO 2006/.

There are four iterative phases in an LCA study (Fig. 2-1):

1) the goal and scope definition phase,

2) the inventory analysis phase,

3) the impact assessment phase, and

4) the interpretation phase.

All phases are iterative as depicted in Fig. 2-1. Therefore, interpretation has to be seen as a continuous process.

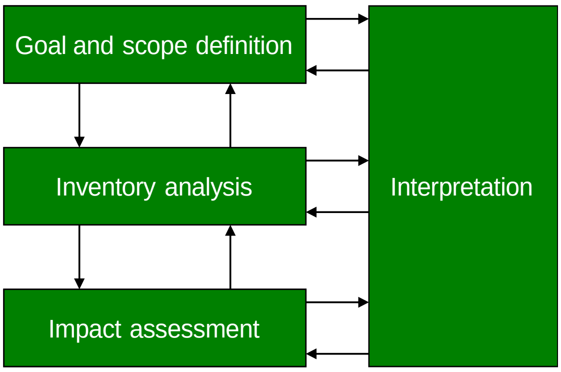


**Fig. 2-1** Phases of an LCA /ISO 2006/.

### The ILCD Handbook

The ISO 14040 and 14044 standards provide the indispensable framework for life cycle assessment. This framework, however, leaves the individual practitioner with a range of choices, which can affect the legitimacy of the results of an LCA study. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance. The International Reference Life cycle Data System (ILCD) has therefore been developed by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC), in co-operation with the Directorate General for the Environment of the European Commission (DG Envi) to provide guidance for consistent and quality assured life cycle assessment data and studies /JRC-IES 2010/.

The ILCD Handbook is a series of technical documents (depicted in Fig. 2-2) that provide detailed guidance on all the steps required to conduct a life cycle assessment (LCA). In the Communication on Integrated Product Policy, the European Commission committed to pro-

duce a handbook on best practice in LCA. The Sustainable Consumption and Production Action Plan confirmed that "(…) consistent and reliable data and methods are required to assess the overall environmental performance of products (…)". The Handbooks' main goal is to ensure quality and consistency of life cycle data, methods and assessments. Its main target audience is LCA practitioners, data providers, and reviewers.

In contrast to the ISO standards on LCA which have been available and used for many years, the ILCD Handbook was only launched in March 2010 and is still under development. Important guidelines, e.g. on life cycle impact assessment have only been published in November 2011. Moreover, the ILCD Handbook's practicability has not been tested yet and it remains to be verified whether it makes sense to follow these guidelines e.g. for future hypothetical biorefinery concepts. Nevertheless, the LCAs carried out for SWEETFUEL took into account the major requirements of the ILCD Handbook.

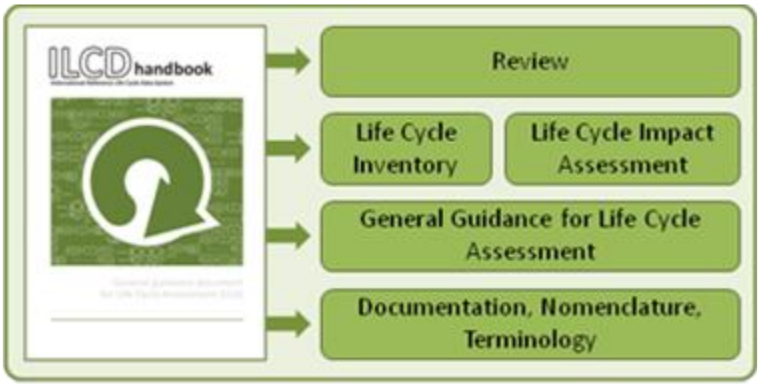


**Fig. 2-2** The ILCD Handbook: a series of technical documents providing guidance for good practice in life cycle assessment /JRC-IES 2010/.

For the life cycle assessment, a two-step approach is applied:

**Screening life cycle assessment**

For the selection of possible value chains, so-called screening life cycle balances are performed. These screening life cycle balances largely follow the above mentioned ISO standards except for a) the level of detail of documentation, b) the quantity of sensitivity analyses and c) the mandatory critical review. Nevertheless, the results of these screening LCAs are quite reliable due to the close conformity with the ISO standards.

**Sensitivity analyses to identify optimisation potentials**

Based on the interpretation of the screening assessments, several sensitivity analyses are calculated to identify the optimisation potentials.

### 2.2.2 Settings for Life cycle Impact Assessment (LCIA)

This project assesses the midpoint indicators listed in Table 2-1. The life cycle inventory (LCI) parameters and the respective characterisation factors are shown in Table 2-2. All impact categories are standard categories in life cycle assessments /JRC-IES 2010/. The pro-

cedures and general data for the calculations are documented in detail in /Borken et al. 1999/. In case of the category greenhouse effect the conversion of other trace gases (e.g. methane, nitrous oxide) into carbon dioxide equivalents ($CO_2$ equiv.) was calculated by using GWP100 factors /IPCC 2007/.

**Table 2-1** Environmental impact categories and their description.

| **Impact category** | **Description** |
|---|---|
| Depletion of non-renewable energy resources | Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas and different types of coal as well as uranium ore. |
| Greenhouse effect | Global warming as a consequence of the anthropogenic release of greenhouse gases. Besides carbon dioxide originating from the combustion of fossil energy carriers, a number of other trace gases – among them methane and nitrous oxide – are included. |
| Acidification | Shift of the acid/base equilibrium in soils and water bodies by acidifying gases (keyword ‘acid rain’). Emissions of sulphur dioxide, nitrogen oxides, ammonia, and hydrogen chloride are playing a major role. |
| Terrestrial eutrophication | Input of nutrients into soils and by gaseous emissions. Excessive nutrient intake into natural ecosystems harm endangered and rare species as well as fragile ecosystems like forests, calcareous grasslands etc. Among others, nitrogen oxides and ammonia are responsible for this. |
| Aquatic eutrophication | Input of nutrients into surface water (marine and freshwater) directly or via input into soils. Excessive nutrient intake into water bodies harms endangered species and can lead to excessive growth of algae. Among others, nitrogen and phosphorous species as well as organic matter contribute to this (keyword ‘algal bloom’). |
| Photochemical ozone formation | Formation of specific reactive substances, e.g. ozone, in presence of nitrogen oxides, volatile hydrocarbons and solar radiation in the lower atmosphere (keyword ‘ozone alert’, ‘summer smog’ or ‘Los Angeles smog’). |
| (Stratospheric) Ozone depletion | Loss of the protective ozone layer in the stratosphere by certain gases such as chlorofluorocarbons (CFCs) or nitrous oxide (keyword ‘ozone hole’). |
| Human toxicity (particulate matter emissions) | Damage to human beings due to air pollutants such as fine, primary particles and secondary particles (mainly from $NO_X$, $NH_3$ and $SO_2$). Heavy industries, electricity and heat production from liquid and solid fuels, as well as road traffic and agriculture are important sources of these pollutants (keyword ‘winter smog’ or ‘London smog’). |

Some impact categories, which are not listed in these tables, are excluded because they are i) irrelevant for the SWEETFUEL systems (e.g. ionising radiation) or ii) still under methodological development (e.g. human and ecotoxicity, water depletion and land use; classified as level III or II/III in the ILCD Handbook). Moreover, LCI data quality for 2020 is limited particularly for human toxicity and ecotoxicity, which cover very many substances. The data available today is not suitable to derive results that are balanced enough for decision support. Therefore, this category as a whole is excluded from the LCA and instead, one aspect of human toxicity, i.e. health risks due to particulate matter emissions, is covered as a midpoint indicator and important impacts on biodiversity are covered within the LC-EIA part (see subchapter 2.3).

**Table 2-2** Indicators, important LCI parameters and characterisation factors for the respective impact categories (/CML 2004/, /IPCC 2007/, /Klöpffer & Renner 1995/, /Leeuw 2002/, /Ravishankara et al. 2009/, /IFEU 2014/ on basis of /IPCC 2007/).

| Impact category | Category indicator | Life cycle inventory (LCI) parameter | Formula | Character. factor |
|---|---|---|---|---|
| Depletion of non-renewable energy resources | Cumulative primary energy use from non-renewable sources | Crude oil<br>Natural gas<br>Hard coal<br>Lignite<br>Uranium ore | — | — |
| Greenhouse effect | $CO_2$ equivalents (carbon dioxide equivalent) | Carbon dioxide fossil<br>Nitrous oxide<br>Methane biogenic*<br>Methane fossil** | $CO_2$<br>$N_2O$<br>$CH_4$<br>$CH_4$ | 1<br>298<br>25<br>27.75 |
| Acidification | $SO_2$ equivalents (sulphur dioxide equivalent) | Sulphur dioxide<br>Nitrogen oxides<br>Ammonia<br>Hydrochloric acid | $SO_2$<br>$NO_X$<br>$NH_3$<br>HCl | 1<br>0.7<br>1.88<br>0.88 |
| Terrestrial eutrophication | $PO_4^{3-}$ equivalents (phosphate equivalent) | Nitrogen oxides<br>Ammonia | $NO_X$<br>$NH_3$ | 0.13<br>0.346 |
| Aquatic eutrophication | $PO_4^{3-}$ equivalents (phosphate equivalent) | Nitrate<br>Nitrogen<br>Phosphorous | $NO_3^-$<br>N<br>P | 0.095<br>0.42<br>3.07 |
| Photochemical ozone formation | $C_2H_4$ equivalents (ethylene equivalents)* | Non-methane hydrocarbons<br>Methane | NMHC<br>$CH_4$ | 1<br>0.006 |
| (Stratospheric) Ozone depletion | CFC-11 equivalents | Nitrous oxide (Dinitrogen oxide) | $N_2O$ | 0.017 |
| Human toxicity | $PM_{10}$ equivalents | Particulate matter (≤10 µm)<br>Sulphur dioxide<br>Nitrogen oxides<br>Non-methane hydrocarbons<br>Ammonia | -<br>$SO_2$<br>$NO_X$<br>NMHC<br>$NH_3$ | 1<br>0.54<br>0.88<br>0.012<br>0.64 |

*without $CO_2$ effect; **with $CO_2$ effect

Regarding ozone depletion, an ODP factor for nitrous oxide from a study by /Ravishankara et al. 2009/ is used although it is not yet commonly accepted because it is the only one available.

### Normalisation

Normalisation helps to better understand the relative magnitude of the results for the different environmental impact categories. It transforms a category indicator result by dividing it by a selected reference value, e.g. a certain emission caused by the system is divided by this emission per capita in a selected area.

In the SWEETFUEL LCA study, the environmental advantages and disadvantages for the European scenarios can be related to the environmental situation in the EU27. The reference information is the yearly average energy demand and the average emissions of various sub-

stances per inhabitant in Europe, the so-called inhabitant equivalent (IE). The reference values are presented in the Annex, Table 8-2, for all environmental impact categories.

Due to the insecurity related to future emissions of various substances, the inhabitant equivalents will be calculated based on 2005 emissions. These values are subsequently used to normalise data which are calculated for 2015 and 2020 (time frame for SWEETFUEL systems). To ensure comparability, results for the non-European scenarios are also normalised using the EU inhabitant equivalents for EU27.

**Weighting**

Weighting will not be applied. Weighting uses numerical factors based on value-choices to compare and sometimes also aggregate indicator results, which are not comparable on a physical basis.

### 2.2.3 System boundaries

The LCA for this project covers the entire value chain from feedstock production to the distribution and usage of the final products including land use change effects with associated changes in carbon stocks (Fig. 2-3). For further descriptions please see chapter 3.

**Systematic exclusion of activity types**

Infrastructure is excluded from the system. This applies to production and processing equipment, vehicles such as tractors, buildings and streets connected with the crops' production and use. In many LCAs assessing bioenergy systems it was shown that infrastructure accounts for less than 10 % of the overall results (see /Nitsch et al. 2004/, /Fritsche et al. 2004/ and /Gärtner 2008/). However, this only applies to the environmental impacts. In contrast, investment and capital costs for process equipment or buildings are an important part of the economic assessment.

### 2.2.4 Further methodological issues

**Biogenic carbon**

There are two possible sources for carbon dioxide ($CO_2$) emissions: (recent) biogenic or fossil carbon stocks. For biofuels, the amount of $CO_2$ released into the atmosphere from direct biofuel combustion equals the amount of $CO_2$ that has been taken up by the plants recently (short carbon cycle). This release of biogenic $CO_2$ is considered carbon neutral, i.e. it does not promote greenhouse effect. Therefore, only fossil carbon is taken into account for calculating greenhouse gas balances in SWEETFUEL, which is the standard approach among LCA practitioners.

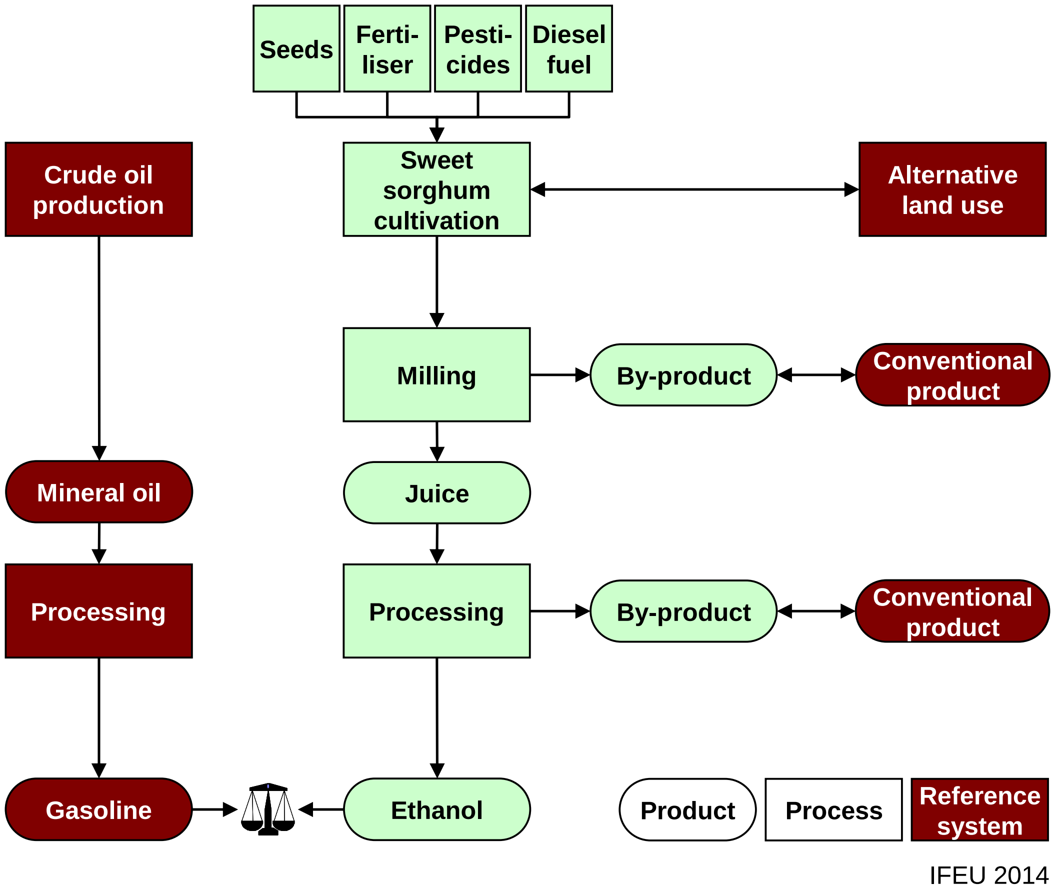


**Fig. 2-3** Basic principle of life cycle comparison between sweet sorghum ethanol and gasoline.

### Direct land use change and changes in organic carbon stocks

Changes in direct land use and related changes in organic carbon stocks of above- and below-ground biomass, soil organic carbon, litter and dead wood will be covered by LCA /IPCC 2006/. Changes in organic carbon stocks may result from extraction of woody biomass or straw for bio-refining, which formerly remained on the field / in the forest. The carbon stock changes and resulting release of greenhouse gases (mainly in the form of $CO_2$) are integrated into the GHG balances by using the above mentioned methodologies if alternative land use options lead to different carbon stocks. The methodologies described by the IPCC guidelines for national greenhouse gas inventories /IPCC 2006/ and the guidelines for the calculation of land carbon stocks for the purpose of Annex V to EU RED /EC 2010/ will be used.

Carbon sequestration, which could also result from a land use change, will not be taken into account. This is because the potential to sequester carbon in soil is very site-specific and highly dependent on former and current agronomic practices, climate and soil properties /Larson 2005/. Moreover, it is impossible to assure that the carbon is sequestered permanently. As there is no scientific consensus about this issue, carbon sequestration in agricultural soils will not be accounted for.

**Indirect effects**

New systems using biomass can indirectly affect environmental indicators by withdrawing resources from other (former) uses. One of the most common indirect effects is indirect land use change: Biomass formerly used for other purposes (e.g. as food or feed) has to be produced elsewhere if it is now used for biorefineries. This can cause a clearing of (semi-)natural ecosystems (= indirect land use change) and hence changes in organic carbon stocks and damages to biodiversity.

Withdrawing biomass from other uses may affect not only land use patterns but also other goods and services. For example, if a SWEETFUEL bioethanol plant is less efficient compared to another energetic biomass use option (e.g. CHP plants) in terms of replacement of crude oil equivalents but more efficient from an economic point of view and hence withdraw biomass from direct energetic use pathways, the crude oil production may even increase.

### 2.2.5 Data origin and data quality

Since sweet sorghum is cultivated in many different regions, for the SWEETFUEL project a multitude of data and information with respect to agricultural production and reference systems are needed. Those data were provided by the project partners.

Data on equivalent products of the outputs and their production chains were deduced by IFEU /IFEU 2014/.

## 2.3 Life cycle environmental impact assessment (LC-EIA)

There are a number of environmental management tools which differ both in terms of subject of study (product, production site or project) and in their potential to address environmental impacts occurring at different spatial levels. Environmental life cycle assessment (eLCA), for example, addresses potential environmental impacts of a product system (see subchapter 2.2). However, for a comprehensive picture of environmental impacts, also site-specific impacts on environmental factors like e.g. biodiversity, water and soil have to be considered. Although methodological developments are under way, these site-specific impacts are not yet covered in standard eLCA studies. Thus, for the time being, eLCA has to be supplemented by elements borrowed from other tools.

The methodology applied in SWEETFUEL borrows elements from environmental impact assessment (EIA) and therefore is called life cycle environmental impact assessment (LC-EIA).

### 2.3.1 Introduction to EIA methodology

Environmental impact assessment (EIA) is a standardised methodology for analysing proposed projects regarding their potential to affect the local environment. It is based on the identification, description and estimation of the project's environmental impacts and is usually applied at an early planning stage, i.e. before the project is carried out. EIA primarily serves as a decision support for project management and authorities which have to decide on ap-

proval. Moreover, it helps decision makers to identify more environmentally friendly alternatives as well as to minimise negative impacts on the environment by applying mitigation and compensation measures.

The environmental impacts of a planned project depend on both the nature / specifications of the project (e.g. a biorefinery plant housing a specific production process and requiring specific raw materials which have to be delivered) and on the specific quality of the environment at a certain geographic location (e.g. occurrence of rare or endangered species, air and water quality etc.). Thus, the same project probably entails different environmental impacts at two different locations. EIA is therefore usually conducted at a site-specific / local level. These environmental impacts are compared to a situation without the project being implemented ("no-action alternative").

**Regulatory frameworks**

As the SWEETFUEL project covers all regions in the world, ideally all regions should be considered.

Within the European Union, it is mandatory to carry out an environmental impact assessment (EIA) for projects according to the Council Directive 85/337 EEC of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment /CEC 1985/. This Directive has been amended three times:

- Council Directive 97/11/EC of 3 March 1997 /CEU 1997/
- Directive 2003/35/EC of 26 May 2003 /EP & CEU 2003/
- Directive 2009/31/EC of 23 April 2009 /EP & CEU 2009/

Another example listed here is India. The concept of environmental protection and resource management has traditionally been given strong emphasis and has been woven in all facets of life. EIA was introduced in 1994 by the Ministry of Environment and Forest (MOEF) by the

- Environment Impact Assessment Notification S. O. 60 (E) /MOEF 1994/, amended by the
- Environment (Protection) Act Notification (2004) – regarding new towns and industrial estates S. O. 801 (E) /MOEF 2004/ and the
- Environment Impact Assessment Notification (2006) S. O. 1533 /MOEF 2006/

With this, it becomes obvious, that there exist all together hundreds of regulations worldwide related to environmental impact assessment differing from country to country or region to region. Taking this in mind, for this project it was most appropriate to follow a generic approach taking the existing regulations into account. Details will be given later in this subchapter.

### EIA methodology

An EIA covers direct and indirect effects of a project on the following **environmental factors** /CEC 1985/:

- Human beings, fauna and flora, biodiversity
- Soil, water, air, climate and the landscape
- Material assets and the cultural heritage
- The interaction between these factors

An EIA generally includes the following steps:

- Screening
- Scoping
- EIA report
    - Project description and consideration of alternatives
    - Description of environmental factors
    - Prediction and evaluation of impacts
    - Mitigation measures
- Monitoring and auditing measures

### Screening

Usually an EIA starts with a screening process to find out whether a project requires an EIA or not. According to article 4 (1) and annex 1 (6) of the EIA Directive, an EIA is mandatory for "Integrated chemical installations, i.e. those installations for the manufacture on an industrial scale of substances using chemical conversion processes, in which several units are juxtaposed and functionally linked to one another and which are (i) "for the production of basic organic chemicals". Referring to annex 1 (6) of the EIA Directive, an EIA would be required if a SWEETFUEL bioethanol plant would be implemented.

### Scoping

Scoping is to determine what should be the coverage or scope of the EIA study for a project as having potentially significant environmental impacts. It helps in developing and selecting alternatives to the proposed action and in identifying the issues to be considered in an EIA. The main objectives of the scoping are:

- Identify concerns and issues for consideration in an EIA.
- Identify the environmental impacts that are relevant for decision-makers.
- Enable those responsible for an EIA study to properly brief the study team on the alternatives and on impacts to be considered at different levels of analysis.
- Determine the assessment methods to be used.

- Provide an opportunity for public involvement in determining the factors to be assessed, and facilitate early agreement on contentious issues

**EIA report**

An EIA report consists of a project description, a description of the status and trends of relevant environmental factors and a consideration of alternatives including against which predicted changes can be compared and evaluated in terms of importance.

- Impact prediction: a description of the likely significant effects of the proposed project on the environment resulting from:
  - The construction / installation of the project; temporary impacts expected, e.g. by noise from construction sites.
  - The existence of the project, i.e. project-related installations and buildings; durable impacts expected e.g. by loss of soil on the plant site.
  - The operation phase of the project; durable impacts expected, e.g. by emission of gases.

Prediction should be based on the available environmental project data. Such predictions are described in quantitative or qualitative terms considering e.g.:

- Quality of impact
- Magnitude of impact
- Extent of impact
- Duration of impact

Mitigation measures are recommended actions to reduce, avoid or offset the potential adverse environmental consequences of development activities. The objective of mitigation measures is to maximise project benefits and minimise undesirable impacts.

**Monitoring and auditing measures**

Monitoring and auditing measures are post-EIA procedures that can contribute to an improvement of the EIA procedure.

Monitoring is used to compare the predicted and actual impacts of a project, so that action can be taken to minimise environmental impacts. Usually, monitoring is constrained to either potentially very harmful impacts or to impacts that cannot be predicted very accurately due to lack of baseline data or methodological problems.

Auditing is aimed at the improvement of EIA in general. It involves the analysis of the quality and adequacy of baseline studies and EIA methodology, the quality and precision of predictions as well as the implementation and efficiency of proposed mitigation measures. Furthermore, the audit may involve an analysis of public participation during the EIA process or the implementation of EIA recommendations in the planning process.

### 2.3.2 The LC-EIA approach in SWEETFUEL

Within this project, a set of different technologies for sweet sorghum use is analysed. Each concept is defined by its inputs, the conversion, the downstream processes and the final products. This is also reflected in the objectives of the sustainability assessment in WP 7: the aim is to qualitatively assess the impacts associated with each of the (hypothetical) investigated concepts (in the sense of technological concepts) at a generic level. The assessment is not meant to be performed for a specific biorefinery plant at a certain geographic location.

Environmental impact assessment (EIA), however, is usually conducted at a site-specific / local level (see subchapter 2.3.1) for a planned (actual) project. For the purpose of this project, which encompasses neither the actual site-specific production of sweet sorghum nor the construction of a plant, it is therefore not appropriate to perform a full-scale EIA according to the regulatory frameworks. Monitoring and auditing measures, for example, become redundant if a project is not implemented, as they are post-project procedures. Consequently, monitoring and auditing measures will be omitted within SWEETFUEL. Nevertheless, elements of environmental impact assessment (EIA) are used to characterise the environmental impacts associated with the SWEETFUEL concepts at a generic level.

The elements of EIA used in this project are shown in Fig. 2-4.

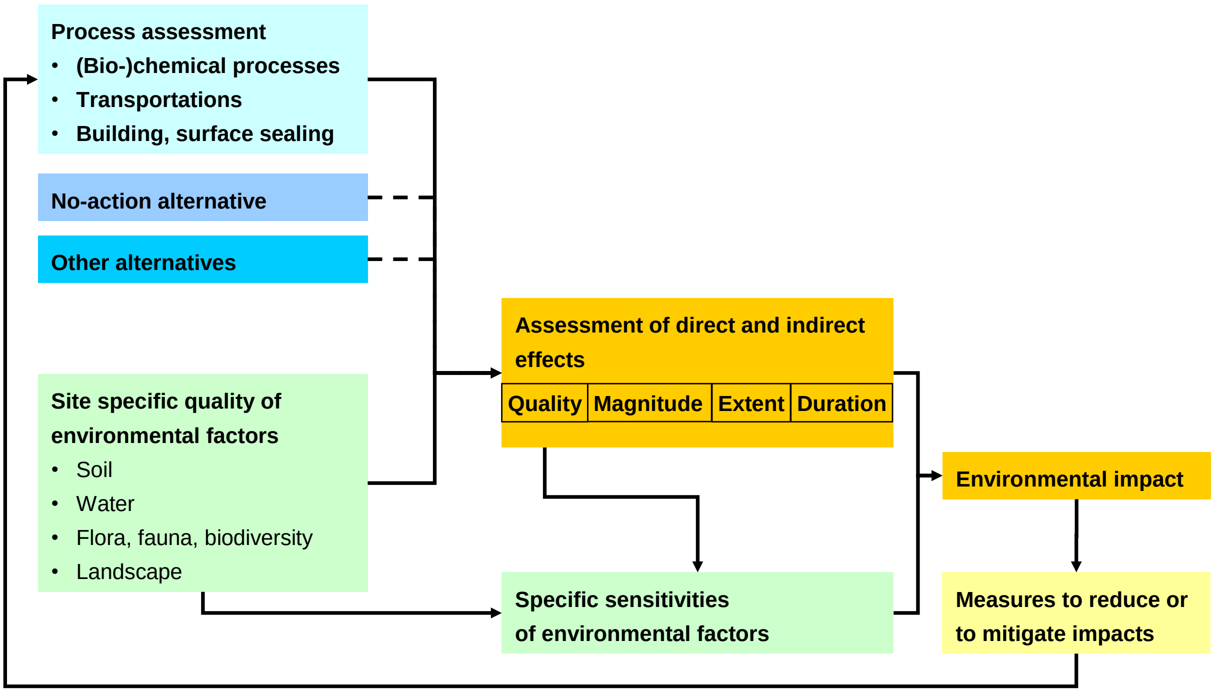


**Fig. 2-4** Structure of an LC-EIA in the SWEETFUEL project.

#### Reference systems

Generally, an EIA compares a planned project to a so-called no-action alternative (a situation without the project being implemented) in terms of environmental impacts. This assessment is restricted to one specific project or site such as a biorefinery. Biomass production sites and / or the impacts associated with the end use of the manufactured products are usually not considered.

For SWEETFUEL, the scope, and therefore also the reference system, of the EIA was chosen to encompass all life cycle stages from biomass production through biomass conversion up to the use of the manufactured products. This corresponds to a life cycle perspective and goes beyond the regulatory frameworks for EIA.

Covering the impacts of biomass production is crucial for the environmental assessment because the land-use impact (including indirect impacts on fauna and flora, biodiversity, soil and water) of biomass production exceeds the land-use impact of biomass conversion by far. Therefore, the reference systems are divided into 1) reference systems for biomass production and 2) reference systems for biomass conversion and use. For further details regarding the descriptions of the reference systems we refer to the report on technological assessment /Braconnier et al. 2013/ and to subchapter 2.1 'alternative land use options' as well as chapter 3.

**Impact assessment**

The assessment of environmental impacts of biomass production, conversion and use is carried out as a benefit and risk assessment. This is useful if no certainty exists regarding the possible future location of biomass cultivation sites and conversion facilities.

**Impact assessment for biomass production**

In the case of biomass production the following factors have been identified to assess the possible benefits and risks of biomass production (see also Fig. 2-5).

- Soil
    - Soil erosion
    - Soil compaction
    - Soil chemistry
    - Soil organic matter
- Water
    - Nutrient leaching / eutrophication (water quality)
    - Use of water resources
- Flora, fauna & landscape:
    - Weed control / pesticides
    - Species diversity / habitat quality

Based on these factors, a biomass-specific assessment of the environmental impact is done in this study. After that, an evaluation of different biomass feedstock relative to the respective reference systems is done by qualitative-descriptive classification in different classes. Moreover, geographic differences are evaluated.

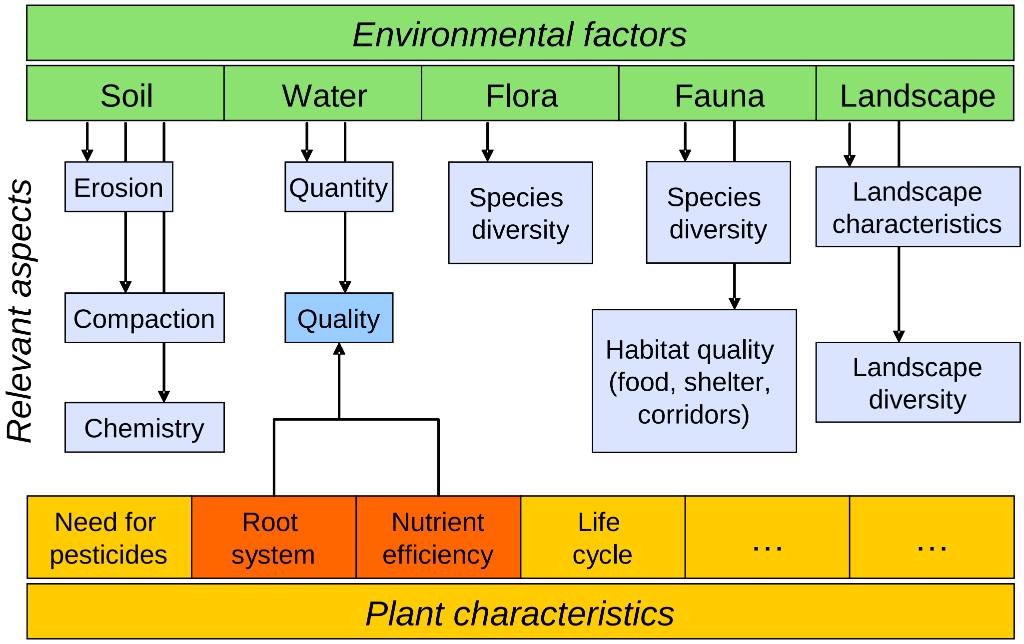


**Fig. 2-5** Identification of factors for the LC-EIA of biomass production.

### Impact assessment for biomass conversion and use

A separate benefit and risk assessment is performed for biomass conversion and use. This assessment covers the impacts caused by a conversion plant, by the use of bio-based energy carriers and products as well as by transportation of biomass feedstock and intermediates. The benefits and risks assessment for conversion, use and transportation investigates potential effects of conversion and use units on the local environment. The aspects human health, soil, flora, fauna and landscape are studied. Effects beyond the local environment (e.g. greenhouse effect) are derived from results of LCA.

The potential environmental benefits and risks of the different conversion technologies are derived from the following factors:

1. Emissions of noise and odour
2. Waste water and waste water treatment
3. Amount of traffic caused by potentially different logistics
4. Size and height of conversion plants related to the different technologies

The environmental issues potentially affected by these factors are shown in Table 2-1.

### Development of conflict matrices

Aggregated conflict matrices will be created based on the biomass-specific benefits and risks, which summarize the impacts of biomass production, conversion and use on the selected environmental factors.

The following qualitative indicators are used in the conflict matrices to compare the environmental impacts of biomass production, conversion and use to the respective reference systems (relative evaluation):

- “Positive”: compared to the reference systems, biomass production, conversion and use is more favourable.
- “Neutral”: biomass production, conversion and use show approximately the same impacts as the reference system.
- “Negative”: compared to the reference systems, biomass production, conversion and use is less favourable.

**Table 2-1** Technology-related factors, environmental issues and potential environmental impacts of biomass conversion and use.

| Technology-related factor | Environmental issue | Potential environmental impact |
|---|---|---|
| Emission of noise and odours | Human health | Annoyance by an increase of environ. noise or gaseous emissions |
| Waste water and waste water treatment | Water | Depletion of water resources<br>Nutrient input into water bodies causing eutrophication |
| Amount of traffic (noise and gaseous emissions) | Human health | Annoyance by an increase of environ. noise or gaseous emissions |
| Size and height of conversion plants | Soil<br>Flora<br>Fauna<br>Landscape | Soil compaction or soil sealing<br>Loss of vegetation<br>Loss of habitat<br>Landscape disturbance |

# 3 Description of scenarios and sensitivity analyses

This project investigates several sweet and biomass sorghum cultivations and use pathways to determine optimised and sustainable sweet and biomass sorghum production and use systems. The systems under investigation are described in subchapters 3.1 and 3.2. Further details can be found in the report on technological assessment /Braconnier et al. 2013/.

## 3.1 Sweet sorghum scenarios

Generally, sweet sorghum cultivation and use is described in three different scenarios: cane fallow, grain to food and syrup production. In all scenarios the main product is ethanol. However, the scenarios differ with respect to the processing of the sugar juice and the use of the by-products. In the cane fallow and syrup scenarios (see subchapters 3.1.1 and 3.1.3) grains are either used as fertiliser, for ethanol production or as feed. In the syrup production scenario the sugar juice is boiled down in a first processing step to syrup, which is used to produce ethanol in a further conversion process. The focus of the grain to food scenario (see subchapter 3.1.2) lies on the use of sweet sorghum as a multi-purpose crop to limit food / fuel trade-offs. This means that the grains are used as food whereas juice is used for energy production. In the following subchapters all scenarios are described in detail.

### 3.1.1 Cane fallow scenarios

In this project prospective conditions imaginable for the year 2020 are considered as main cane fallow scenario. Additionally, the situation in 2015 is described since this reflects the state of the art at the end of the project. Both scenarios are almost identical except the use of grains. In 2020, it is expected that the grains of sweet sorghum are used for ethanol production; however, in 2015 grains of sweet sorghum remain on the field, thus reducing the demand of mineral fertiliser.

**Cane fallow**

An overview of the cane fallow scenario is given in Fig. 3-1. After harvest, the sweet sorghum stalks and grains are transported from the villages to centralised ethanol facilities. The leaves either remain on the field (1 a) replacing mineral fertiliser or are used for energy production (1 b).

In the central ethanol production units, the sweet sorghum stalks are crushed and the juice is pressed out, leaving bagasse. The juice is fermented into ethanol which is used as transport fuel, replacing conventional gasoline.

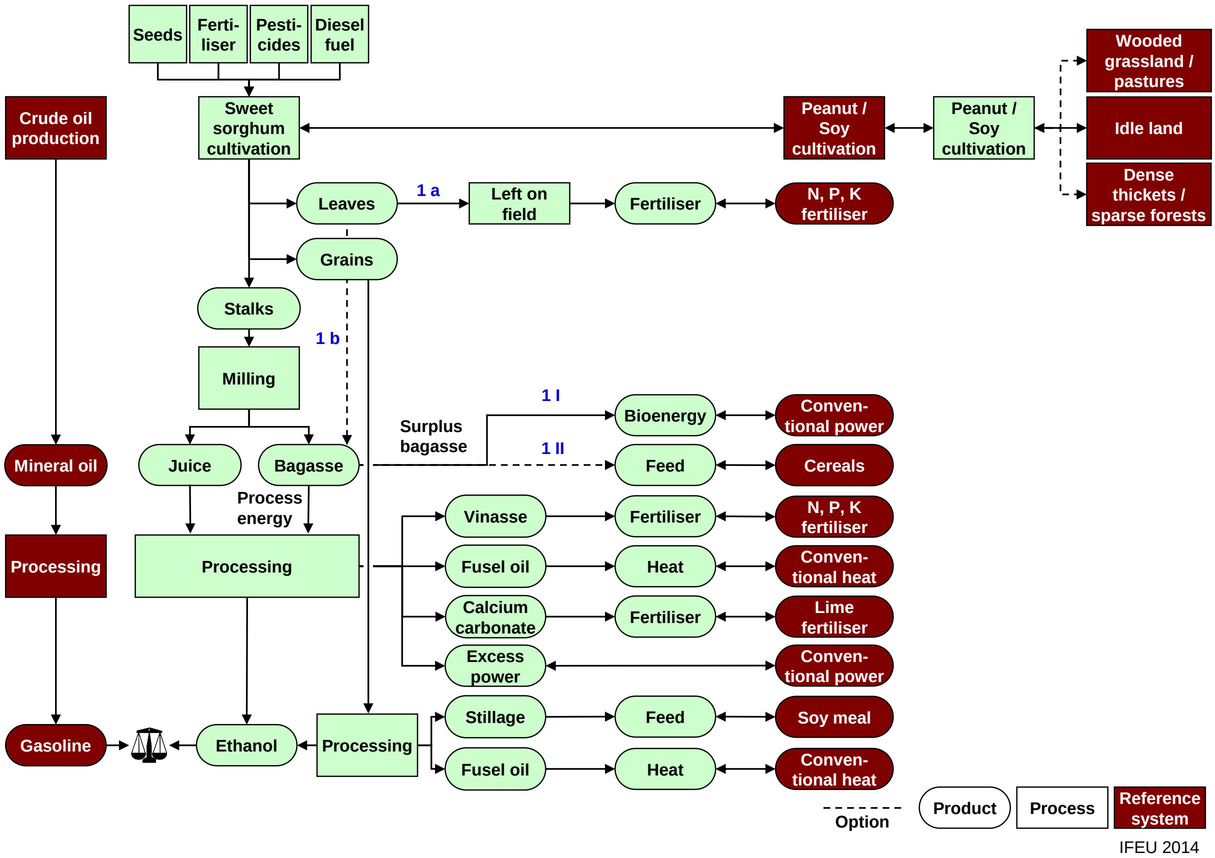


**Fig. 3-1** Schematic overview of the cane fallow scenario; numbers indicate scenario numbers (for a summary, see Table 3-1).

From the bagasse process energy is generated which is used internally in the ethanol production process. Surplus bagasse is either used for generating green power that is fed into the power grid, replacing conventionally produced electricity (1 I) or as animal feed, replacing cereals (1 II). In certain regions, bagasse is a very popular animal feed.

Other by-products derived during ethanol production are vinasse, stillage, excess power, fusel oils and carbonation lime. Vinasse is obtained as a by-product if sugar juice is processed and can be used as fertiliser, replacing mineral fertiliser. Stillage is a by-product, which occurs if grains are processed to ethanol and can be used as feed, replacing soy meal. Excess power can occur while process energy is generated from the bagasse, replacing conventional power. For energy generation, bagasse is combusted in a combined heat and power unit. If the heat demand is covered but less power is needed for the conversion process, excess power occurs which can be sold. Fusel oils are converted into heat, replacing conventional heat. In case of ethanol production from juice, carbonation lime is also derived as a by-product. Carbonation lime is used as fertiliser, replacing lime fertiliser.

### Cane fallow 2015

An overview of the cane fallow scenario 2015 is given in Fig. 3-2. Cane fallow 2015 is almost identical to the cane fallow scenario (see subchapter "cane fallow"), except that nowadays sugarcane or forage harvesters are used for harvesting sweet sorghum. This technology works fine for stalks but grains and leaves are cut and left on field, thus a usage of both is

not pursued. Consequently, by-products derived from ethanol production out of grains were not considered in the cane fallow 2015 scenario. By-products derived from ethanol production out of juice are identical to those of the cane fallow scenario. Surplus bagasse can either be used for generating green power, replacing conventional power (2 I) or as animal feed, replacing cereals (2 II).

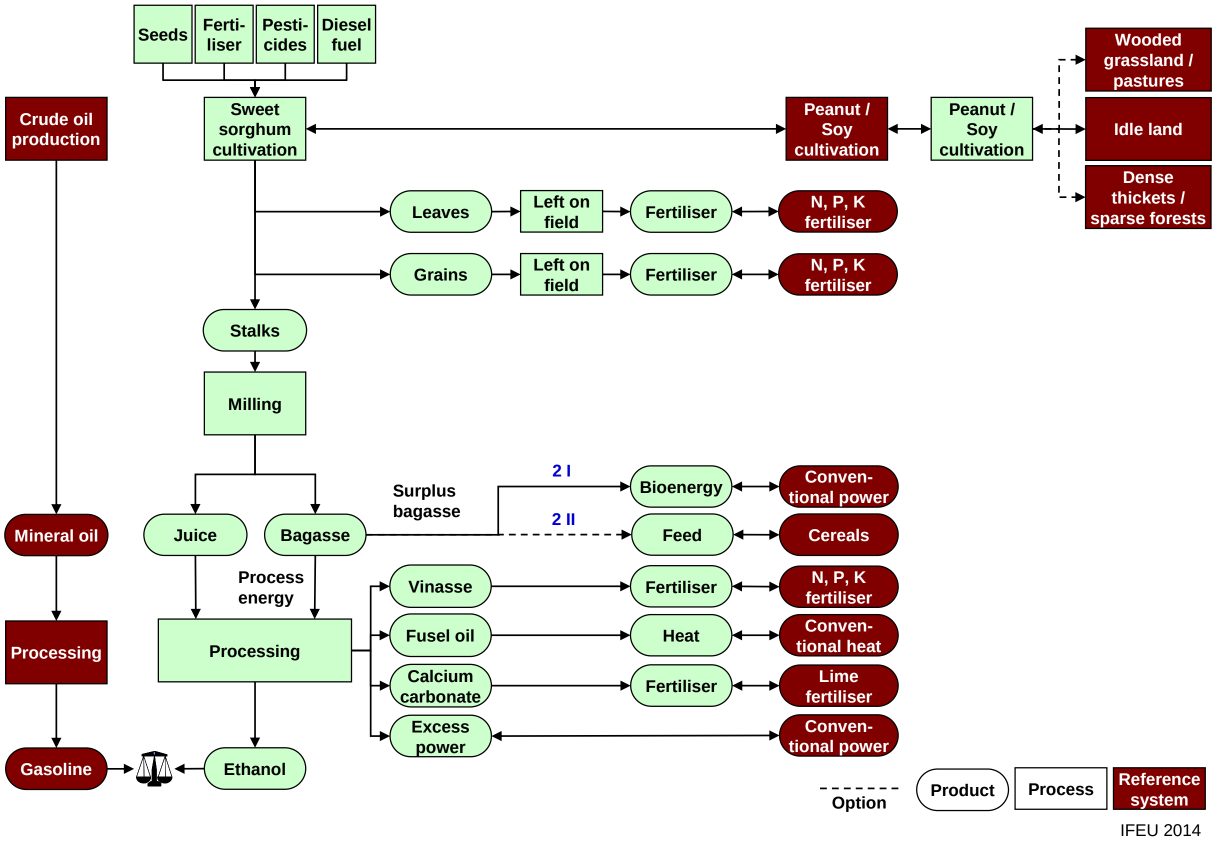


**Fig. 3-2** Schematic overview of the cane fallow scenario 2015; numbers indicate scenario numbers (for a summary, see Table 3-1).

### 3.1.2 Grain to food scenarios

In some regions sweet sorghum might not be grown as intermediate crop but replace grain sorghum cultivation. This has not been current practice so far but is conceivable in the future e.g. in semi-arid regions such as Southern Africa or North-eastern Mexico. We assume that sweet sorghum cultivars grown in those areas produce less grain than grain sorghum. Since the grains of grain sorghum are used in some countries for food and in others for feed, replacing grain sorghum with sweet sorghum might jeopardise food / feed security in those areas (Fig. 3-3, “Initial situation”). To further guarantee food / feed security, differences in grain yield need to be balanced by cultivating additional grain sorghum. This requires an additional area which is e.g. in Southern Africa, transformed out of idle land that becomes free due to the intensification of existing land use or that is not used at present (see Fig. 3-3, “Grain to food”). For example: if the grain yield of sweet sorghum is 2.5 t / ha / year and of grain sorghum 3 t / ha / year, an additional area of 0.17 ha is needed to balance the difference of 0.5 t of grain yield (see Fig. 3-3). Some people argue that there are sweet sorghum

hybrids which produce more grains than grain sorghum if cultivated on the same ground and under similar cultivation and climate conditions. However, this is far of today's reality and there is still a lot of research and breeding necessary to be able to use such hybrids commercially. Thus, as it cannot be foreseen whether those breeding efforts can be successful, especially since grain sorghum can also be further developed, this scenario is not considered in this report.

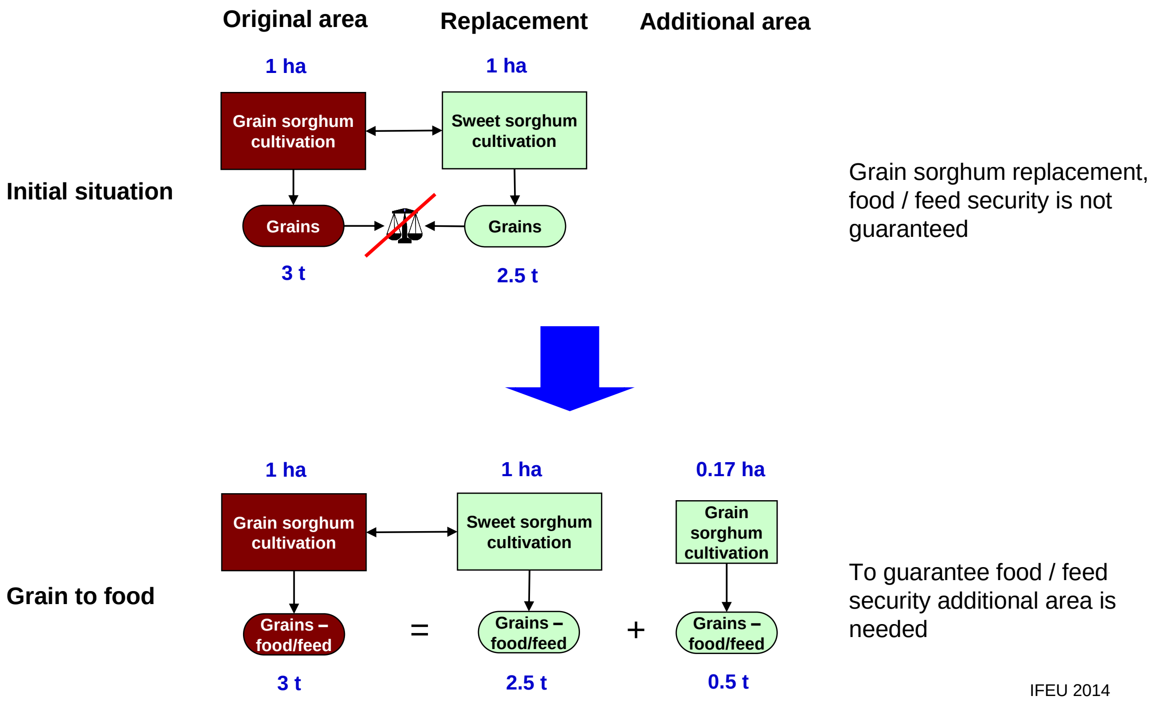


**Fig. 3-3** Schematic overview of the grain to food scenario. Numbers are examples for illustration, see text.

An overview of the grain to food scenario is given in Fig. 3-4. As described above, in this scenario grains of sweet sorghum are used as food / feed to guarantee food / feed security. Leaves are separated during harvest and remain on the field, replacing mineral fertiliser (3 a). Since also the use of leaves as animal feed is promoted and might be an option in some regions, also this use was assessed. In this case, cereals are replaced as feed (3 b). Stalks are processed in a central ethanol production unit which correspond to the processing (including all by-products) described in the cane fallow scenario (see Fig. 3-1 and corresponding descriptions).

### Extra high yield scenarios

Besides semi-arid regions grain sorghum is also cultivated in regions such as Central-western Mexico with conditions preferable for an extra high yield. Three land use options are conceivable in those regions as described in the following paragraphs (Fig. 3-5).

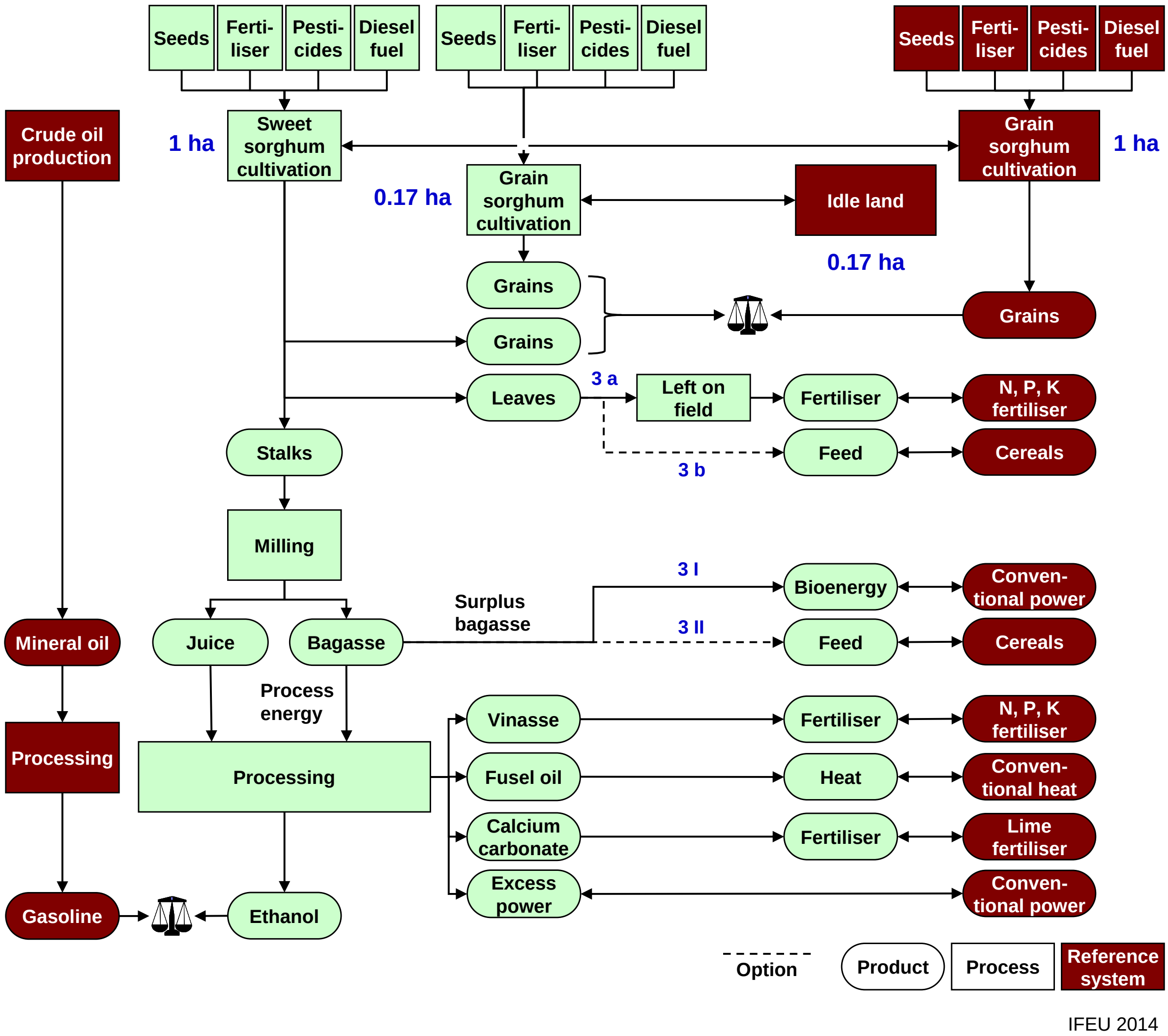


**Fig. 3-4** Schematic overview of the grain to food scenario; numbers indicate scenario numbers (for a summary, see Table 3-1). Large numbers are examples for illustration, see text.

## Option I

This option is identical to the grain to food scenario described before (see Fig. 3-3 and Fig. 3-4 and corresponding explanations); however regions such as Central-western Mexico are characterised by preferable environmental conditions (e.g. high annual precipitation) which allow high grain yields of about 10 t per hectare per year. Since in those regions sweet sorghum yield might also be higher than in semi-arid regions grain sorghum is here replaced by high-yield sweet sorghum.

However, since there is no idle land in Central-western Mexico anymore, the additional area needs to be recruited in other regions where yields are expected to be lower. For example: if the grain yield of sweet sorghum is 7 t / ha / year and of grain sorghum 5 t / ha / year an additional area of 0.6 ha is needed to balance the difference of 3 t of grain yield if grain sorghum is cultivated (Fig. 3-5).

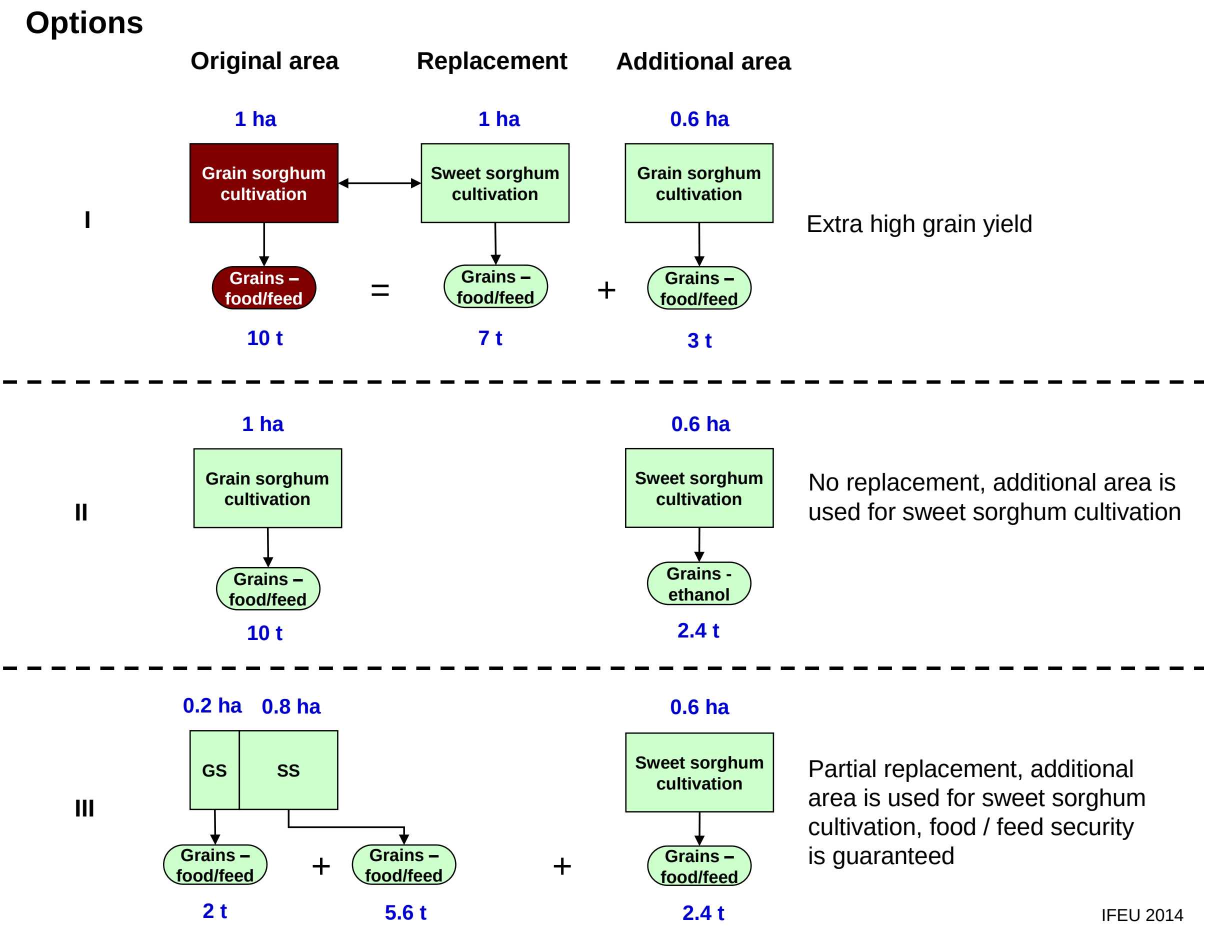


**Fig. 3-5** Schematic overview of the two land use options of the extra high scenario. Blue numbers are examples for illustration, see text.

### Option II

The same production area as in option I is assumed (Fig. 3-5, option II). Grain sorghum is not replaced and sweet sorghum is only grown on the additional area. Grains of grain sorghum are used as food / feed to guarantee food / feed security, whereas grains and juice of sweet sorghum are processed to ethanol in a central ethanol production unit, which corresponds to the processing described in the cane fallow scenario (see Fig. 3-1 and corresponding descriptions). For example: high grain yield of grain sorghum cultivation is about 10 t and grain yield of sweet sorghum cultivation on the additional area is about 2.4 t, if high case sweet sorghum cultivation as described in the grain to food scenario (grain yield: 4 t / ha / year) is taken as a basis.

### Option III

Another option, assuming again the same production area as in option I, contains a partial replacement of grain sorghum (Fig. 3-5, option III). Thus, sweet sorghum is cultivated on parts of the original grain sorghum cultivation area and on the additional area. The proportion was chosen in the way that grains out of sweet and grain sorghum cultivation still guarantee food / feed security. Thus, grains from grain and sweet sorghum are used as food or feed and the juice of sweet sorghum is processed in a central ethanol production unit which corre-

sponds to the processing described in the cane fallow scenario 2015 (see Fig. 3-2 and corresponding descriptions). For example: if grain yield of sweet sorghum that is cultivated on the additional area is about 2.4 t, sweet sorghum can be grown on 0.8 ha (if high yield sweet sorghum as described in option I is taken as a basis) and grain sorghum on 0.2 ha (if extra high yield grain sorghum as described in option I is taken as a basis) of the original area to gain still a grain yield of 10 t in total.

### 3.1.3 Syrup production scenario

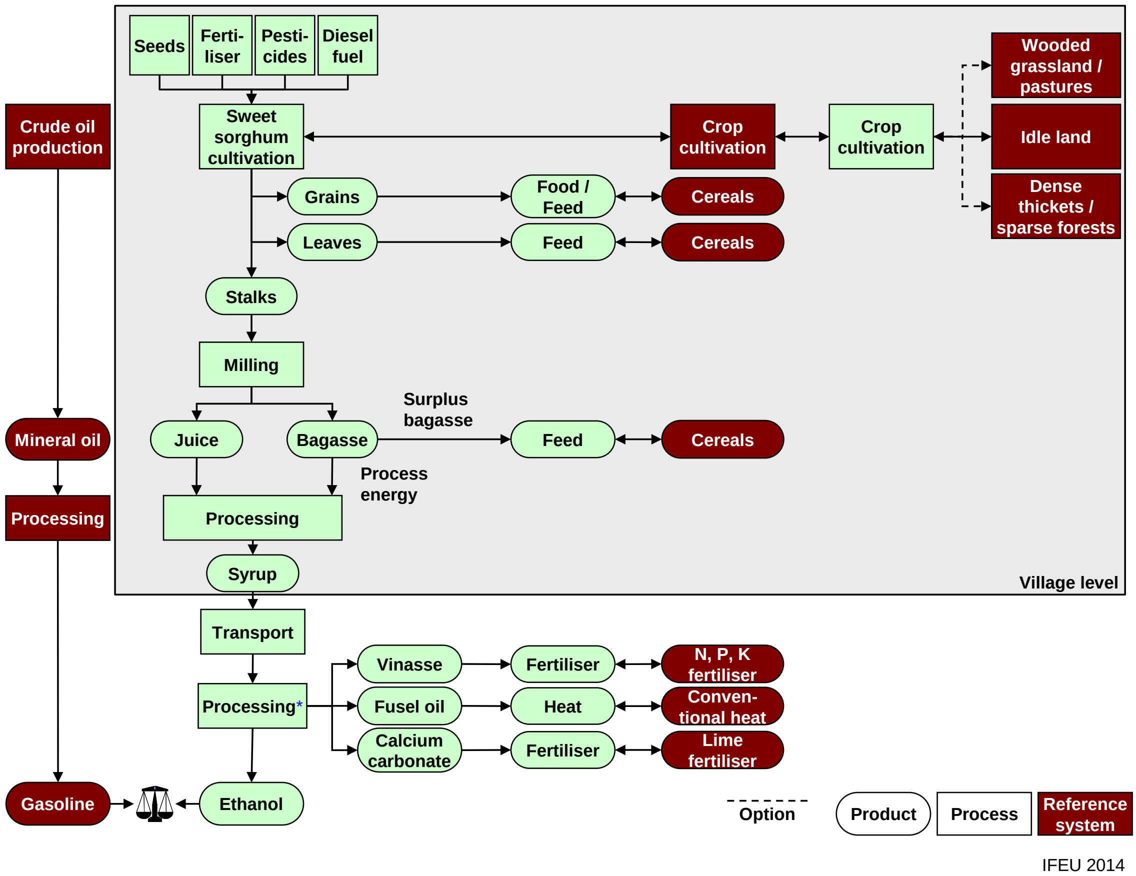


**Fig. 3-6** Schematic overview of the syrup production scenario for a decentralised production; numbers indicate scenario numbers (for a summary, see Table 3-1). *For the ethanol production unit in the syrup scenario external energy carriers are needed which can either be fossil energy carriers (4 I) or rice straw (4 II).

In some cases, infrastructure for biomass transportation to large centralised production units may be insufficient or not existent. Therefore, partially decentralised processing might be another option to grow and use sweet sorghum. Additionally, central ethanol producers often face the difficulty of a rather narrow production window where large amounts of sweet sorghum need to be processed. In such cases the syrup production from sweet sorghum juice might be an advantage. Since the syrup can be stored slightly longer than the sweet sorghum juice, the ethanol production facility can ease production and expand the production window. In this scenario (Fig. 3-6) the sweet sorghum stalks are milled at village level and the juice is further processed into syrup, which is transported to central ethanol units. The

grains are separated before harvest and used as feed or food, replacing cereals. The leaves are used as feed, replacing also cereals. The bagasse which is obtained during stalk milling is used at village level for heat production that is needed to concentrate the juice into syrup. If there is surplus bagasse, it is used as animal feed, replacing cereals. The syrup is transported to a centralised ethanol production unit and it is treated just as the juice in the cane fallow scenario. For the central ethanol unit, external energy carriers need to be used since the bagasse from syrup production is left in the villages. External energy carriers can either be fossil energy carriers such as coal and oil or rice straw. An overview of the syrup scenario is given in Table 3-1.

### 3.1.4 Sensitivity analyses

As already specified in the general settings and in the proceeding scenario chapters, sweet sorghum is cultivated in various regions covering multiple climatic conditions and cultivation practices (e.g. the amount of fertiliser as well as harvesting expenditures) which can result in strong variations in yield. The influence of those yield differences are assessed via sensitivity analyses. Thus, low, typical and high case values are defined to cover the bandwidths of such parameters.

Since there are also variations in the juice content of stalks and the sugar content of juice, also, low, typical and high datasets are determined to cover a certain bandwidth.

Furthermore, due to various process technologies used in multiple regions different conversion efficiencies may occur. Thus, also for this parameter, low, typical and high datasets are defined to cover a bandwidth of the parameter.

Besides yield differences also alternative land use options are analysed via sensitivity analyses (for detailed descriptions see subchapter 2.1, “alternative land use options”).

**Cane fallow and grain to food scenarios**

The typical dataset can be described as follows:

- Average biomass yield
- Average juice content in stalks and sugar content in juice
- Medium conversion efficiency

For the low dataset of the cane fallow and grain to food scenarios, yield variable parameters were set assuming low biomass yields as well as a low juice and sugar content. The conversion efficiency parameter is set in the way that low expenditure savings are achieved:

- Low biomass yield and sugar content
- Low juice content in stalks and sugar content in juice
- Low conversion efficiency

For the high dataset of the cane fallow and grain to food scenarios, yield variable parameters were set assuming high biomass yields as well as a high juice and sugar content. The conversion efficiency parameter is set in the way that high expenditure savings are achieved:

- High biomass yield and sugar content
- High juice content in stalks and sugar content in juice
- High conversion efficiency

**Syrup scenario**

For the syrup scenario the same sensitivity analysis were conducted as for the cane fallow and grain to food scenarios. However, in the syrup scenario the extraction efficiency differs, since it is not expected that in a decentralised production system the extraction efficiency is 95 % as it is assumed for the processing in a centralised production unit. Thus, low, typical and high datasets were defined to assess the influence of extraction efficiency differences in the syrup scenario. Furthermore, in the syrup scenarios, external energy carriers are needed for the ethanol processing in the central ethanol unit since the bagasse from syrup production is left in the villages. Thus, a sensitivity analysis is conducted for different external energy carriers such as coal, oil or rice straw.

**Grain sorghum as reference system**

Since the yield of grains produced by grain sorghum is also dependent on climate conditions low, typical and high datasets of grain yield were defined for grain sorghum as a reference system as well.

## 3.2 Biomass sorghum scenarios

Besides sweet sorghum, biomass sorghum is also considered in this project. Biomass sorghum is cultivated mainly to gain high biomass yields for biogas production.

The target systems are centralised, mechanised systems in industrialised settings. The focus lies on high biomass yields, whereas sugar content and grain yields are of less importance. Accordingly, the crop is used as a whole. Several options of energy production from biomass sorghum were assessed in order to give a bandwidth on different use options and to include both first and second generation technologies. The main focus was laid on biogas and biomethane production. Alternatively, the combustion of the biomass and the production of fuel is analysed with the focus on second generation technologies. Two options were assessed here: a) second generation ethanol produced from lignocellulose and b) biomass gasification with the synthesis of the gas into biofuel.

Biomass sorghum is mainly cultivated on land which becomes free due to the intensification of existing land use. Also idle land can be used to grow biomass sorghum. In the further course of the report all these land use options are referred to as “idle land”. Forest conversion is forbidden in all countries within Europe. Thus, no sensitivity analyses for alternative land use options were conducted.

The yield differences due to multiple climatic conditions in the temperate zone were assessed via sensitivity analyses.

### 3.2.1 Biogas and biomethane production

An overview of biogas and biomethane production is given in Fig. 3-7. For the biogas production, the biomass sorghum is chopped and ensilaged after harvest. Subsequently, the silage is fermented into biogas. Biomass sorghum can be fermented together with co-substrates such as manure or corn. However, the main objective is to assess the use of biomass sorghum from a certain area. Therefore, biomass sorghum digestion was assessed without any co-substrate. The biogas is either used for heat and power (5 I A) or only for power production (5 I B), replacing conventionally produced heat and power or power only, respectively.

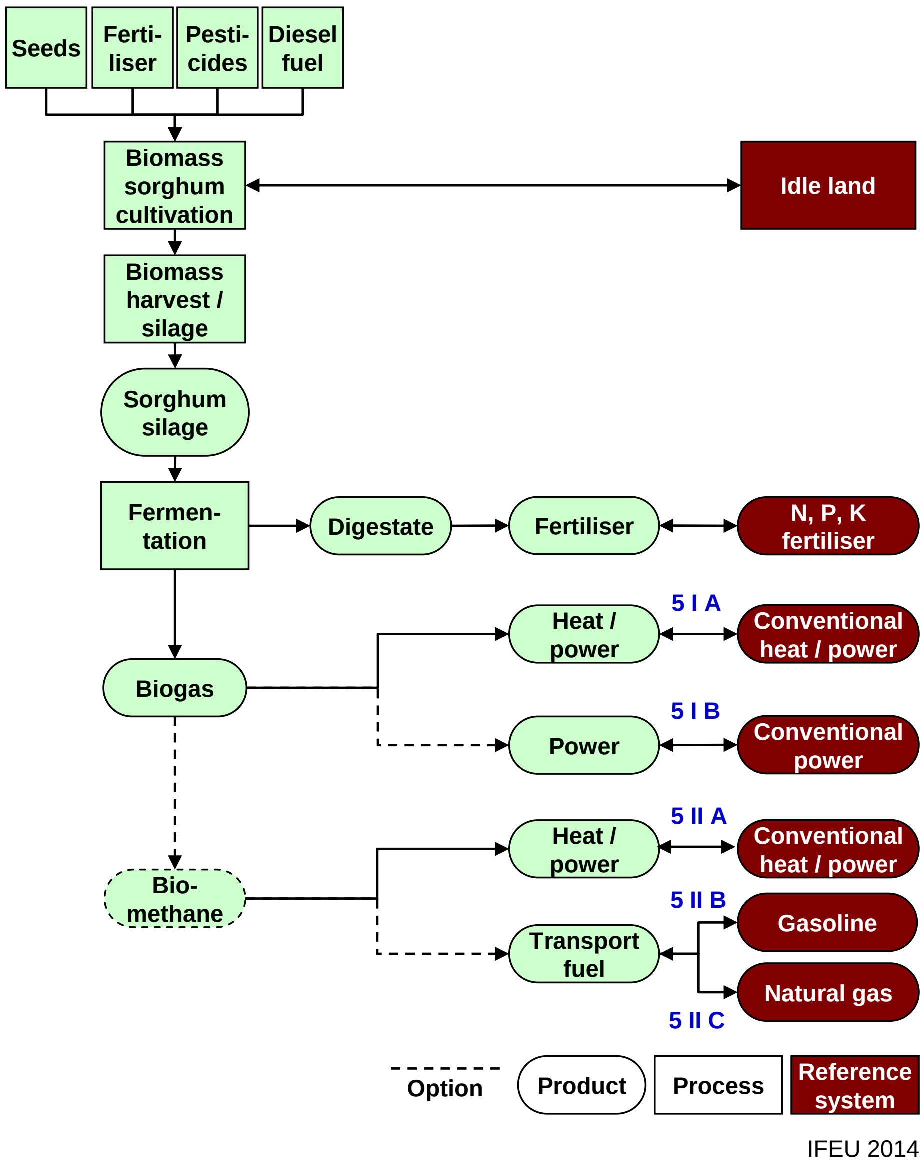


**Fig. 3-7** Schematic overview of biogas production from biomass sorghum for the temperate climate; numbers indicate scenario numbers (for a summary, see Table 3-2).

Alternatively, the biogas can be further processed into biomethane and used

1. for heat and power production, which replaces conventional heat and power (5 II A), or
2. as a transport fuel replacing conventional gasoline (5 II B) and natural gas (5 II C), respectively.

In all processes, digestate is produced as a by-product. It is used as fertiliser replacing mineral fertilisers.

### 3.2.2 Second generation ethanol

An alternative to the conversion of biomass sorghum into biogas or biomethane is the production of ethanol from the lignocellulosic fraction of biomass sorghum (5 a). An overview of this scenario is given in Fig. 3-8. The biomass is harvested and pre-treated in order to render the cellulose and hemicellulose accessible for a subsequent hydrolysis step. After the hydrolysis of the cellulose and hemicellulose for breaking down the long chains into C6 sugars (e.g. glucose) and C5 sugars (e.g. xylose), the substrate is fermented. The ethanol is used as transport fuel, replacing conventional gasoline.

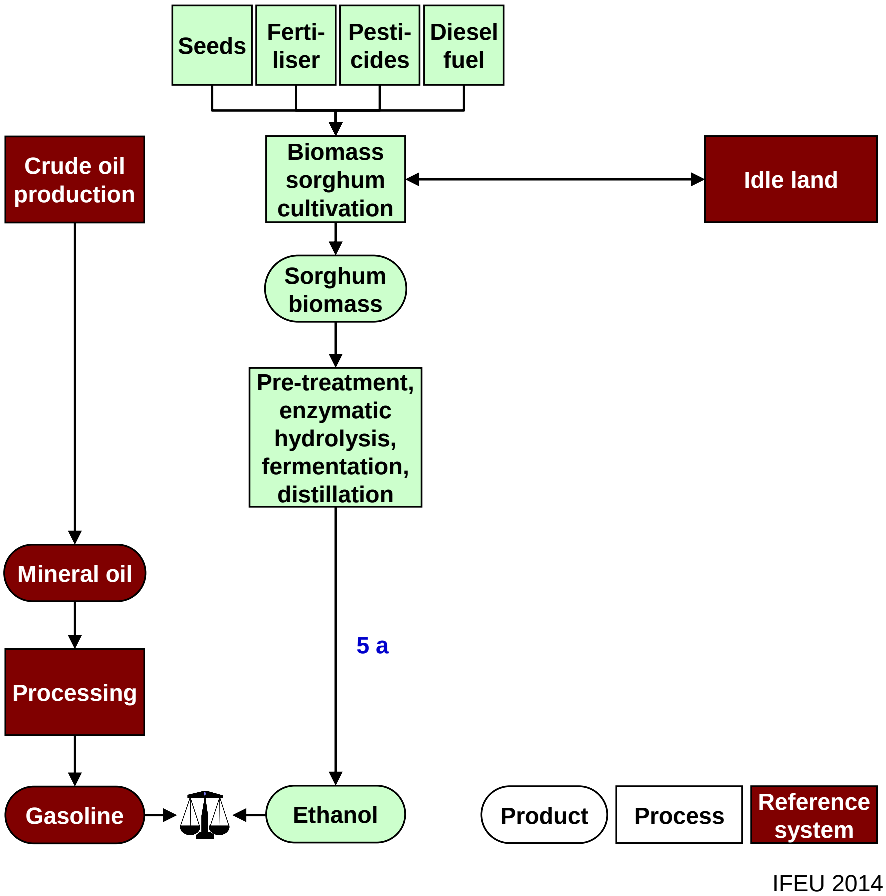


**Fig. 3-8** Schematic overview of second generation ethanol production from biomass sorghum lignocellulose for the temperate climate; numbers indicate scenario numbers (for a summary, see Table 3-2).

### 3.2.3 Direct combustion

Another option to convert biomass sorghum into energy is direct combustion (Fig. 3-9). Since this process requires comparatively dry biomass, direct combustion is especially feasible in the southern regions of Europe such as in the southern part of Spain, Italy or Greece. Here, the stalks remain on the field after harvest for drying. After collection, they can be directly used for combustion in the direct combustion process.

During the combustion process, heat and power are produced that replace conventionally produced heat and power (5 b I). Furthermore, either power or heat can be produced separately. Power production replaces conventional power (5 b II) while heat production either replaces natural gas (5 b III A) or fuel oil (5 b III B).

In all processes ash is produced as a by-product which has to be disposed in landfills.

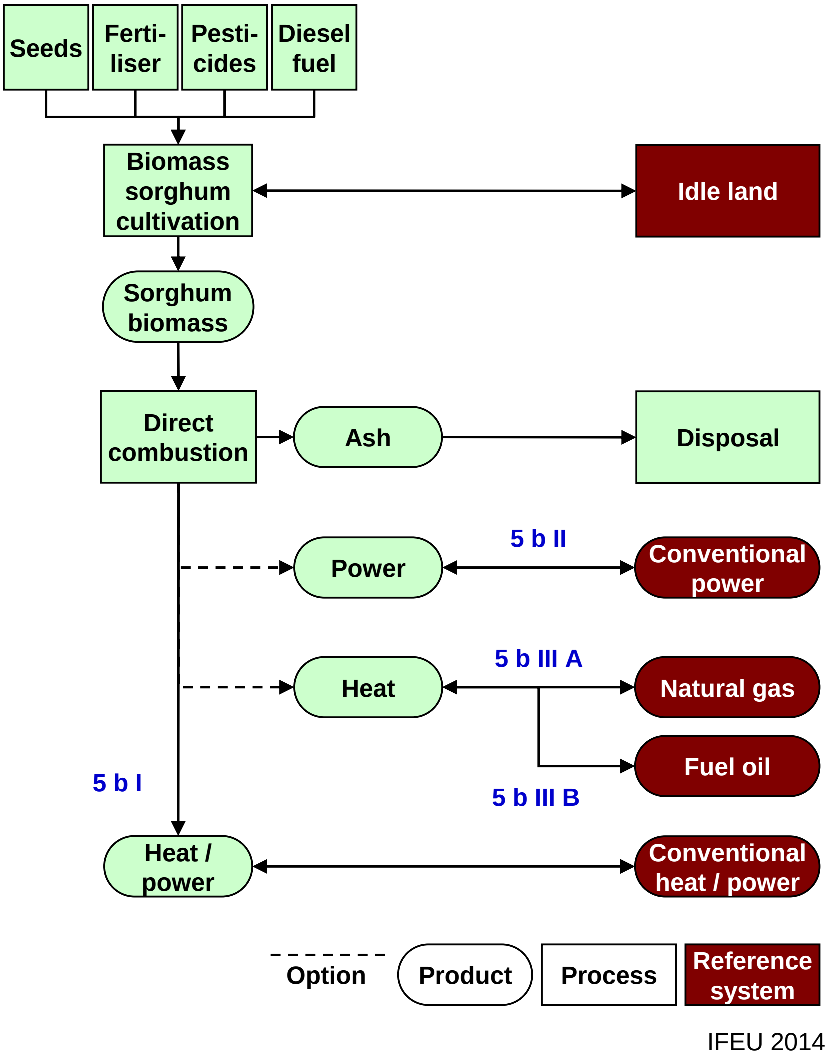


**Fig. 3-9** Schematic overview of direct combustion of biomass sorghum for the temperate climate; numbers indicate scenario numbers (for a summary, see Table 3-2).

### 3.2.4 Gasification

Besides direct combustion, dry biomass is also needed for biomass sorghum gasification (Fig. 3-10).

For biomass gasification, two options are analysed: first the direct gasification (5 c I), second the gasification with a prior pyrolysis of the biomass (5 c II).

For both options, the biomass needs to be comparatively dry as a precondition. For drying the biomass could either be longer left on the field or waste heat from the gasification process could be used as energy supply in the case of direct gasification. For the pyrolysis, however, external energy supply is needed. As a next step, the biomass or the pyrolysis oil is gasified into a synthesis gas. It is a mixture of hydrogen and carbon monoxide. After cleaning the gas, it is synthesised into the so-called BtL (Biomass-to-Liquid) fuels. The standard synthesis is the Fischer-Tropsch synthesis where FT fuels are produced. If there is surplus bioenergy from the process, it is fed into the grid and replaces conventional energy.

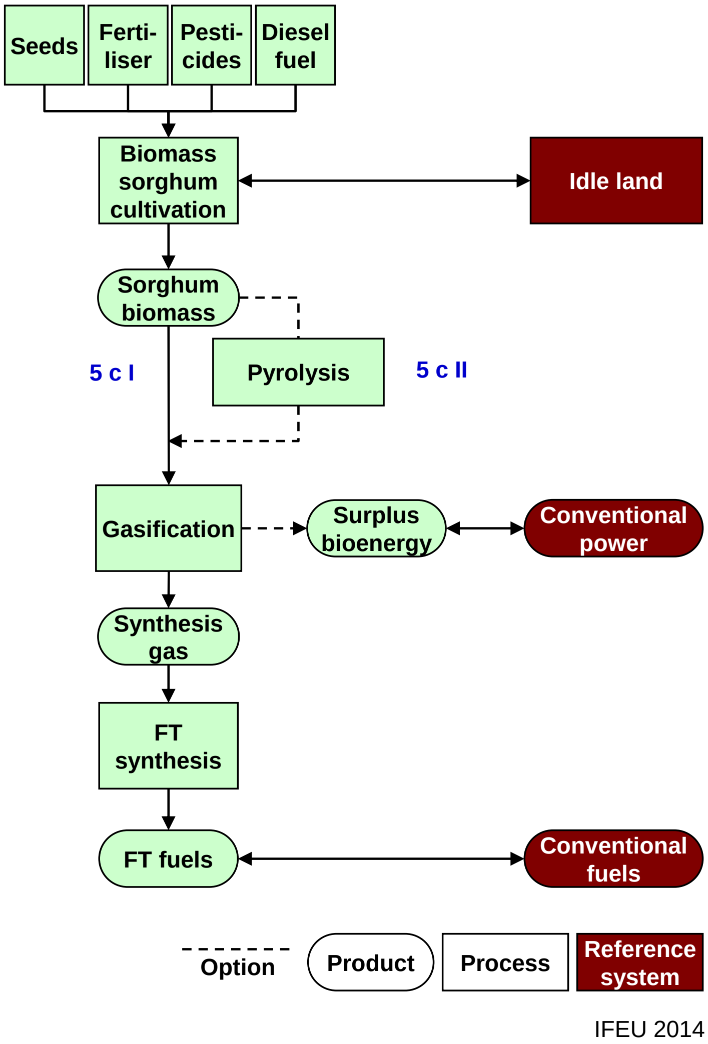


**Fig. 3-10** Schematic overview of FT fuel production from biomass sorghum gasification for the temperate climate; numbers indicate scenario numbers (for a summary, see Table 3-2).

### 3.2.5 Sensitivity analyses

Similar as for sweet sorghum, biomass sorghum is also cultivated in various regions covering different climate and soil conditions as well as cultivation practices. The influence of those yield differences is assessed via sensitivity analyses. Thus, low, typical and high cases are defined to cover the bandwidths of such parameters.

For the biogas scenarios also different conversion efficiencies and plant types (including differences in the storage of the digestate) are considered. Thus, also for this parameter, low, typical and high datasets are defined to cover a certain bandwidth.

Thus, the typical dataset for the biogas scenarios can be described as follows:

- Average biomass yield
- Medium conversion efficiency
- Typical conversion plant with open digestate storage tanks and a digestate incorporation after 24 hours

The low dataset of the biogas scenarios contains:

- Low biomass yield
- Low conversion efficiency
- Conversion plant with open digestate storage tanks, high $CH_4$ emissions and a digestate incorporation after 24 hours

The high dataset of the biogas scenarios can be described as follows:

- High biomass yield
- High conversion efficiency
- Conversion plant with covered, gas-tight digestate storage tanks and a digestate incorporation after 1 hour

## 3.3 Summary: scenario overview

Table 3-1, Table 3-2 and Table 3-3 summarise all scenarios under investigation and sensitivity analyses.

**Table 3-1** Overview of all sweet sorghum scenarios. Bold: Main scenarios.

| | Sweet sorghum | | | | |
|---|---|---|---|---|---|
| | Scenario | Option | Use of surplus bagasse | Option** | Use of leaves |
| 1 | **Cane fallow** | 1 I | **Bioenergy** | 1 I a | **Fertiliser (left on field)** |
| | | | | 1 I b | Together with bagasse |
| | | 1 II | Feed | 1 II a | Fertiliser (left on field) |
| | | | | 1 II b | Together with bagasse |
| 2 | Cane fallow 2015 | 2 I | Bioenergy | | Fertiliser (left on field) |
| | | 2 II | Feed | | |
| 3 | **Grain to food** | 3 I | **Bioenergy** | 3 I a | **Fertiliser (left on field)** |
| | | | | 3 I b | Feed |
| | | 3 II | Feed | 3 II a | Fertiliser (left on field) |
| | | | | 3 II b | Feed |
| 4 | **Syrup** | 4 I* | **Feed** | | **Feed** |
| | | 4 II* | Feed | | |

* For the ethanol production unit in the syrup scenario external energy carriers are needed which can either be fossil energy carriers (4 I) or rice straw (4 II).
** The option numbers listed here are combinations of the alternative use pathways of surplus bagasse and of leaves.

**Table 3-2** Overview of all biomass sorghum scenarios. Bold: Main scenario.

| | Biomass sorghum | | | | |
|---|---|---|---|---|---|
| | Conversion process | Option | Main product / method | Option* | Use of main product |
| 5 | **Biogas production** | 5 I | **Biogas** | 5 I A | **Heat and power** |
| | | | | 5 I B | Power |
| | | 5 II | Biomethane | 5 II A | Heat and power |
| | | | | 5 II B | Transport fuel replacing gasoline |
| | | | | 5 II C | Transport fuel replacing natural gas |
| Alternatives | | | | | |
| 5 a | 2G ethanol production | 5 a | Ethanol | | Transport fuel |
| 5 b | Direct combustion | 5 b I | Heat & power | | Heat and power |
| | | 5 b II | Power | | Power |
| | | 5 b III | Heat | 5 b III A | Natural gas |
| | | | | 5 b III B | Fuel oil |
| 5 c | Gasification | 5 c I | Direct gasification | | Transport fuel |
| | | 5 c II | Gasification with prior pyrolysis | | Transport fuel |

* The option numbers listed here are combinations of the alternative methods of biomass conversion and of the use pathways of the main product.

**Table 3-3** Overview of all sensitivity analyses for sweet and biomass sorghum scenarios.

| Sensitivity analyses | | |
|---|---|---|
| | Varied parameters | Scenarios |
| Biomass production* | Yield, fertilisers, tractor diesel consumption | Sweet sorghum scenarios, biomass sorghum scenarios, grain sorghum reference scenario |
| | Juice content, sugar content | Sweet sorghum scenarios |
| | Juice extraction efficiency | Syrup scenario |
| Conversion | Conversion efficiency* | Sweet sorghum scenarios, biogas scenarios |
| | External energy carriers | Syrup scenario |
| Digestate storage* | Cover | Biogas scenarios |
| Land use | Alternative land use | Cane fallow and syrup scenario |

* Bandwidth of these parameters is covered by low, typical and high datasets.

# 4 Results: Life cycle assessment

In the following subchapters, the results of the life cycle assessment of the sweet and biomass sorghum scenarios are presented. Subchapter 4.1 focusses on sweet sorghum and subchapter 4.2 on biomass sorghum scenarios.

In all scenarios, the substituted power production corresponds to a marginal electricity mix within the UCTE (Union for the Co-ordination of Transmission of Electricity) network. Power is generated from 50 % coal and 50 % natural gas. The substituted heat production corresponds to a marginal mix from 50 % natural gas and 50 % fuel oil. In case of the direct combustion of biomass sorghum, heat is generated either out of 100 % natural gas or 100 % fuel oil.

## 4.1 Sweet sorghum scenarios

In this subchapter the results of the life cycle assessment of all sweet sorghum scenarios, namely cane fallow, grain to food and syrup production are presented (subchapters 4.1.1 to 4.1.3). The results are summarized and concluded in subchapter 4.1.4.

### 4.1.1 Cane fallow scenarios

First, the influence of different life cycle stages on the overall result is described exemplarily for the cane fallow scenario and one impact category. The results for all environmental impact categories are presented in subchapter 4.1.1.1. The influence of single life cycle stages on the overall results is described in subchapter 4.1.1.2. In subchapter 4.1.1.3 the results of the sensitivity analyses are presented.

Fig. 4-1 depicts the entire life cycle of the cane fallow scenario. All light green processes arise if bioethanol is produced out of sweet sorghum. All brown production steps are conventional processes that are replaced by bioethanol production from sweet sorghum in the cane fallow scenario. For a detailed scenario description see subchapter 3.1.1.

The environmental impacts of this scenario are exemplarily shown for the impact category greenhouse effect in Fig. 4-2. Illustrated are the impacts of individual life cycle stages (coloured sections of upper bar) and how they contribute to the overall result (light brown bar). There are expenditures associated with each life cycle, which are depicted as positive (additional) emissions in Fig. 4-2. They arise from the light green processes in Fig. 4-1 for the production and use of bioethanol from sweet sorghum. The avoided emissions from the replaced processes (brown production steps in Fig. 4-1) are credited to the bioethanol production and are thus depicted as negative emissions in Fig. 4-2. The net result is calculated in the way that the credits for the bioethanol production are subtracted from the expenditures. Thus, the net result shows the amount in the respective impact category which can be saved or is caused by the use of bioethanol from sweet sorghum in the cane fallow scenario instead of a conventional product. For the impact category greenhouse effect, for example, the net

result is negative (-4.5 t $CO_2$ equiv. / ha / yr), which means that about 4.5 tons of greenhouse gases can be saved per hectare per year if bioethanol is produced instead of gasoline.

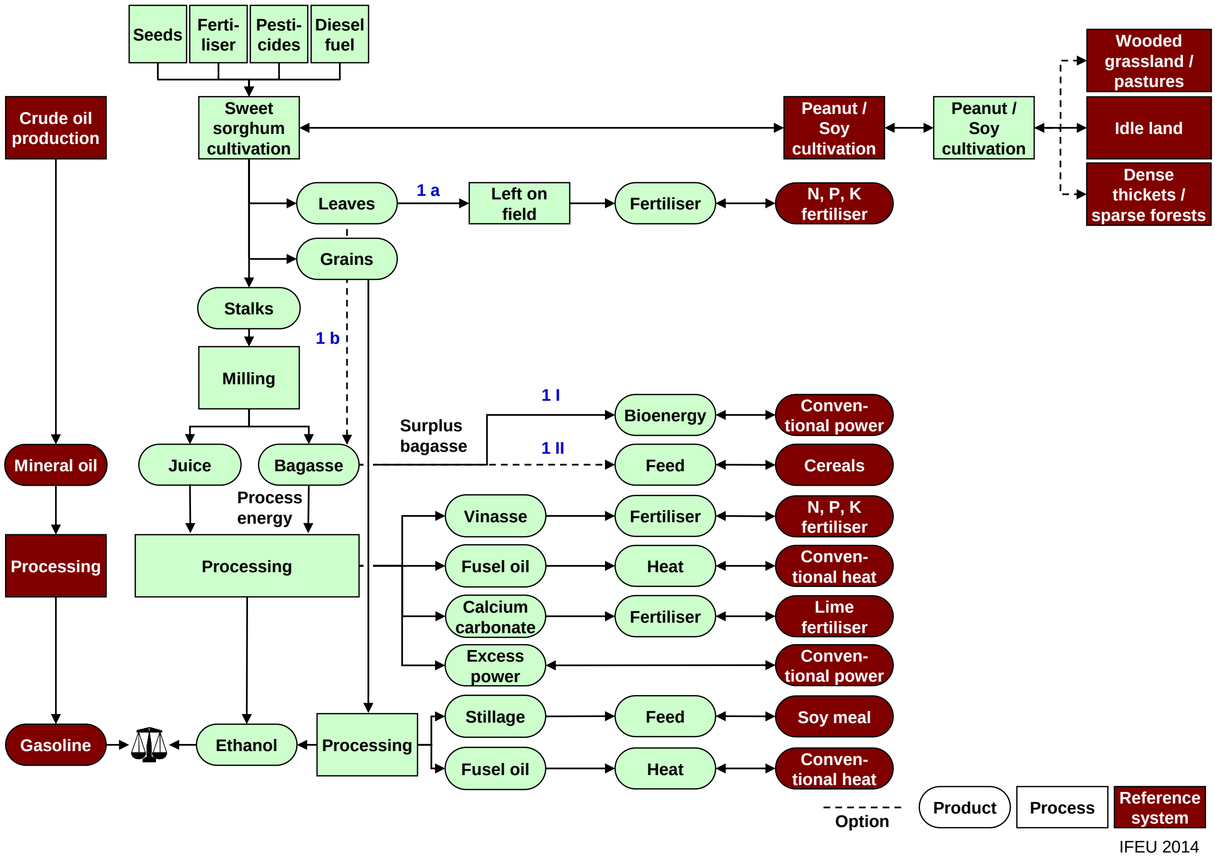


**Fig. 4-1** Schematic overview of ethanol production from sweet sorghum in the cane fallow scenario; numbers indicate scenario numbers (for a summary, see Table 3-1).

#### 4.1.1.1 Results of all environmental impact categories

Even though the greenhouse gas balance of the cane fallow scenario shows advantageous results, bioethanol from sweet sorghum in the cane fallow scenario is not per se environmentally friendly, but causes also disadvantages for the environment. Thus, under most conditions, additional environmental burdens are caused in the environmental impact categories acidification, terrestrial and aquatic eutrophication, ozone depletion and human toxicity. Besides greenhouse effect, mitigation of environmental burdens is also achieved regarding the categories depletion of non-renewable energy resources and photochemical ozone formation (photosmog) (Fig. 4-3). For photosmog, however, the suggested models aggregating the potential ozone creating substances are still debated on among experts. Due to the complex chemical reactions involved in the troposphere ozone formation, base data in the category photosmog has a high uncertainty – different hydrocarbons have diverse characterisation factors and are very variable between different engines or processes that provide the same products or services. Furthermore, the amounts of given credits and expenditures in this category are very similar, therefore only slight modifications in the base data for either the sweet sorghum ethanol or the fossil fuel life cycle may change the sign of the net result (versus advantage or disadvantage).

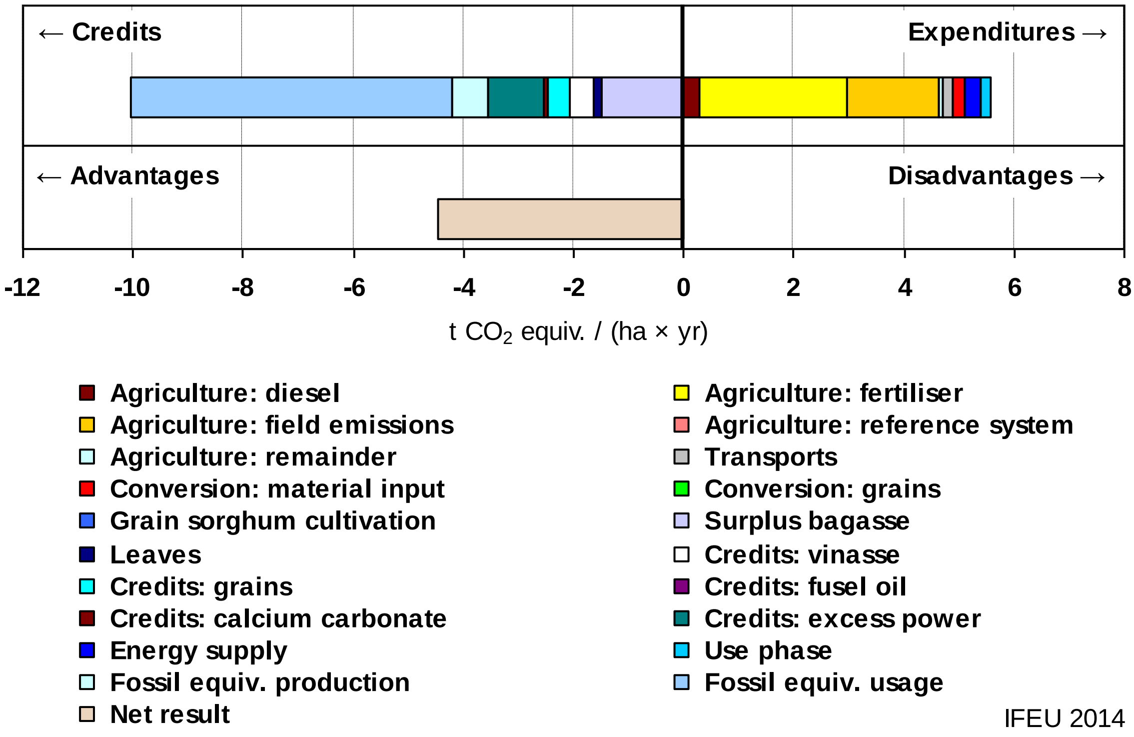


**Fig. 4-2** Contributions of individual life cycle steps (coloured bar) to the overall net result (light brown bar) of sweet sorghum ethanol production and use compared to the production and use of its fossil equivalent gasoline in the cane fallow scenario for the environmental impact category greenhouse effect. Results are based on typical cultivation and conversion conditions.

**How to read Fig. 4-2**

If sweet sorghum bioethanol from 1 ha is used instead of conventional gasoline, credits (upper left bar) and expenditures (upper right bar) from different life-cycle steps add up to a saving of about 4.5 tonnes of greenhouse gases per year (lower bar). More details regarding the individual contributions to credits and expenditures are explained in the text (subchapter 4.1.1.2).

**Conclusions**

Even though greenhouse gas and energy balances of bioethanol production and use from sweet sorghum show advantageous results compared to conventional gasoline, bioethanol from sweet sorghum is not per se environmentally friendly but causes also disadvantages for the environment. Thus, to improve bioethanol production, optimisation is necessary to reduce disadvantages and increase advantages. For the impact category photosmog, the data basis is uncertain and the amounts of given credits and expenditures are very similar. Therefore the results cannot be considered as robust. Thus, the category photosmog is not further presented in the following subchapters.

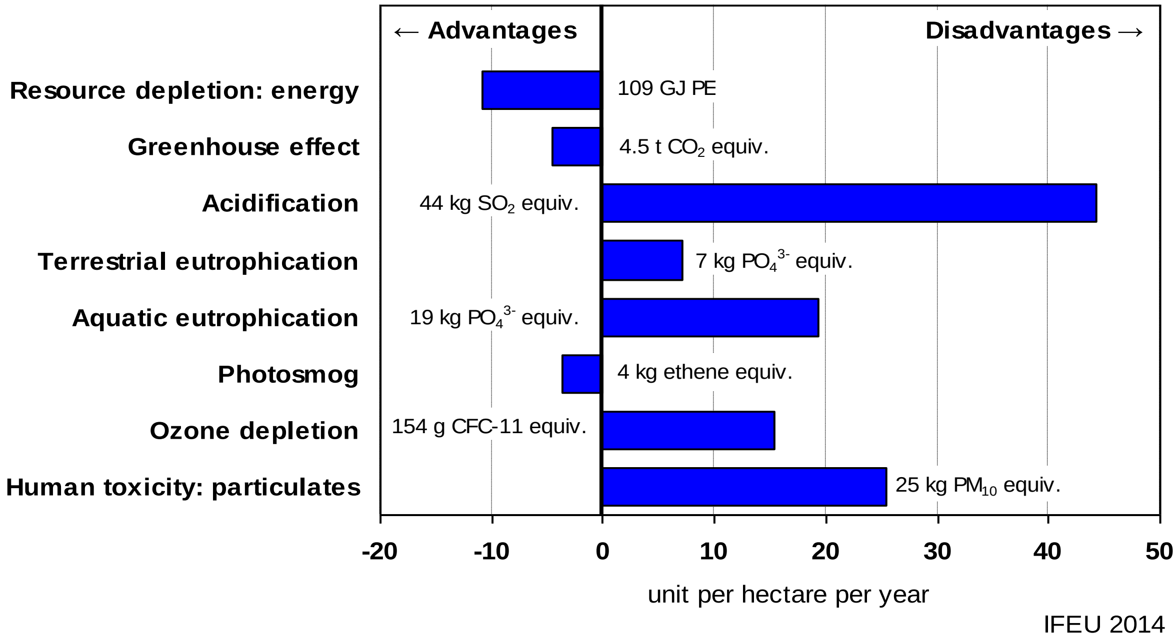


**Fig. 4-3** Net results for bioethanol production from sweet sorghum per hectare per year compared to gasoline in the cane fallow scenario. Results include all investigated environmental impact categories and are based on typical cultivation and conversion conditions.

### Results for decision makers

If there are conflicts between advantageous results of a scenario in one environmental impact category and disadvantageous results in another category, the question comes up how to compare these figures. As specified in the methodology section (subchapter 2.2.2), a decision to accept certain disadvantages in favour of other advantages requires weighting on the basis of value choices beyond scientific arguments, which is not done in this study. Nevertheless, a comparison of the magnitude, not the severity, of different impacts on a scientific basis can be done based on inhabitant equivalents. In this case, the impacts per space and time, thus, per hectare per year are compared (normalised) to the average annual impact that is caused by an inhabitant of the reference region (here European Union). For normalisation factors see Annex, subchapter 8.2.

Fig. 4-4 shows that the impact of all presented categories is in the same order of magnitude. In other words, there is no single result in an impact category that is extremely more disadvantageous or advantageous than the others.

**Conclusions**

The production and use of sweet sorghum bioethanol is advantageous and disadvantageous for the environment compared to its fossil equivalent gasoline depending on the environmental impact. Since, however, impacts of all presented categories are in the same order of magnitude, an objective decision for or against bioethanol from sweet sorghum cannot be made. However, based on a subjective value system a decision is possible: If, e.g. energy savings and greenhouse effect are given the highest priority, bioethanol from sweet sorghum performs better than gasoline.

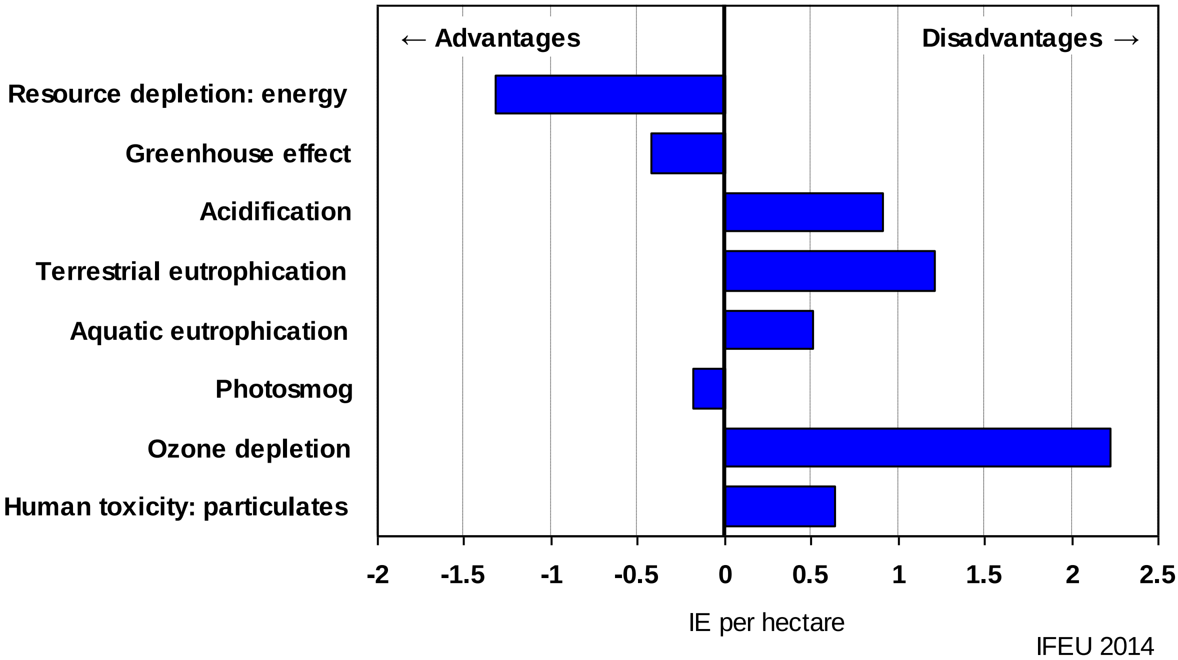


**Fig. 4-4** Net results for sweet sorghum bioethanol production in the cane fallow scenario per hectare per year normalised to inhabitant equivalents (IE).

**How to read the first bar in Fig. 4-4:**

If bioethanol is produced from 1 ha sweet sorghum and replaces fossil gasoline, as much of non-renewable energy resources are saved as about 1.3 European inhabitants consume each year.

### 4.1.1.2 Influence of single life cycle stages

Since bioethanol production from sweet sorghum in the cane fallow scenario is not per se environmentally friendly, optimisation is necessary. In order to identify important life cycle steps that can be optimised the influence of all production steps on the overall outcome is described in the following.

In the impact category greenhouse effect (Fig. 4-5, greenhouse effect) credits are dominated by avoided environmental impacts that mainly derive from the substitution of gasoline through bioethanol ("Fossil equiv. usage"). Additionally, a large proportion of credits is given for the use of the by-product surplus bagasse for energy. Excess power, which occurs during process energy production, also proves important. Expenditures, however, are dominated by environmental impacts that occur during biomass cultivation ("Agriculture: fertiliser", "Agriculture: field emissions"). Similar looks the pattern for the impact category depletion of non-renewable energy resources, except that field emissions do not contribute to this category (Annex, Fig. 8-1, resource depletion, 'Typical').

For the impact category acidification (Fig. 4-5, acidification), a similar choice of important life cycle steps can be observed, except that the by-product vinasse replaces surplus bagasse as a dominant life cycle step and that excess power is not that dominant. Surplus bagasse even causes additional environmental burdens since the combustion of biomass-based ma-

terial often emits more $SO_2$ and $NO_X$ than the mix of substituted conventional energy carriers. Thus, not only the life cycle step surplus bagasse is affected but also the life cycle stage energy supply since here bagasse is combusted as well for process energy production. Additionally, a large proportion of expenditures in this category is caused by the use phase of bioethanol since here also a great amount of $NO_X$ is emitted.

For the other categories, terrestrial eutrophication, ozone depletion and human toxicity, the pattern of results is similar as for the category acidification (Annex, Fig. 8-1, 'Typical') except that the life cycle step "Fossil equiv. usage" is not that dominant in the impact category ozone depletion since this category is just influenced by $N_2O$ that occurs only to a relatively small degree during fossil energy carrier combustion. The pattern for the impact category aquatic eutrophication (Fig. 4-5, aquatic eutrophication) looks slightly different, since this category is mainly influenced by field emissions (due to $NO_3^-$ emissions which are caused by nitrification processes of microorganisms in the soil) and the use of the by-product vinasse (can be used as fertiliser that reduces the amount of applied mineral fertilisers, thus saves $NO_3^-$ emissions during mineral fertiliser application).

The dominating life cycle steps are particularly relevant to numerous environmental impacts and therefore represent important starting points for optimising bioethanol production in the cane fallow scenario. The other life cycle steps have either no or only little impact on the analysed impact categories, thus, their optimisation potential is relatively low.

To further illustrate and discuss the optimisation potential of the dominating life cycle steps, the following sensitivity analyses were conducted:

- Biomass production specific variations (including variations in biomass and sugar yield, fertiliser application and field emissions)
- Conversion plant specific variations (including conversion efficiency)
- Different use options of the by-products (including grains, leaves and surplus bagasse; partially represented by the cane fallow 2015 scenario)

Furthermore, an excursus shows whether a larger transportation distance influences the net results of the investigated impact categories significantly. Besides, a further sensitivity analysis was conducted to show the impact of different land use options.

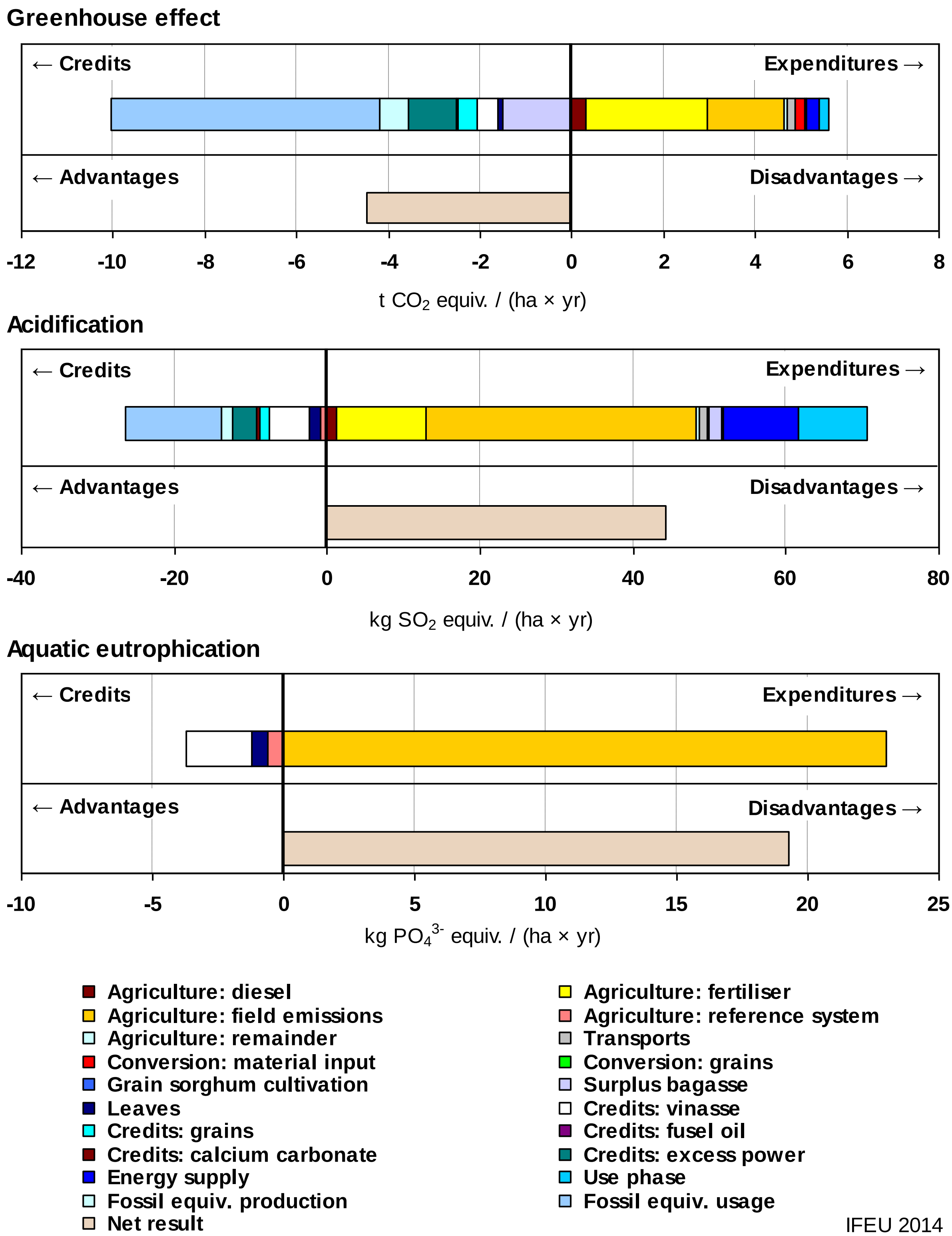


**Fig. 4-5** Contributions of individual life cycle steps (coloured bars) to the overall net result (light brown bar) of sweet sorghum ethanol production and use compared to the production and use of its fossil equivalent gasoline in the cane fallow scenario for the environmental impact categories greenhouse effect, acidification and aquatic eutrophication. Results are based on typical cultivation and conversion conditions. For further results see Annex, Fig. 8-1, 'Typical'.

**Conclusions**

Some life cycle stages are particularly relevant to the results of numerous environmental impact categories and therefore represent starting points for optimising bioethanol production from sweet sorghum. These important life cycle steps include fertilisation (especially nitrogen fertilisation), field emissions (influenced by fertilisation), use of the by-products (surplus bagasse, vinasse) and sometimes excess power, which occurs during process energy production. Another optimisation variable in most categories is represented by credits given for the avoided expenses for the use of conventional gasoline. Thus, several sensitivity analyses are conducted to further discuss all optimisation potentials of the relevant life cycle steps (see the following subchapter 4.1.1.3).

#### 4.1.1.3 Sensitivity analyses

This subchapter describes the results of different sensitivity analyses in the cane fallow scenario.

**Biomass production**

In this section the influence of different biomass yields on the overall results of the cane fallow scenario is described. Results for the impact categories greenhouse effect and acidification are illustrated in Fig. 4-6. Further results of the other investigated impact categories are shown in the Annex, Fig. 8-1.

Generally, high yielding systems require a higher input of fertilisers; hence induce more emissions that lead to higher expenditures. Additionally, since more sugar juice needs to be converted, higher yields also lead to higher expenditures for the conversion process. However, as shown in Fig. 4-6 (greenhouse effect, 'High yield'), these higher inputs and emissions are far outweighed by higher outputs of bioethanol and excess power, so that the overall result is clearly advantageous. A similar pattern can be found for the category depletion of non-renewable energy resources (Annex, Fig. 8-1, resource depletion). Thus, an increase of biomass yield shows higher savings of greenhouse gases and fossil energy carriers. In contrast, low biomass yields lead to fewer savings. For the impact categories acidification (Fig. 4-6, acidification), terrestrial and aquatic eutrophication, human toxicity and ozone depletion (Annex, Fig. 8-1), however, high yielding systems lead to additional environmental burdens since the extra credits for a higher output of bioethanol (and by-products) still cannot outweigh higher expenditures for cultivation and conversion.

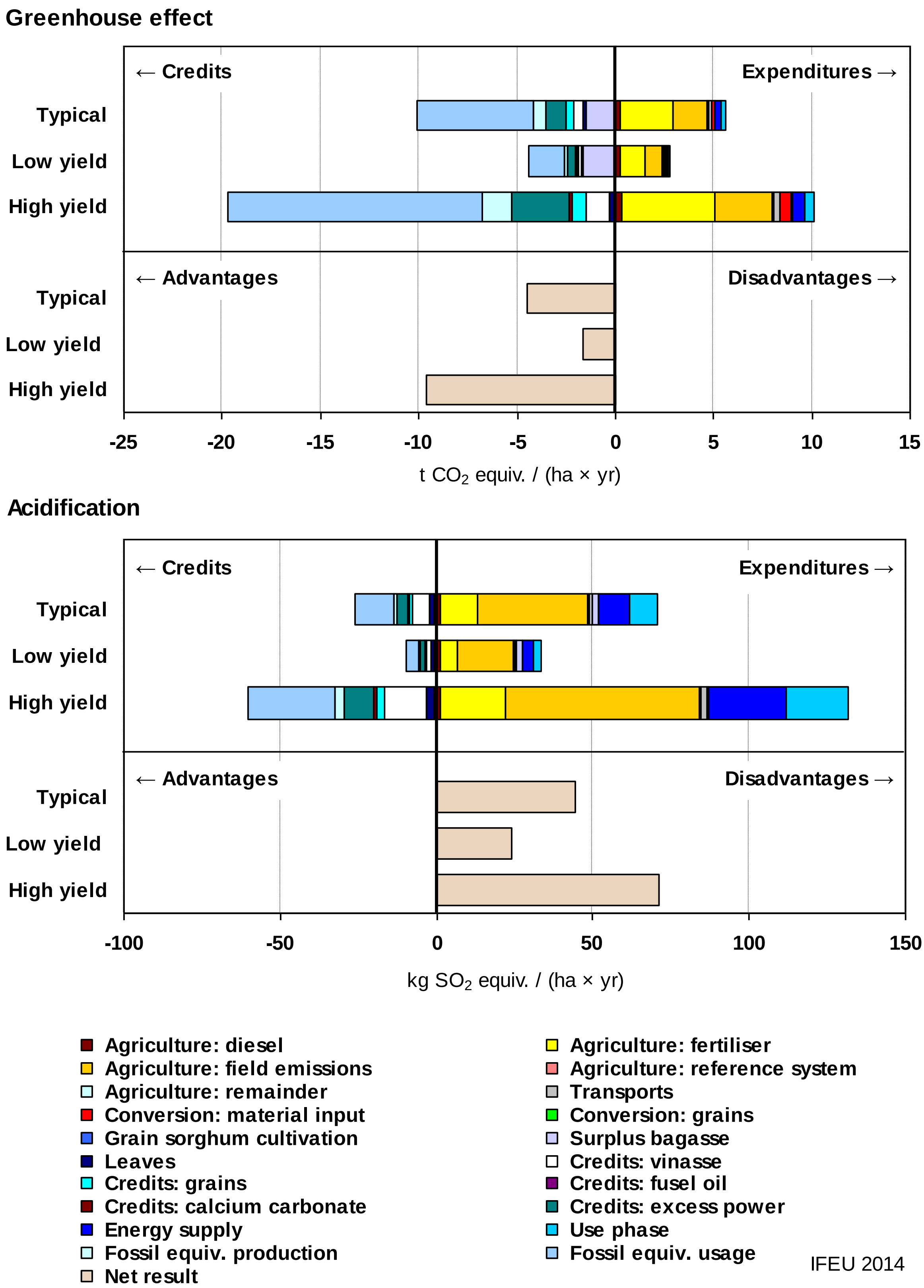


**Fig. 4-6** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) of sweet sorghum ethanol production and use compared to the production and use of its fossil equivalent gasoline in the cane fallow scenario and under different biomass yield assumptions (low, high) for the impact categories greenhouse effect and acidification. For further categories see Annex, Fig. 8-1.

### Nutrient content in the harvested biomass

Since expenditures in general are especially influenced by the amount of mineral fertilisers and associated field emissions, one way to reduce expenses could be the reduction of the needed amount of applied fertilisers. However, in this project, the amount of applied fertilisers is calculated according to sustainable cultivation practices (amount of fertiliser = nutrient removal + losses, see Annex, Table 8-1), thus, a reduction of applied mineral fertilisers can only be reached by decreasing the amount of nutrients that are removed from the field. Fig. 4-7 shows an example how big the impact of a decreased amount of applied fertilisers, hence of nutrients that are removed from the field can be. A decreased amount of applied fertilisers leads to higher savings of greenhouse gases and energy resources. Particularly strong, however, is the influence of a reduced fertiliser input on the other impact categories, thus, additional burdens can be reduced significantly.

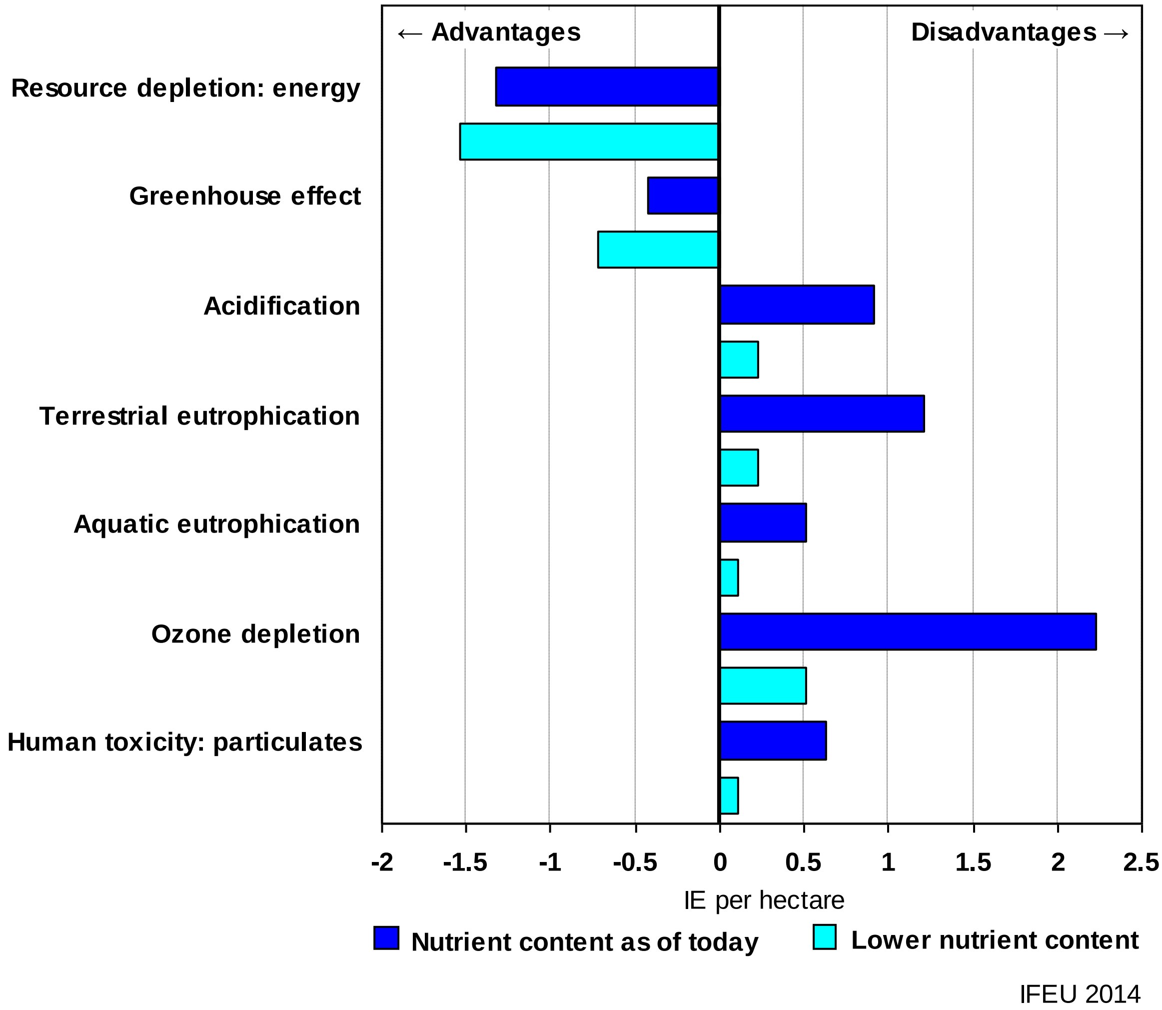


**Fig. 4-7** Net results of the environmental impact categories for sweet sorghum ethanol production and use compared to the production and use of its fossil equivalent gasoline in the cane fallow scenario, separated by a different amount of applied mineral fertilisers, hence a different amount of nutrient content in the harvested biomass. Results are based on typical cultivation and conversion conditions defined for the cane fallow scenario.

**Conclusions**

The production and use of sweet sorghum bioethanol saves more greenhouse gases and fossil energy carriers the higher the biomass yield of sweet sorghum. Thus, one option to optimise bioethanol production from sweet sorghum includes aiming at higher yields. However, it should be kept in mind that higher yields also lead to additional environmental burdens in the other investigated impact categories. Since all categories are strongly influenced by the amount of applied mineral fertilisers (especially N fertiliser), another way to improve the outcome of the balances of all environmental impact categories, is to reduce the nutrient content in the harvested biomass while still sustainable cultivation practices are guaranteed.

**Comparison of conversion efficiencies**

In this paragraph the influence of different conversion efficiencies on the overall results of the cane fallow scenario is described.

On the one hand, a high conversion efficiency means that more ethanol per hectare per year can be gained out of one ton of sugar, on the other hand a high conversion efficiency includes that less bagasse is needed to produce the same amount of energy for the conversion process. Both parameters mainly influence the following life cycle steps:

- Fossil equivalent production and use: A high conversion efficiency leads to a higher ethanol yield which means more credits for avoided expenses for the production and use of fossil energy carriers.
- Surplus bagasse: A high ethanol yield leads to a higher energy demand for the ethanol treatment. However, since a higher conversion efficiency also means that less bagasse is needed to get the same amount of energy, both impacts more or less even out.
- Excess power: Since a higher ethanol output leads to a higher energy demand, more excess power occurs.

If all three life cycle steps are considered together, net results show that a higher conversion efficiency leads to more advantageous results in the impact categories greenhouse effect and depletion of non-renewable energy resources (see exemplarily Fig. 4-8, greenhouse effect) and to less disadvantageous results in the other investigated impact categories (see exemplarily Fig. 4-8, acidification), whereas the magnitude is relatively small due to partially contradictory results.

**Conclusions**

Thus, the higher the conversion efficiency of sweet sorghum bioethanol, the better the results of all environmental impact categories. However, since the impact on the overall results is relatively small, the conversion efficiency holds only a small potential for optimising bioethanol production from sweet sorghum.

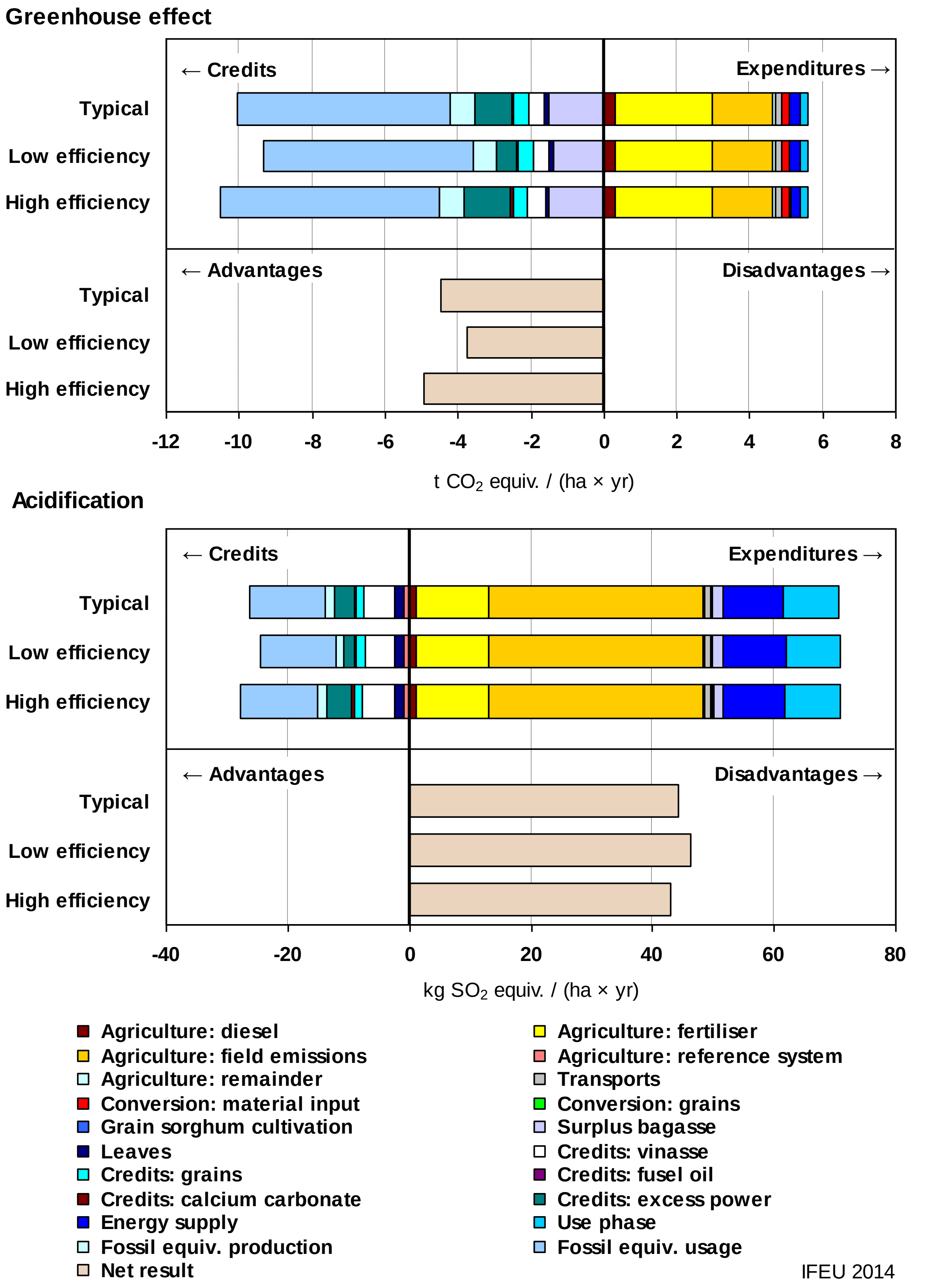


**Fig. 4-8** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) of sweet sorghum bioethanol production and use compared to its fossil equivalent gasoline in the cane fallow scenario and under different conversion efficiency assumptions (low, high) for the impact categories greenhouse effect and acidification. Results are based on typical cultivation conditions.

**Comparison of by-product use options**

In this paragraph the influence of different use options of the by-products (leaves, grains and surplus bagasse) on the overall results is described for the cane fallow scenario. The alternative use option of the grains (grains left on field) is represented by the cane fallow 2015 scenario. Results for the impact categories greenhouse effect and acidification are illustrated in Fig. 4-9. Further results of the other investigated impact categories are shown in the Annex, Fig. 8-2.

- In this project, **surplus bagasse** is either used to generate bioenergy (typical scenario) or used as feed (Fig. 4-9, 'Typical' and 'Surpl. bagasse: feed'). If surplus bagasse is used for energy production, a higher amount of greenhouse gases can be saved compared to the other use option, since the combustion of fossil energy carriers (product substituted by bioenergy generation) emits quantitatively more greenhouse gases than the production of cereals (product substituted by feed). However, this result is only valid if the greenhouse gas balance per hectare of directly used land (area where sweet sorghum is cultivated on) is considered. If the net area is taken into account, thus, also the area that can be saved if sweet sorghum by-products such as surplus bagasse are used as feed, even more greenhouse gases might be saved. This is due to the fact, that less cultivation area is needed in total since the area where cereals (as the substituted product) were grown can now be used for other purposes.
- **Leaves** are either left on field (Fig. 4-9, 'Typical'), used for bioenergy production (Fig. 4-9, 'Leaves + surpl. bagasse: bioenergy') or as feed (Fig. 4-9, 'Leaves + surpl. bagasse: feed'). If leaves are used for bioenergy production the highest amount of greenhouse gases can be saved compared to the other use options. Least savings are observed if leaves are used as a fertiliser. However, it should be kept in mind that a removal of the leaves from the field can have a great effect on the soil organic matter, which in the long term might have a negative impact on the greenhouse gas emissions.
- If **grains** are used for ethanol production (Fig. 4-9, 'Typical') the highest amount of greenhouse gases can be saved, since more ethanol is produced per hectare per year than if the grains are left on the field (Fig. 4-9, 'Cane f. 2015 (grains / leaves: field)').

Similar are the results for the impact category depletion of non-renewable energy resources (Annex, Fig. 8-2, resource depletion). The other environmental impact categories often show most additional environmental burdens if leaves and bagasse are used to generate bioenergy and grains are used for bioethanol production (see exemplarily Fig. 4-9, acidification or Annex, Fig. 8-2), whereby the difference to the typical scenario is only small (see also green bar "Bandwidth" showing the spectrum of the net results due to the use of the by-products). In the category aquatic eutrophication, the cane fallow 2015 scenario shows best results since a usage of grains and leaves for fertilising saves a lot of mineral fertiliser which leads to highly advantageous results in this category.

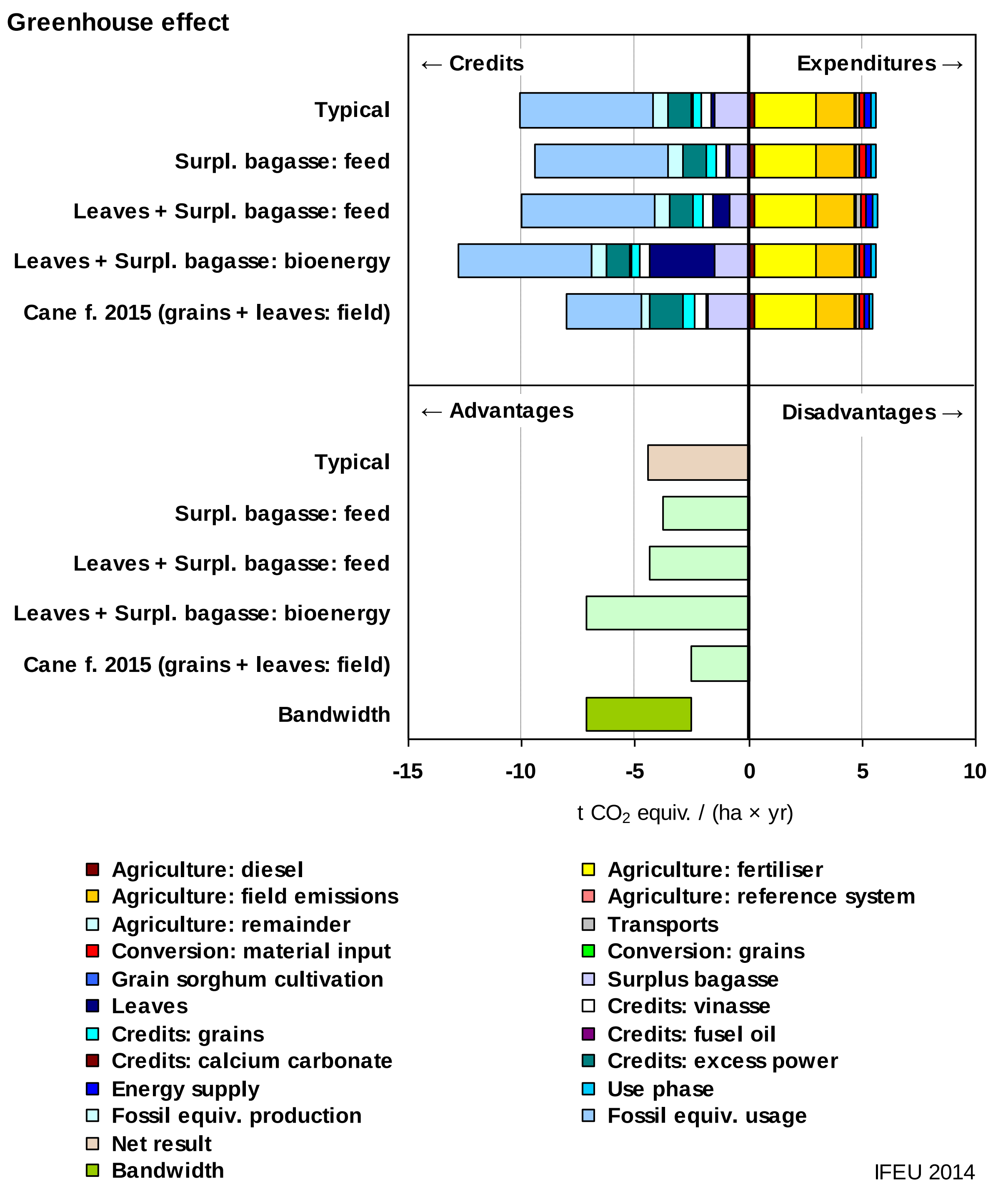


**Fig. 4-9** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) of sweet sorghum ethanol production and use compared to its fossil equivalent gasoline in the cane fallow and the cane fallow 2015 scenario as well as in the alternative use option scenarios of the by-products (Surpl. bagasse: feed; Leaves + Surpl. bagasse: feed; Leaves + Surpl. bagasse: bioenergy) for the impact categories greenhouse effect and acidification. Results are based on typical cultivation and conversion conditions. For further categories see Annex, Fig. 8-2).

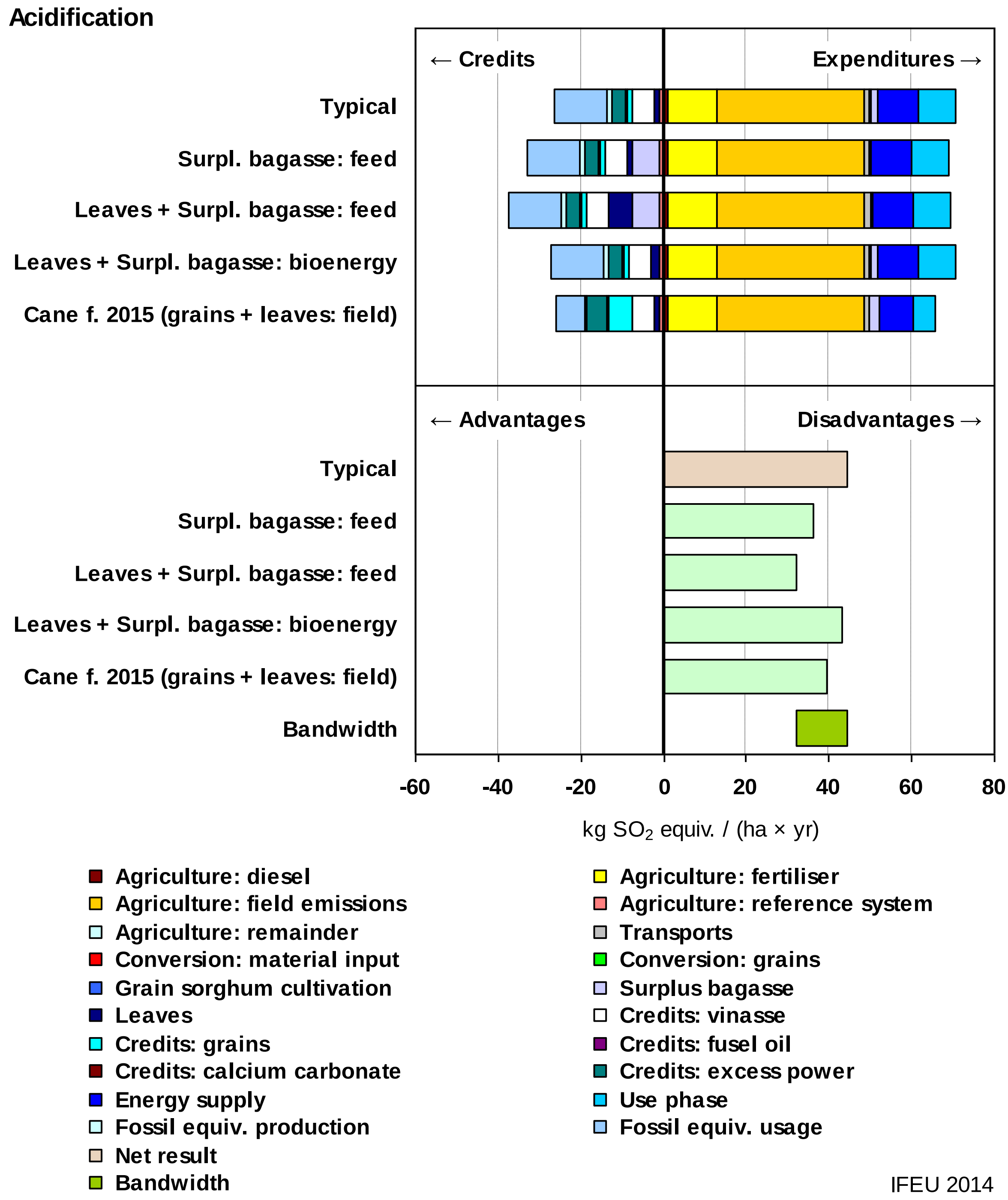


**Fig. 4-9** (continued)

**Conclusions**

The different use options of the by-products represent a huge optimisation potential to make bioethanol production from sweet sorghum more environmentally friendly. The by-product leaves should be used for bioenergy production. However, the by-products grains and surplus bagasse (not required for process energy provision) should only be used for bioenergy production if grains are not needed as food (see subchapter 4.1.2) and the use of surplus bagasse as feed is not needed to relieve pressure on regional land availability.

**Excursus: Variation on transport distances**

In the cane fallow scenario, the mean transport distance of sweet sorghum stalks from the field to the central ethanol unit is considered as 30 km. However, since this distance could be much longer in some regions, we also analysed, if a longer transport distance (100 km) has an impact on the investigated impact categories. However, as depicted in Fig. 4-10, a longer transportation distance has only little influence on the greenhouse gas balance. Similar patterns can be found for the other investigated impact categories.

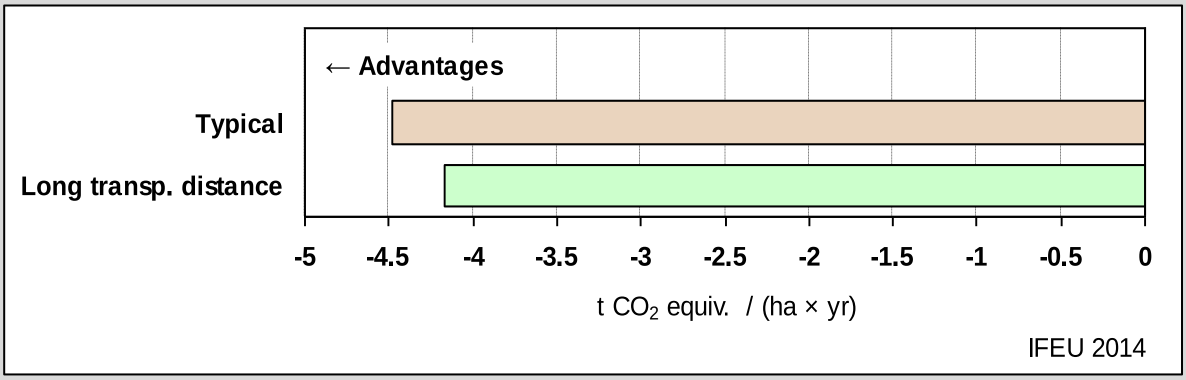


**Fig. 4-10** Comparison of net results for sweet sorghum ethanol production in the typical cane fallow scenario with a long transport distance variation.

**Conclusions**

The transportation distance of sweet sorghum stalks from field to the central ethanol unit has only little influence on the outcome of all investigated environmental impact categories.

**Comparison of reference systems**

This paragraph compares the contributions of different reference systems to the overall results for the impact category greenhouse effect (Fig. 4-11).

The choice of the area for the cultivation of sweet sorghum has a strong influence on the greenhouse gas balance of sweet sorghum ethanol. The higher the carbon stock of the natural vegetation, the higher are the carbon losses if sweet sorghum is cultivated. Two different amortisation rates are considered: amortisation is either completed after 25 years, which correspond to a generation cycle in the developing countries or after 100 years as it is general practice in the studies of the IPCC report. Both options are based on social conventions but there is no scientific reason to favour one over the other. Thus, in this report, both rates are considered to demonstrate the impact of the amortisation time on the overall result.

If sweet sorghum is cultivated on wooded grasslands and pastures, the greenhouse gas balance is still advantageous no matter if carbon change is amortised after 25 or 100 years as the expenditures due to carbon losses are overcompensated by the ethanol production and credits for the use of the by-products. However, in both cases, fewer savings of greenhouse gases can be observed than in the typical scenario. If sweet sorghum is cultivated on an area originally covered with dense thickets and sparse forests, the greenhouse gas balance becomes even disadvantageous if carbon change is amortised after 25 years. It stays negative

if an amortisation time of 100 years is considered but savings are much lower compared to a cultivation of sweet sorghum on idle land.

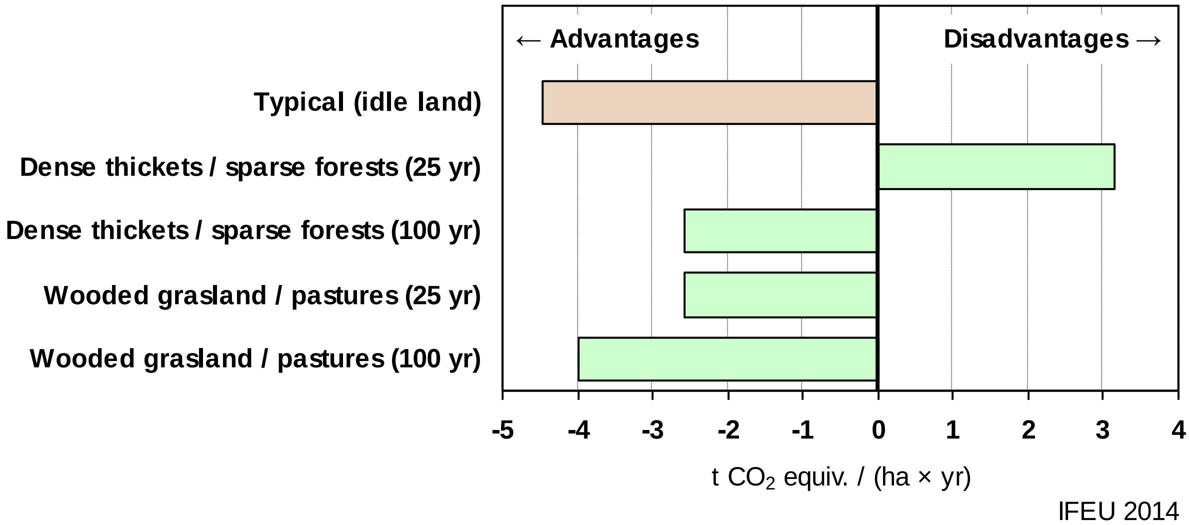


**Fig. 4-11** Comparison of the net results for different reference systems of sweet sorghum ethanol production and use in the cane fallow scenario for the environmental impact category greenhouse effect. Carbon change is either amortised after 25 or 100 years. Results are based on typical cultivation and conversion conditions defined for the cane fallow scenario.

**Conclusions**

If land cover changes are involved to cultivate sweet sorghum, the outcome of the greenhouse gas balance of sweet sorghum ethanol compared to gasoline depends largely on the carbon stocks of the area. Any accumulative or depleting change has an immediate and clear impact on the greenhouse gas balance. Therefore, if a piece of land is developed for sweet sorghum cultivation, a reduction of the carbon inventory of this area must be prevented. Results are strongly dependent on the time of amortisation.

### 4.1.2 Grain to food scenarios

In the grain to food scenario, sweet sorghum is not grown as an intermediate crop, but replaces grain sorghum as it is conducted for example in Southern Africa. In those regions, we assume that sweet sorghum cultivars produce fewer grains than grain sorghum. However, since the grains of grain sorghum are used in some countries for food and in others for feed, replacing grain sorghum with sweet sorghum might jeopardise food / feed security in those areas. To further guarantee food / feed security, differences in grain yield need to be balanced by cultivating additional grain sorghum. Therefore, an additional area is required. Fig. 4-12 depicts the entire life cycle of the grain to food scenario. All light green processes arise if bioethanol is produced out of sweet sorghum. All brown processes are conventional processes that are replaced by bioethanol production in the grain to food scenario. For a detailed scenario description see subchapter 3.1.2.

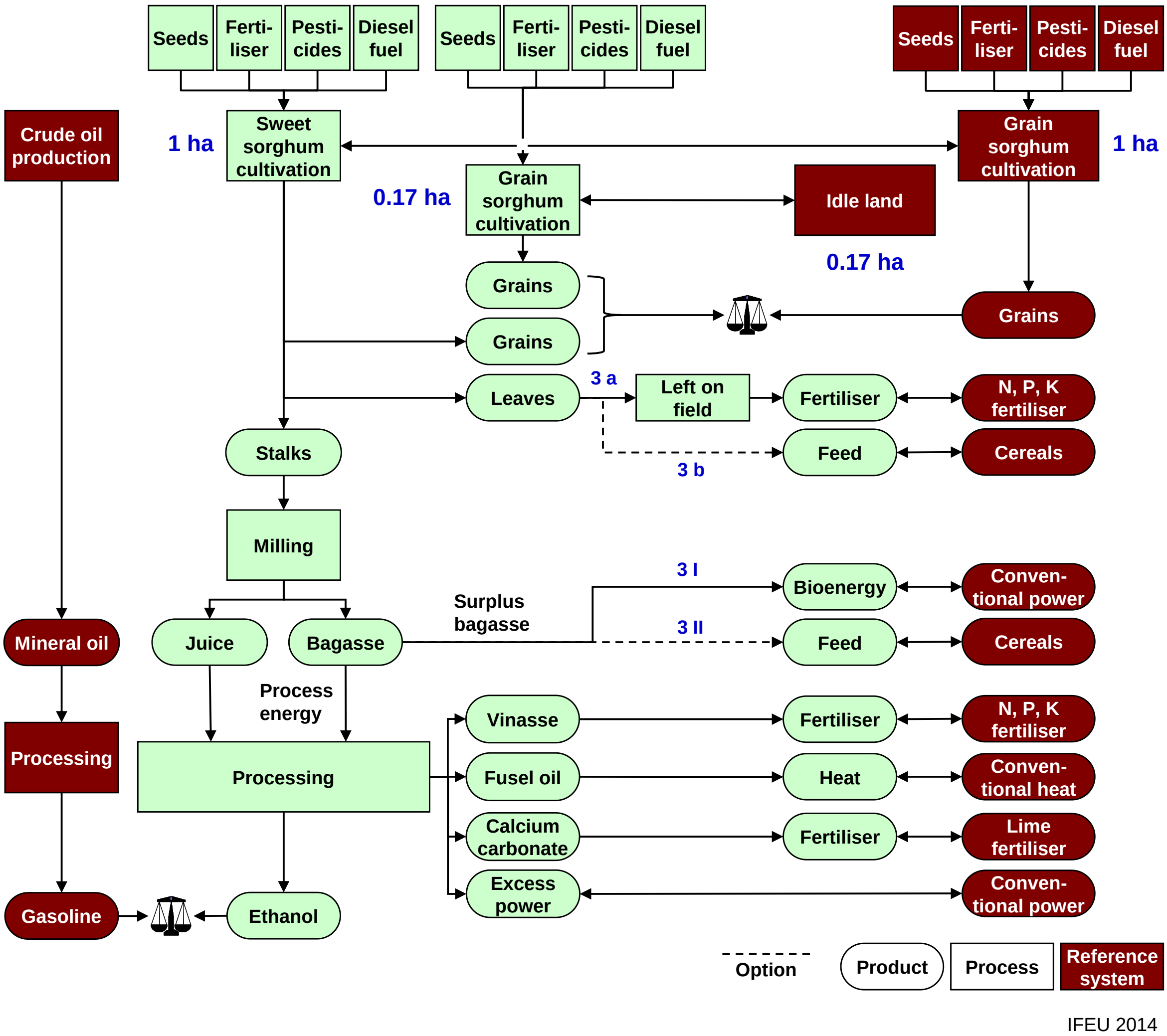


**Fig. 4-12** Schematic overview of ethanol production from sweet sorghum in the grain to food scenario; numbers indicate scenario numbers (for a summary, see Table 3-1). For large numbers see subchapter 3.1.2.

The grain to food scenario resembles the cane fallow scenario regarding a centralised ethanol production system. However, in the grain to food scenario it is assumed that biomass yields in areas such as Southern Africa are slightly lower than in the cane fallow scenario since climate conditions and / or cultivation experiences might be worse. Thus, the pattern of the results is similar to the cane fallow scenario but the magnitude of credits and expenditures are lower (Fig. 4-13). Altogether, credits of about 6 t $CO_2$ equiv. / ha / year and expenditures of about 4 t $CO_2$ equiv. / ha / year can be observed in the grain to food scenario. Hence, overall savings of greenhouse gases are lower in the grain to food (about 2 t $CO_2$ equiv. / ha / year) than in the cane fallow scenario (about 4.5 t $CO_2$ equiv. / ha / year).

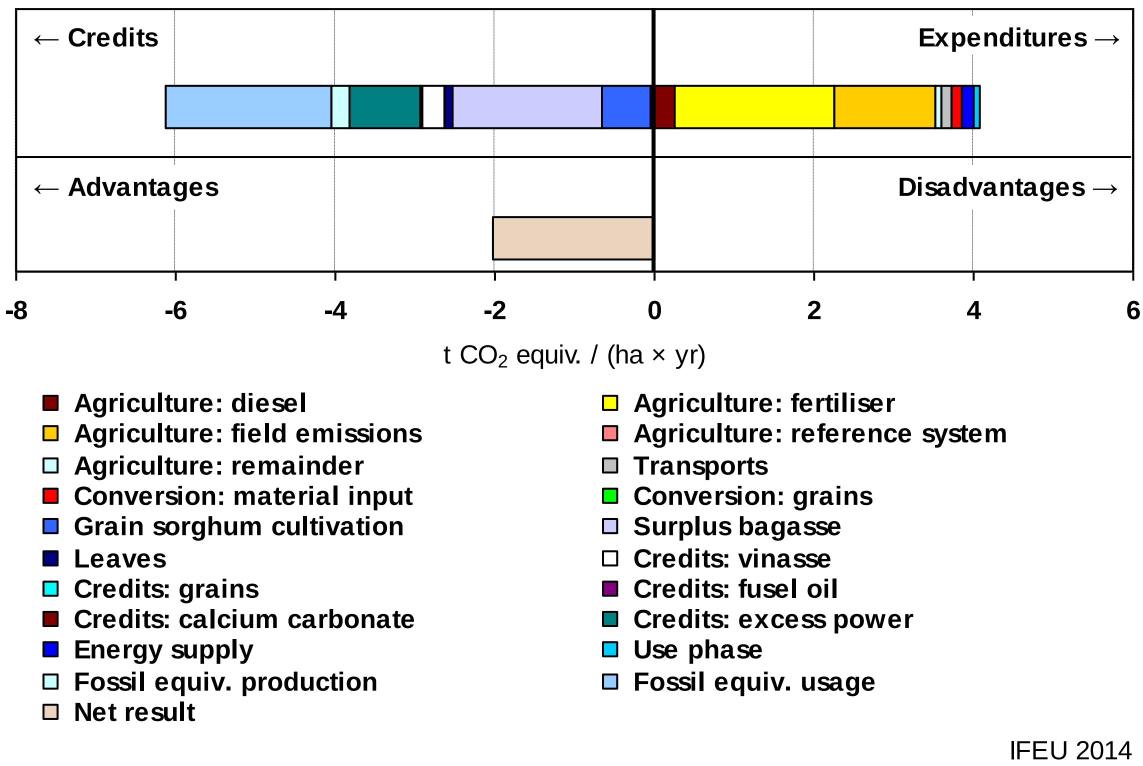


**Fig. 4-13** Contributions of individual life cycle steps (coloured bars) to the overall net result (light brown bar) of sweet sorghum ethanol production and use compared to the production and use of its fossil equivalent gasoline in the grain to food scenario for the environmental impact category greenhouse effect. Results are based on typical cultivation and conversion conditions defined for the grain to food scenario.

**How to read Fig. 4-13:**

If sweet sorghum bioethanol from 1 ha is used instead of conventional gasoline, credits (upper left bar) and expenditures (upper right bar) from different life-cycle steps add up to a saving of about 2 tonnes of greenhouse gases per year (lower bar). More details regarding the individual contributions to credits and expenditures are explained in the text (subchapter 4.1.2.2).

### 4.1.2.1 Results of all environmental impact categories

Even though the greenhouse gas balance shows advantageous results, bioethanol from sweet sorghum in the grain to food scenario is not per se environmentally friendly, but causes also disadvantages for the environment compared to conventional gasoline. The pattern is similar to the cane fallow scenario, but the magnitude is lower for advantages as well as disadvantages. Under most conditions, additional environmental burdens are caused in the environmental impact categories acidification, terrestrial and aquatic eutrophication, ozone depletion and human toxicity (Fig. 4-14). Besides greenhouse effect, mitigation of environmental burdens is also achieved regarding the categories depletion of non-renewable energy resources and photochemical ozone formation (summer smog). However, as already described for the cane fallow scenario, the data basis for the category photosmog is very uncertain. Furthermore, the amounts of given credits and expenditures are very similar, therefore

only slight modifications in the base data for either the sweet sorghum ethanol or the fossil fuel life cycle may change the sign of the net result (versus advantage or disadvantage).

**Conclusions**

In case, sweet sorghum is cultivated instead of grain sorghum, bioethanol production from sweet sorghum is not per se environmentally friendly, thus, optimisation is necessary to decrease environmental disadvantages but also increase environmental advantages. As for the cane fallow scenario, results in the category photosmog cannot be considered as robust, thus, they are not further presented in the grain to food scenario.

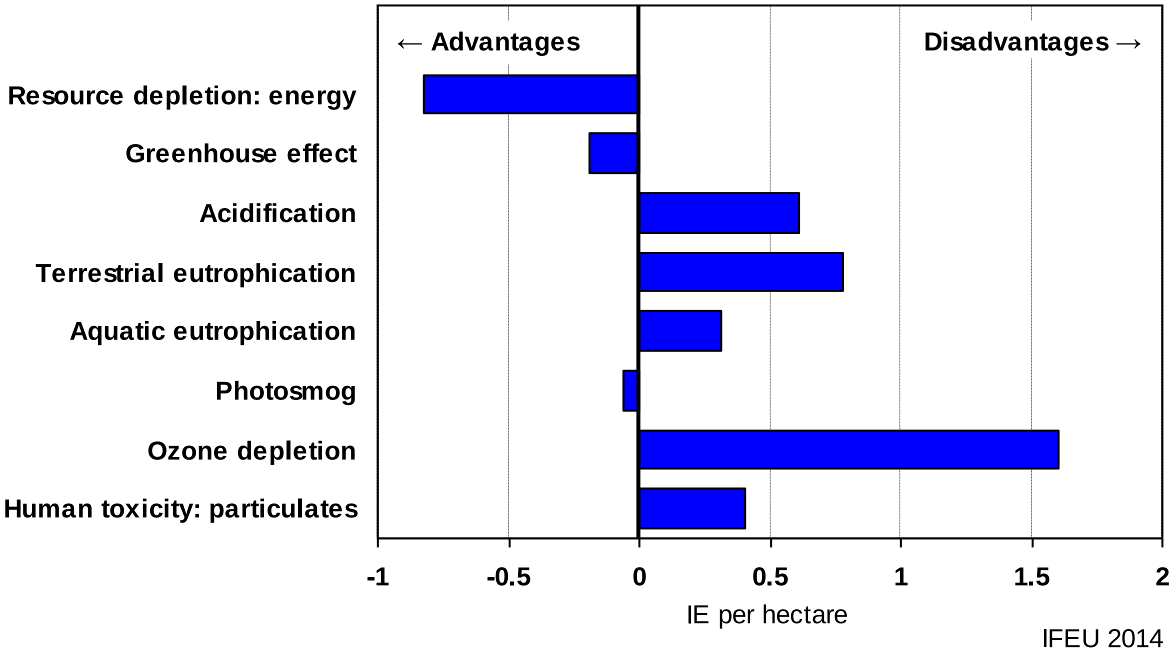


**Fig. 4-14** Net results for sweet sorghum bioethanol production in the grain to food scenario per hectare per year normalised to inhabitant equivalents (IE).

**How to read the first bar in Fig. 4-14:**

If bioethanol is produced from 1 ha sweet sorghum and replaces fossil gasoline, as much of non-renewable energy resources are saved as about 0.8 European inhabitants consume each year.

### 4.1.2.2 Influence of single life cycle stages

As already described in the cane fallow scenario, there are important life cycle steps that can be optimised to improve bioethanol production from sweet sorghum (subchapter 4.1.1.2). In most cases, those important life cycle steps can also be observed in the grain to food scenario.

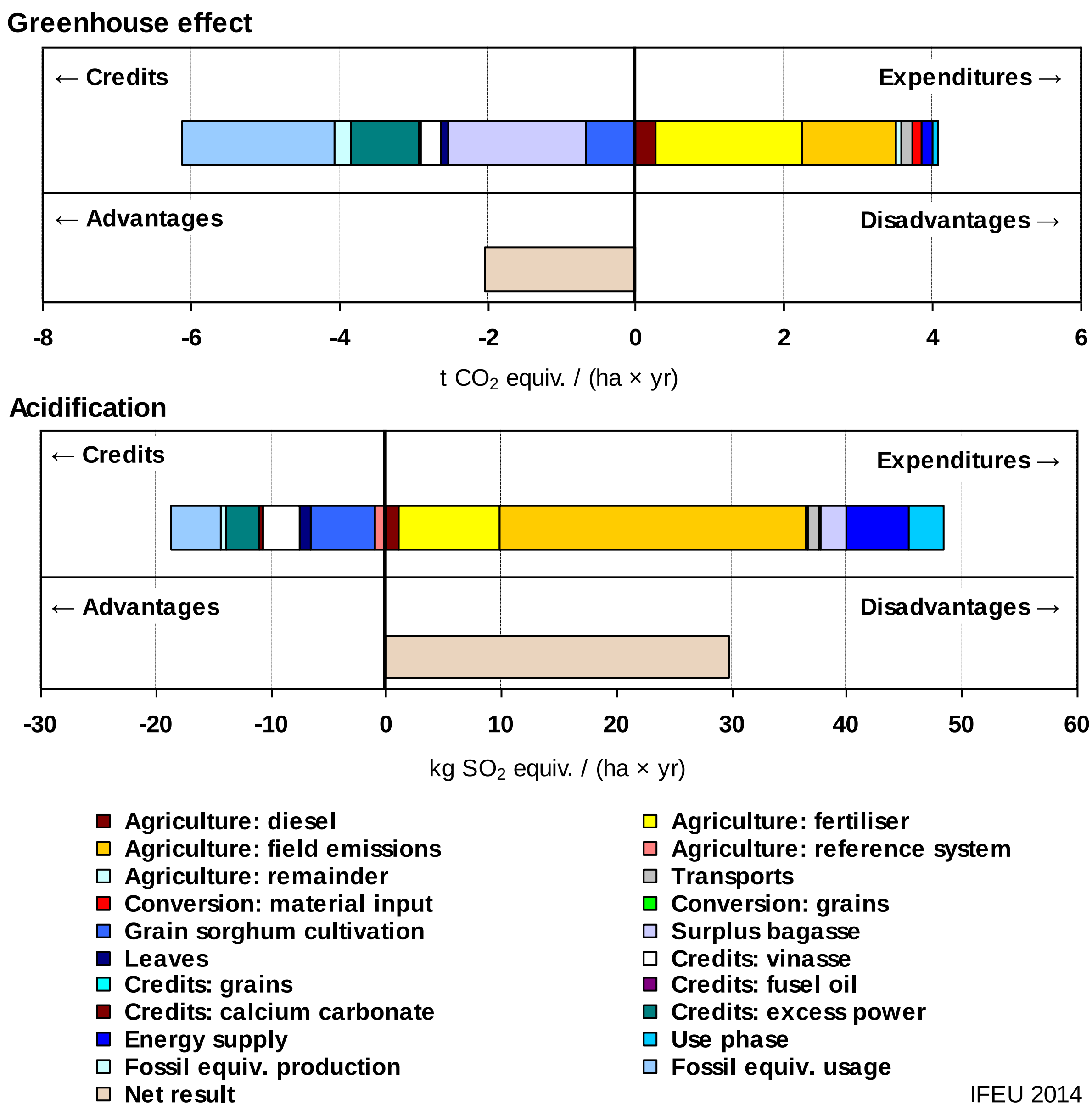


**Fig. 4-15** Contributions of individual life cycle steps (coloured bars) to the overall net result (light brown bar) of sweet sorghum bioethanol production and use compared to its fossil equivalent gasoline in case sweet sorghum is cultivated instead of grain sorghum for the environmental impact categories greenhouse effect and acidification. Results are based on typical cultivation and conversion conditions defined for the grain to food scenario. For further results see Annex, Fig. 8-3 ('Typical').

Thus, in the impact category greenhouse effect (Fig. 4-15, greenhouse effect) credits are dominated by avoided environmental impacts which mainly derive from the substitution of gasoline through bioethanol ("Fossil equiv. usage"), by credits for the use of the by-product ("Surplus bagasse") and by electricity that occurs during process energy production ("Credits: excess power"). Additionally, in the grain to food scenario a relatively large proportion of credits is also given for avoided expenditures for the grain sorghum cultivation. Expenditures are dominated by the same environmental impacts as in the cane fallow scenario ("Agriculture: fertiliser", "Agriculture: field emissions"). The pattern for the impact category depletion of

non-renewable energy resources looks similar, except that field emissions do not contribute to this category (Annex, Fig. 8-3, resource depletion). For the impact category acidification (Fig. 4-15, acidification), the important life cycle steps are the same as for the cane fallow scenario plus the avoided expenditures for the grain sorghum cultivation.

For the other categories terrestrial eutrophication, human toxicity and ozone depletion, the pattern is similar as for the category acidification (Annex, Fig. 8-3), except that in the category ozone depletion the life cycle step “Fossil equiv. usage” is not that dominant. For the impact category aquatic eutrophication, the pattern looks slightly different (Annex Fig. 8-3, aquatic eutrophication) as already described for the cane fallow scenario (see subchapter 4.1.1.2).

Thus, as for the cane fallow scenario some dominating life cycle steps were observed in the grain to food scenario that represent important starting points for optimising bioethanol production. To illustrate and discuss the optimisation potential, several sensitivity analyses were conducted for the grain to food scenario, of which most are analogue to the cane fallow scenario:

- Biomass production specific variations (including variations in biomass and sugar yield, fertiliser application, field emissions)
- Conversion plant specific variations (conversion efficiency)
- Different use options of the by-products leaves and bagasse

However, since an additional area is needed in the grain to food scenario, an extra sensitivity analysis was conducted to compare several possibilities how to use this area:

- Extra high yield scenarios (including different area allocations)

**Conclusions**

Some life cycle stages are particularly relevant to the results of numerous environmental impact categories and therefore represent starting points for optimising bioethanol production from sweet sorghum. These include the same life cycle stages as already described for the cane fallow scenario (fertilisation, field emissions, credits for bioethanol output, use of by-products and excess power, see subchapter 4.1.1.2). Additionally to those, in case sweet sorghum is cultivated instead of grain sorghum, a further optimisation variable is represented by credits given for avoided expenditures for the grain sorghum cultivation. Several sensitivity analyses are conducted to discuss all optimisation potentials of the relevant life cycle stages (see the following subchapter 4.1.2.3).

#### 4.1.2.3 Sensitivity analyses

This subchapter describes the results of different sensitivity analyses in the grain to food scenario. Since most sensitivity analyses are analogue to the cane fallow scenario (biomass production, conversion efficiency and use of the by-products, leaves and surplus bagasse) and results show similar patterns, the outcome is only briefly described in the following section. For more details see corresponding descriptions in subchapter 4.1.1.3. Results of the sensitivity analyses of the extra high yield scenarios, however, are described in more detail.

**Sensitivity analyses analogue to cane fallow**

**Biomass production.** As already described for the cane fallow scenario, high yielding systems lead to a higher bioethanol output but also require a higher input of fertilisers and cause additional expenditures during conversion. However, also in the grain to food scenario credits still outweigh higher expenditures. Thus, the higher the yield, the more greenhouse gases can be saved. Results for the category depletion of non-renewable energy resources are similar. For the other impact categories, however, high yielding systems lead to more additional environmental burdens compared to conventional gasoline.

**Conversion efficiency.** A high conversion efficiency means on the one hand that more ethanol per hectare per year can be gained out of one ton of sugar, on the other hand that less bagasse is needed to produce the same amount of energy for the conversion process. These premises influence some life cycle steps differently. But as described for the cane fallow scenario, in total, a higher conversion efficiency leads to less greenhouse gas emissions and less depletion of non-renewable energy resources and to less extra emissions in the other investigated impact categories. The overall impact on the net result, however, is only relatively small.

**Use options of the by-products (surplus bagasse and leaves).** A use of the by-product surplus bagasse for energy production shows most advantageous results in the categories greenhouse effect and depletion of non-renewable energy resources compared to the other use option (feed). In all other categories, a use of surplus bagasse for energy production leads to disadvantageous results compared to the use option feed. The leaves show better results in the categories greenhouse effect and depletion of non-renewable energy resources if used for feed than for fertilisation.

**Conclusions**

As for the cane fallow scenario, if sweet sorghum is cultivated instead of grain sorghum in the grain to food scenario, higher biomass yields of sweet sorghum result in saving more greenhouse gases and fossil energy carriers. Thus, one option to optimise bioethanol production includes aiming at higher yields. Furthermore, bioethanol production from sweet sorghum in the grain to food scenario show most advantageous greenhouse gas and energy balances if surplus bagasse is used for energy production and leaves as feed. As for the cane fallow scenario, the conversion efficiency of sweet sorghum to bioethanol has only little impact on the overall results of the investigated impact categories, thus the optimisation potential here is low as well.

**Extra high yield scenarios**

In this section the influence of different extra high yield scenarios (including various land use options) on the overall results of the grain to food scenario are presented. For a schematic overview see Fig. 4-16; for further descriptions of the extra high yield scenario see subchapter 3.1.2 section ‘Extra high yield scenarios’ The result for the impact category greenhouse effect is illustrated in Fig. 4-17. For the results of further categories see Annex, Fig. 8-4.

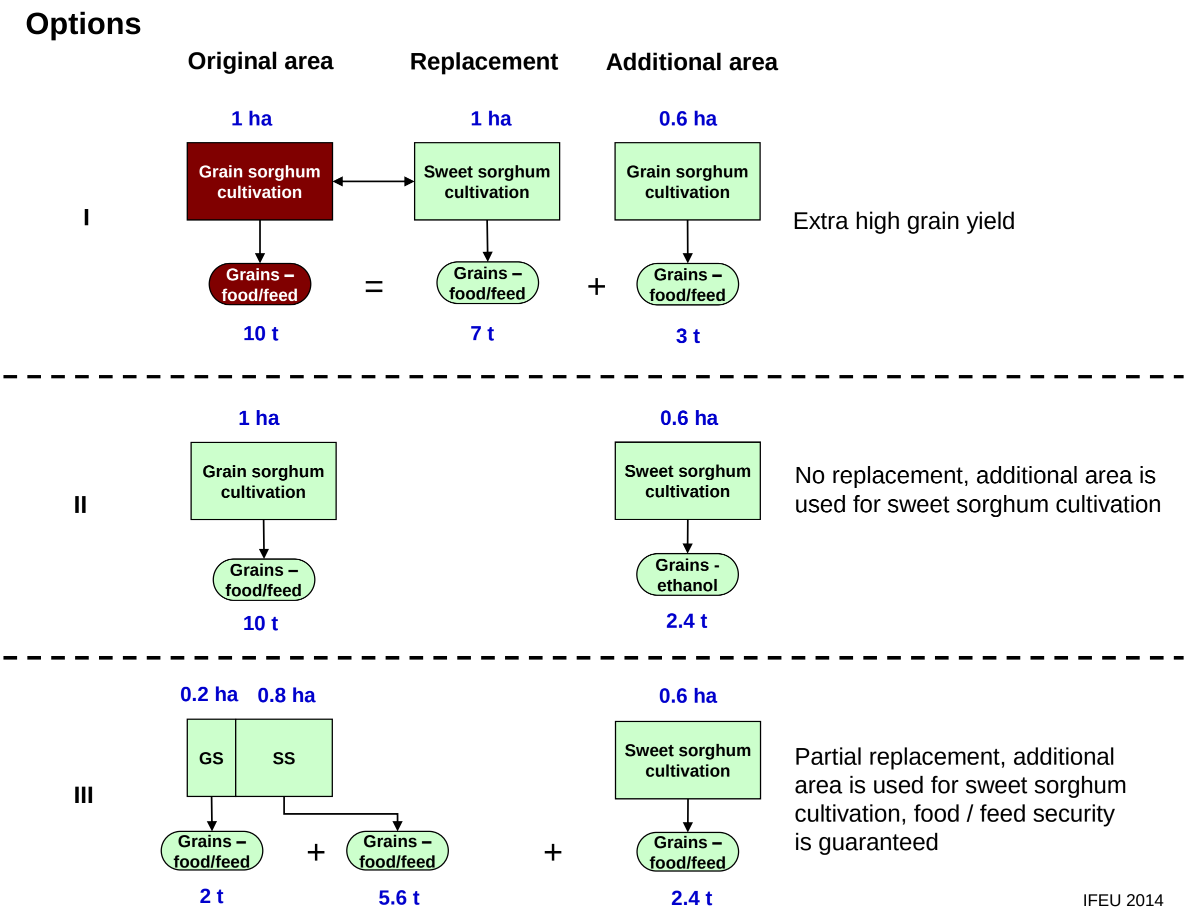


**Fig. 4-16** Schematic overview of different land use options for sweet sorghum cultivation on traditional grain sorghum land. Option I corresponds to the typical grain to food scenario but is based on extra high yields. Options II and III are further alternatives of land use. Blue numbers are examples for illustration. For further descriptions see subchapter 3.1.2.

The cultivation of sweet sorghum instead of grain sorghum in a high yielding area, as it can be found in Eastern Mexico, shows considerably high savings of greenhouse gases due to higher yields in those regions (Fig. 4-17). If grain sorghum is not replaced and sweet sorghum is only cultivated on the additional area, however, much less greenhouse gases can be saved, since only a much smaller amount of sugar juice and grains can be processed to ethanol. Most greenhouse gases can be saved if only a part of the grain sorghum cultivation area is replaced while the additional area is also cultivated by sweet sorghum. In this case, the area cultivated with sweet sorghum is slightly largest, so that a higher amount of sugar juice can be harvested, while still food security is guaranteed. A similar pattern can be observed for the impact category depletion of non-renewable energy resources (Annex, Fig. 8-4, resource depletion). In the other impact categories, the pattern is the other way round (Annex, Fig. 8-4): the land use option that leads to most greenhouse gas and energy resource savings causes most additional burdens in the other categories. A partial replacement of grain sorghum with sweet sorghum, thus, shows slightly more disadvantageous results compared to a total replacement. However, if grain sorghum cultivation stays as it is and sweet sorghum is only cultivated on additional land, additional expenditures decrease enormously.

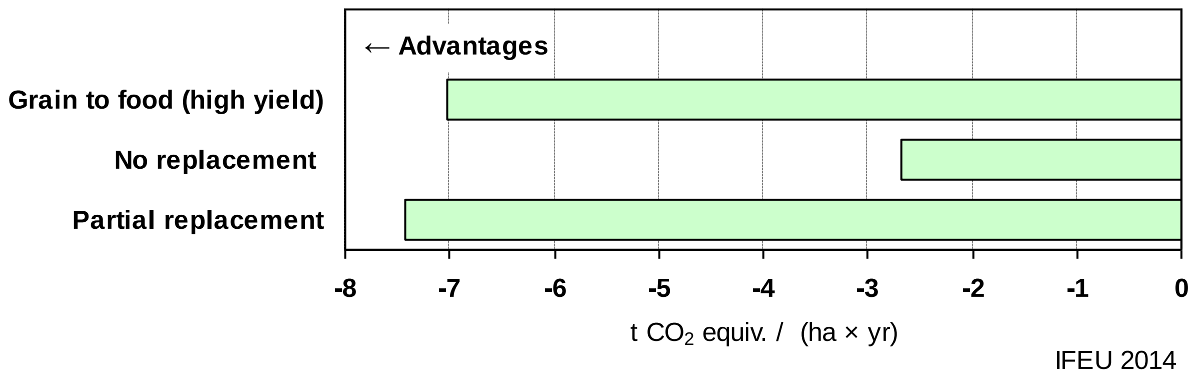


**Fig. 4-17** Comparison of net results of sweet sorghum ethanol production under different land use options in the extra high yield scenario for the environmental impact category greenhouse effect.

**Conclusions**

If sweet sorghum is cultivated instead of grain sorghum, there is no great difference in the overall results if grain sorghum is totally or only partially replaced. However, from a climate protection point of view, the option that grain sorghum is still cultivated and sweet sorghum is only grown on the additional area (option II, no replacement) should not be pursued, since this reduces greenhouse gas savings significantly.

### 4.1.3 Syrup production scenario

In some cases, infrastructure for biomass transportation to large centralised production units may be insufficient or not existent. Therefore and due to other reasons, a partially decentralised processing of sugar juice into syrup and a later production of ethanol in a central ethanol production unit might be an option to grow and use sweet sorghum in these areas.

Fig. 4-18 depicts the entire life cycle of the syrup production scenario. All light green processes arise if bioethanol is produced from sweet sorghum. All brown processes are conventional processes that are replaced by bioethanol production in the syrup scenario. For a detailed scenario description see subchapter 3.1.3.

As shown in Fig. 4-19, a partially decentralised production system, however, leads to a slightly different composition of credits (about 7 t $CO_2$ equiv. / ha / yr) and expenditures (about 8.5 t $CO_2$ equiv. / ha / yr) compared to the cane fallow and the grain to food scenarios. Thus, in the syrup production scenario, additional greenhouse gas emissions of about 1.5 t $CO_2$ equiv. / ha / yr occur.

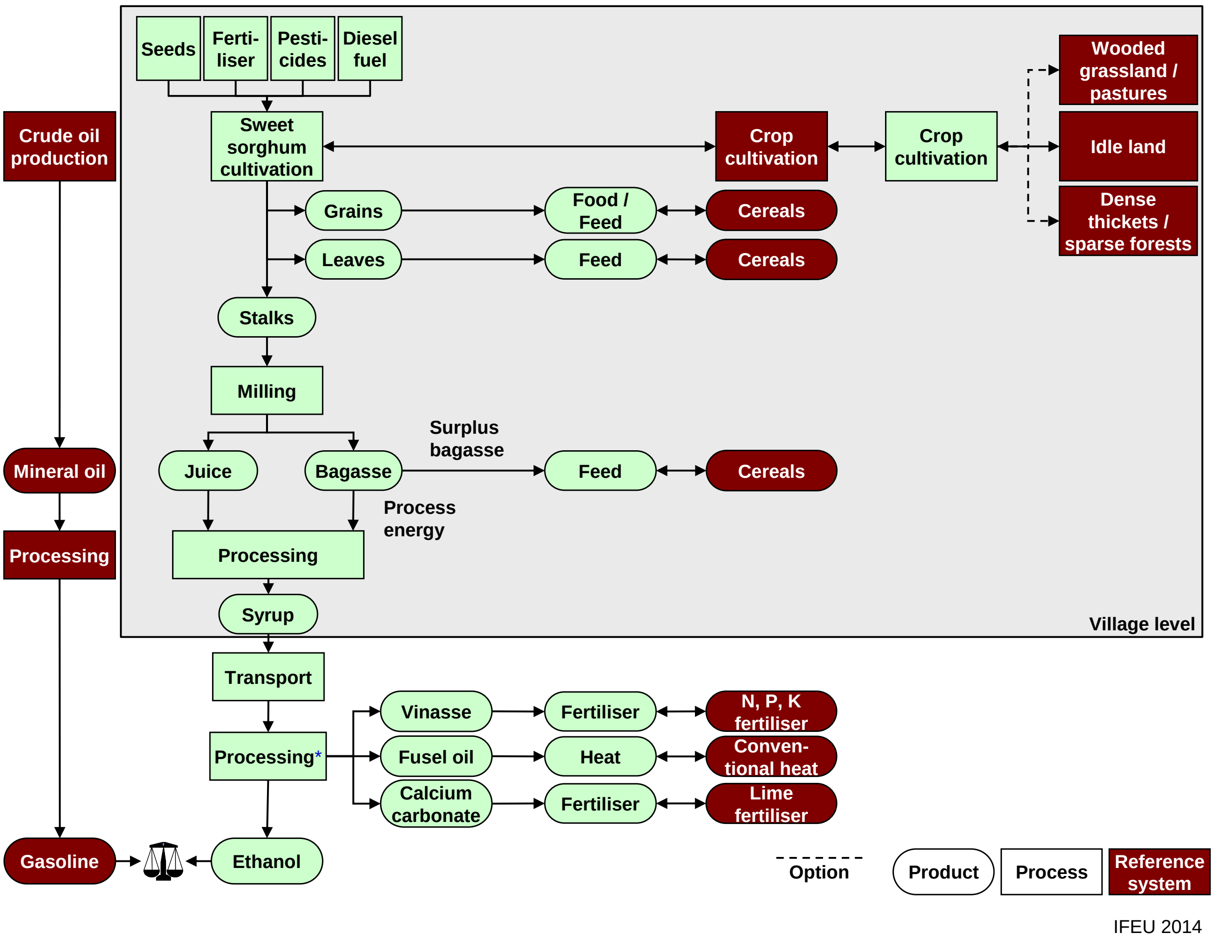


**Fig. 4-18** Schematic overview of sweet sorghum ethanol production in the syrup production scenario for decentralised production (for a summary, see Table 3-1). *For the ethanol production unit in the syrup scenario external energy carriers are needed which can either be fossil energy carriers (4 I) or rice straw (4 II).

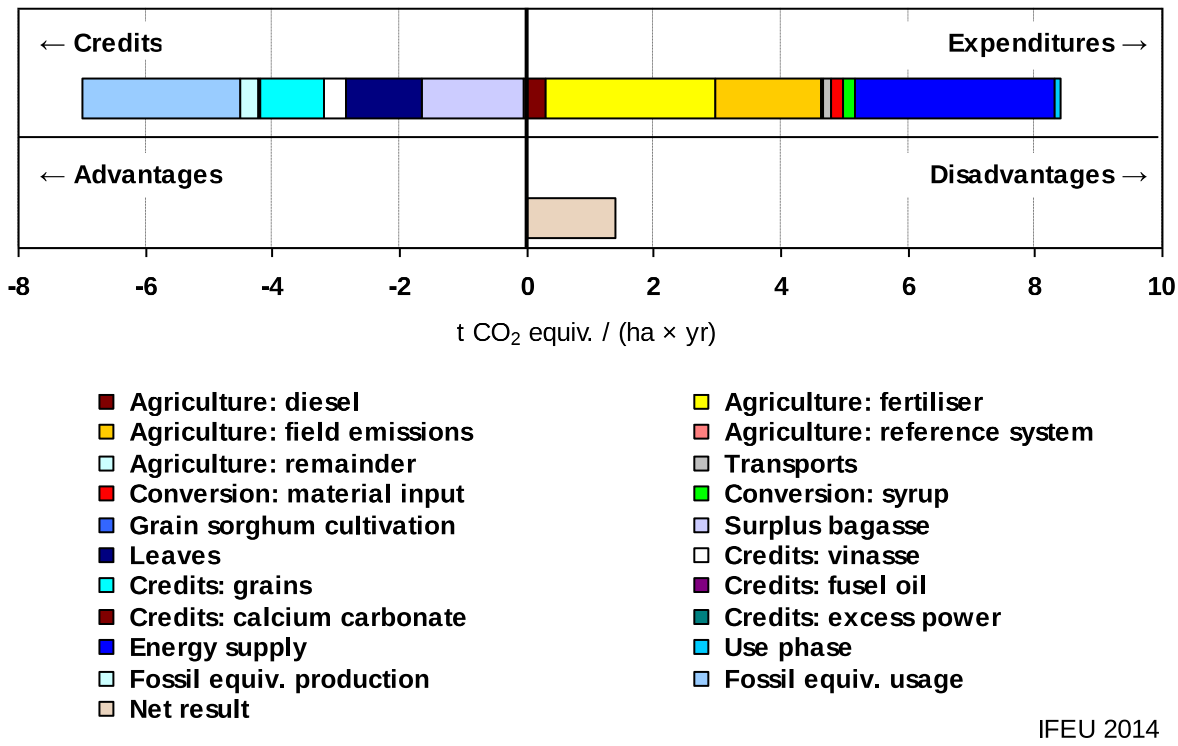


**Fig. 4-19** Contributions of individual life cycle steps (coloured bars) to the overall net result (light brown bar) of sweet sorghum ethanol production and use compared to the production and use of its fossil equivalent gasoline in the syrup production scenario for the environmental impact category greenhouse effect. Results are based on typical cultivation and conversion conditions defined for the syrup production scenario.

**How to read Fig. 4-19:**

If sweet sorghum bioethanol from 1 ha is used instead of conventional gasoline, credits (upper left bar) and expenditures (upper right bar) from different life-cycle steps add up to an additional release of about 1.5 tonnes of greenhouse gases per year (lower bar). More details regarding the individual contributions to credits and expenditures are explained in the text (subchapter 4.1.3.2).

### 4.1.3.1 Results of all environmental impact categories

In the syrup production scenario, not only the greenhouse gas balance of bioethanol production shows disadvantageous results, but also the balances of almost all other investigated impact categories. Thus, under most conditions, additional environmental burdens are caused in the environmental impact categories greenhouse effect, depletion of non-renewable energy resources, acidification, terrestrial and aquatic eutrophication, ozone depletion and human toxicity (Fig. 4-20). For the impact category photochemical ozone formation (summer smog) the results are more or less balanced. However, as already described for the other two scenarios, the data basis for the category photosmog is very uncertain. Furthermore, the amounts of given credits and expenditures are very similar, therefore only slight modifications in the base data for either the sweet sorghum ethanol or the fossil fuel life cycle may change the sign of the net result (versus advantage or disadvantage).

**Conclusions**

In case, sugar juice is converted into syrup locally and then further processed in a central conversion unit, bioethanol production and use from sweet sorghum shows disadvantageous results in almost all environmental impact categories compared to conventional gasoline. Regarding the categories greenhouse effect and resource depletion, this pattern differs from results shown for the cane fallow and grain to food scenario. Thus, great optimisation is needed to improve bioethanol production. As for the other two scenarios, results in the category photosmog cannot be considered as robust, thus, they are not further presented in the syrup production scenario.

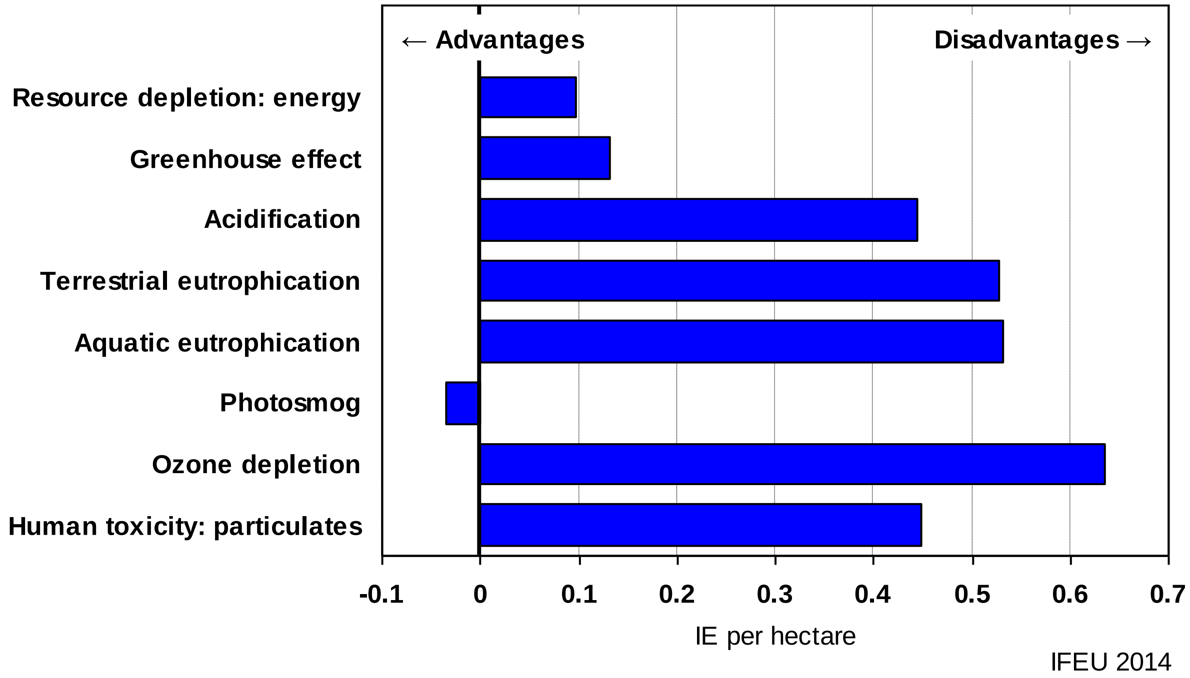


**Fig. 4-20** Net results for sweet sorghum bioethanol production in the syrup production scenario per hectare normalised to inhabitant equivalents (IE).

**How to read the first bar in Fig. 4-20:**

If bioethanol is produced from 1 ha sweet sorghum and replaces fossil gasoline, as much of non-renewable energy resources are additionally used as about 0.1 European inhabitants consume each year.

### 4.1.3.2 Influence of single life cycle stages

As already described in the cane fallow and grain to food scenarios (subchapters 4.1.1.2 and 4.1.2.2), there are important life cycle steps which should be optimised to improve bioethanol production from sweet sorghum. In most cases these important life cycle steps are the same for the syrup production scenario. Thus, in the impact category greenhouse effect (Fig. 4-21, greenhouse effect) credits are dominated by avoided environmental impacts which mainly derive from the substitution of gasoline through bioethanol ("Fossil equiv. usage") and by credits for the use of the by-products (surplus bagasse, leaves and grains). In contrast to the

other two scenarios, excess power does not occur, since here the additional heat is produced in boilers and not in a combined heat and power unit. Expenditures are especially dominated by fertilisation ("Agriculture: fertiliser", "Agriculture: field emissions") as it is the case for the cane fallow and the grain to food scenario. Additionally, however, in the syrup production scenario, a relatively large share of expenditures is caused by the life cycle step energy supply. This is because external energy carriers are needed for the conversion of syrup into ethanol, since the bagasse has already been used to boil down the sugar juice into syrup.

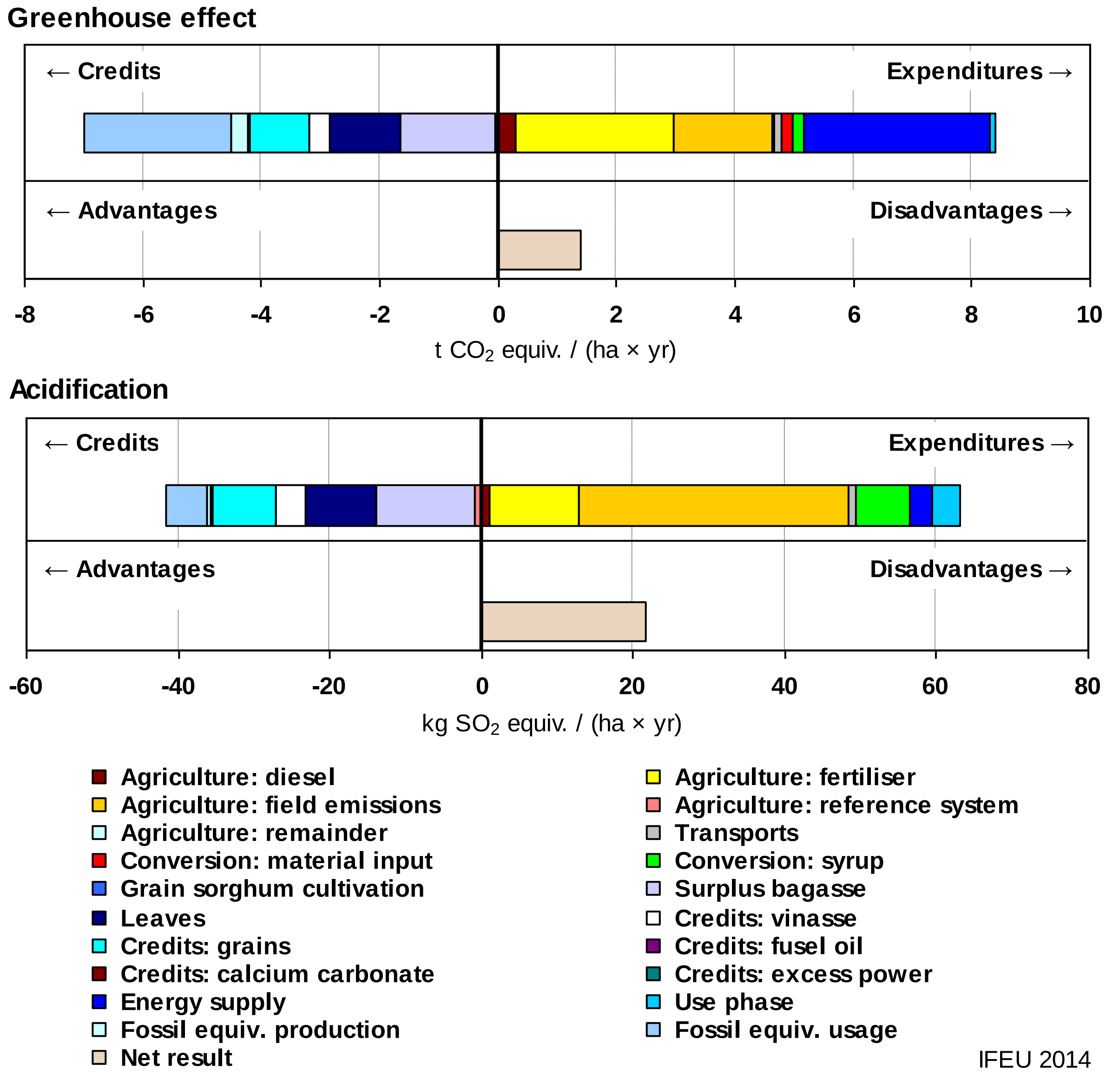


**Fig. 4-21** Contributions of individual life cycle steps (coloured bars) to the overall net result (light brown bar) of sweet sorghum ethanol production and use compared to its fossil equivalent gasoline in the syrup production scenario for the environmental impact categories greenhouse effect and acidification. Results are based on typical cultivation and conversion conditions. For further results see Annex, Fig. 8-5, 'Typical'.

The pattern for the impact category depletion of non-renewable energy resources looks similar, except that field emissions do not contribute to this category (Annex, Fig. 8-5, 'Typical'). For the impact category acidification (Fig. 4-21, acidification) important life cycle steps are the same as for the cane fallow scenario, whereas a large proportion of expenditures is caused by the process to boil down the sugar juice into syrup, since here bagasse is burned that causes high $SO_2$ and $NO_X$ emissions.

For the other categories terrestrial eutrophication, ozone depletion and human toxicity, the pattern is similar as for the category acidification (Annex, Fig. 8-5, 'Typical') except that the evaporation process is often not that important in the other categories and that the life cycle step "Fossil equiv. usage" is not that dominant in the category ozone depletion. The pattern for the impact category aquatic eutrophication (Annex, Fig. 8-5, 'Typical') is slightly different as already described for the cane fallow scenario (see subchapter 4.1.1.2.).

Thus, as for the other scenarios, the dominating life cycle steps are particularly relevant to numerous environmental impacts and therefore represent important starting points for optimising bioethanol production in the syrup scenario. The other life cycle steps have either no or only little influence on the analysed impact categories, thus, their optimisation potential is relatively low. This also includes the life cycle step "Transports" even though the transport distances are much higher (10 km for the distance from the field to syrup evaporation and 100 km from syrup evaporation to the central ethanol unit) than in the cane fallow and the grain to food scenarios. However, as already illustrated in subchapter 4.1.1.3 (Excursus: Transportation distance) a transport distance like this is still too small to have a significant impact on the considered categories.

To illustrate and discuss the optimisation potential of the dominating life cycle steps in the syrup production scenario, several sensitivity analyses were conducted. Some of them are analogue to the cane fallow and the grain to food scenario:

- Biomass production specific variations (including variations in biomass and sugar yield, fertiliser application, field emissions and extraction efficiency of the sugar juice)
- Conversion plant specific variations (conversion efficiency)

Besides, as for the cane fallow scenario a further sensitivity analysis was conducted to show the impact of different land use options.

Since in the syrup production scenario external energy carriers are needed, an additional sensitivity analysis was conducted to show the impact of rice straw on the overall result in comparison to fossil energy carriers.

**Conclusions**

Some life cycle stages are particularly relevant to the results of different environmental impact categories and therefore represent starting points for optimising bioethanol production from sweet sorghum. These include the same life cycle stages as already described for the cane fallow and the grain to food scenarios: fertilisation, field emissions, credits for the bioethanol output and the use of the by-products (bagasse, leaves, grains). (Continued on next page.)

(Continued) In case sugar juice from sweet sorghum is primarily concentrated into syrup, however, two further life cycle steps are relevant: energy supply and the conversion of sugar juice into syrup (“Conversion: syrup”). Thus, several sensitivity analyses were conducted to discuss all optimisation potentials of the relevant life cycle stages (see the following subchapter 4.1.3.3).

#### 4.1.3.3 Sensitivity analyses

This subchapter describes the results of different sensitivity analyses in the syrup production scenario.

**Biomass production**

In this section, the influence of different biomass yields on the overall results of the syrup scenario is described. Results for the impact categories greenhouse effect and acidification are illustrated in Fig. 4-22. Further results of the other investigated impact categories are shown in the Annex, Fig. 8-5.

As already described for the cane fallow and the grain to food scenarios, high yielding systems require a higher input of fertilisers; hence induce more emissions that lead to higher expenditures. Furthermore, in the syrup production scenario, higher yields and a higher extraction efficiency of the sugar juice lead to higher expenditures for the conversion process since more sugar juice needs to be boiled down into syrup. However, since in the syrup scenario expenditures are not outweighed by credits, higher yielding systems (as well as a higher extraction efficiency of the sugar juice) lead to additional greenhouse gas emissions in contrast to the other scenarios (Fig. 4-22). The result for a low yielding system (including a low extraction efficiency of the sugar juice), however, fluctuates around the baseline, thus, compared to conventional gasoline almost no additional environmental burdens are caused. For all other investigated impact categories, a similar pattern can be observed (see exemplarily Fig. 4-22, acidification), whereas the magnitude might differ.

**Conclusions**

Thus, unlike in the cane fallow and grain to food scenario, higher yields lead to disadvantageous results in case the sugar juice of sweet sorghum is primarily evaporated into syrup. As long as there are no optimisation arrangements to reduce especially the expenditures (e.g. by reducing the nutrient content of harvested biomass or by decreasing expenses from external energy carriers), aiming at higher yields should not be pursued in the first place.

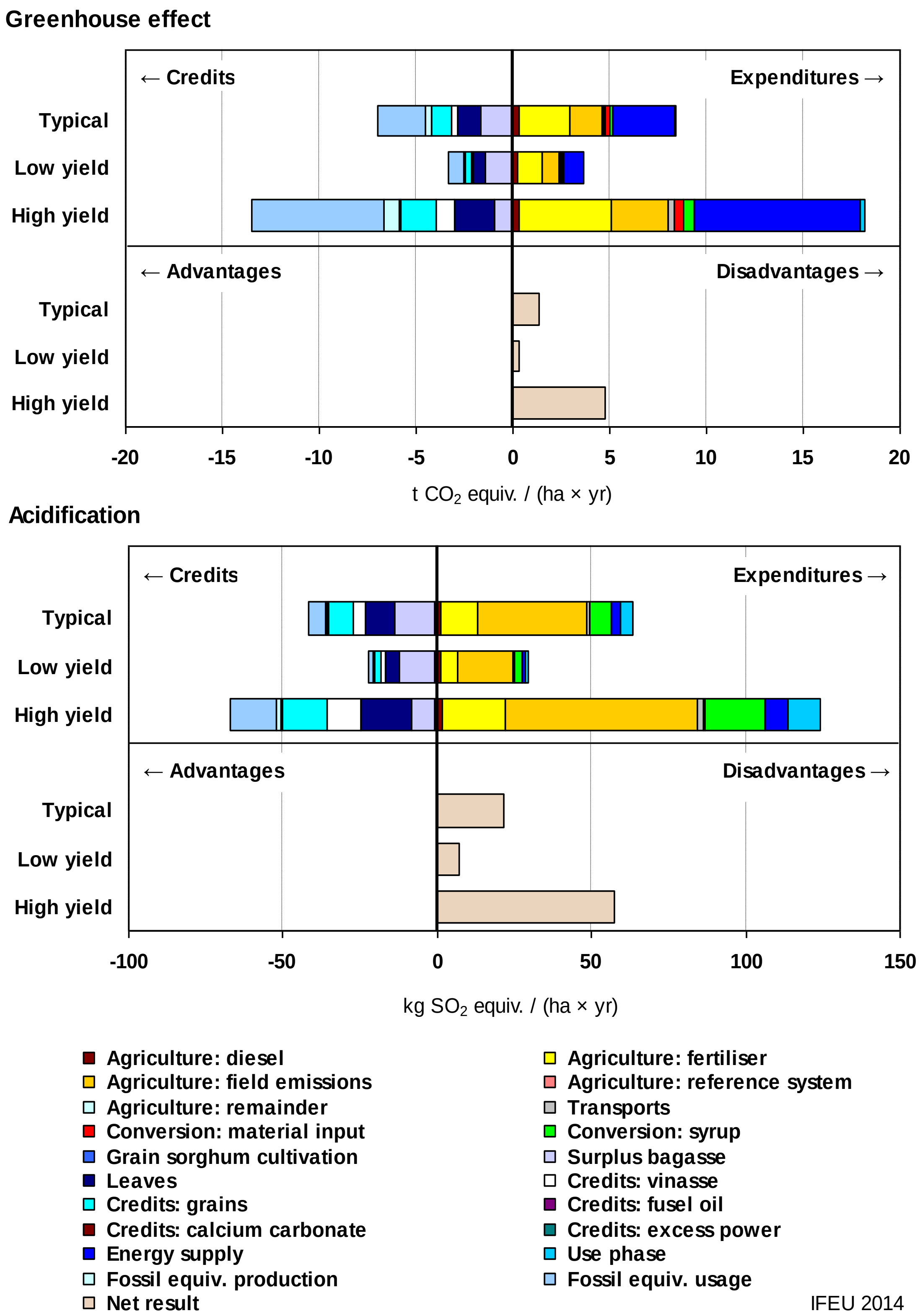


**Fig. 4-22** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) of sweet sorghum ethanol production and use compared to the production and use of its fossil equivalent gasoline in the syrup production scenario and under different biomass yield assumptions (low, high) for the impact categories greenhouse effect and acidification. For further categories see Annex, Fig. 8-5.

**Variation of conversion efficiencies**

This paragraph compares the influence of different conversion efficiencies on the overall results. For the impact categories greenhouse effect and acidification, results are illustrated in Fig. 4-23.

As already described for the cane fallow and the grain to food scenario, a high conversion efficiency means on the one hand that more ethanol per hectare per year can be gained out of one ton of sugar, on the other hand that less energy carriers (bagasse and conventional energy carriers) are needed to produce the same amount of energy. In the syrup production scenario a change in the conversion efficiency influences more or less the same life cycle stages as in the cane fallow scenario except that there is no excess power. Slightly better results can be observed if a higher conversion efficiency is assumed. In this case, the differences are pronounced slightly stronger in the syrup scenario than in the cane fallow and the grain to food scenario, since here the amount of bagasse needed to boil down the sugar juice into syrup is linearly increasing with the amount of sugar juice and does not even out. Thus, the higher the conversion efficiency, the less bagasse is needed for combustion and thus, more surplus bagasse can be credited.

**Conclusions**

As already described for the cane fallow and the grain to food scenarios, the higher the conversion efficiency in the syrup production scenario, the better the results of all environmental impact categories. However, even though differences between net results are slightly stronger pronounced in the syrup scenario, the impact of the conversion efficiency on the overall result is still small; thus, conversion efficiency comprises only a small potential for optimising bioethanol production.

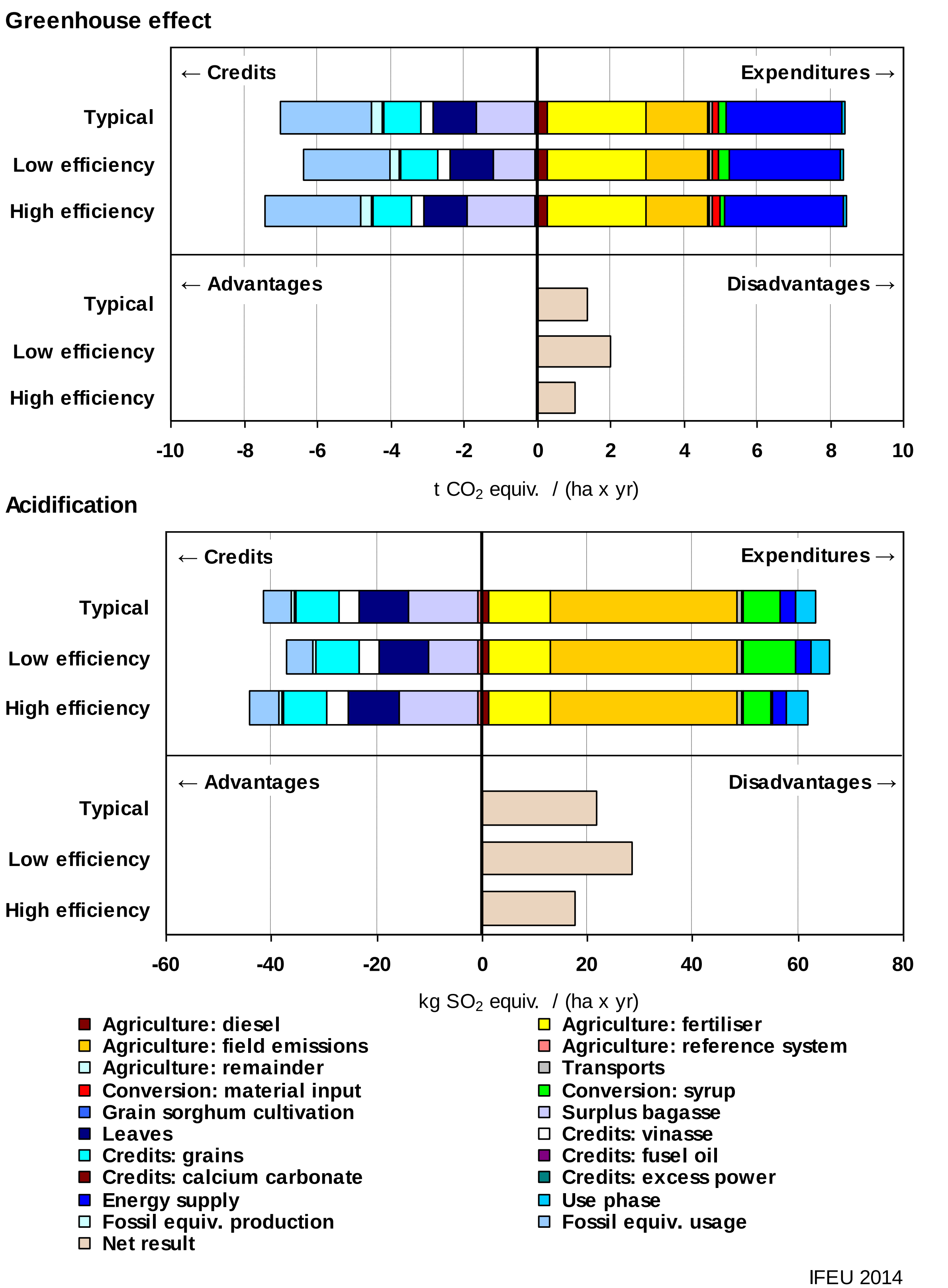


**Fig. 4-23** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) of sweet sorghum ethanol production and use compared to the production and use of its fossil equivalent gasoline in the syrup production scenario and under different conversion efficiency assumptions (low, high) for the impact categories greenhouse effect and acidification.

### Comparison of different energy carriers

This paragraph compares the influence of rice straw as external energy carrier on the overall results with the typical syrup production scenario. For the impact categories greenhouse effect and acidification, results are illustrated in Fig. 4-24.

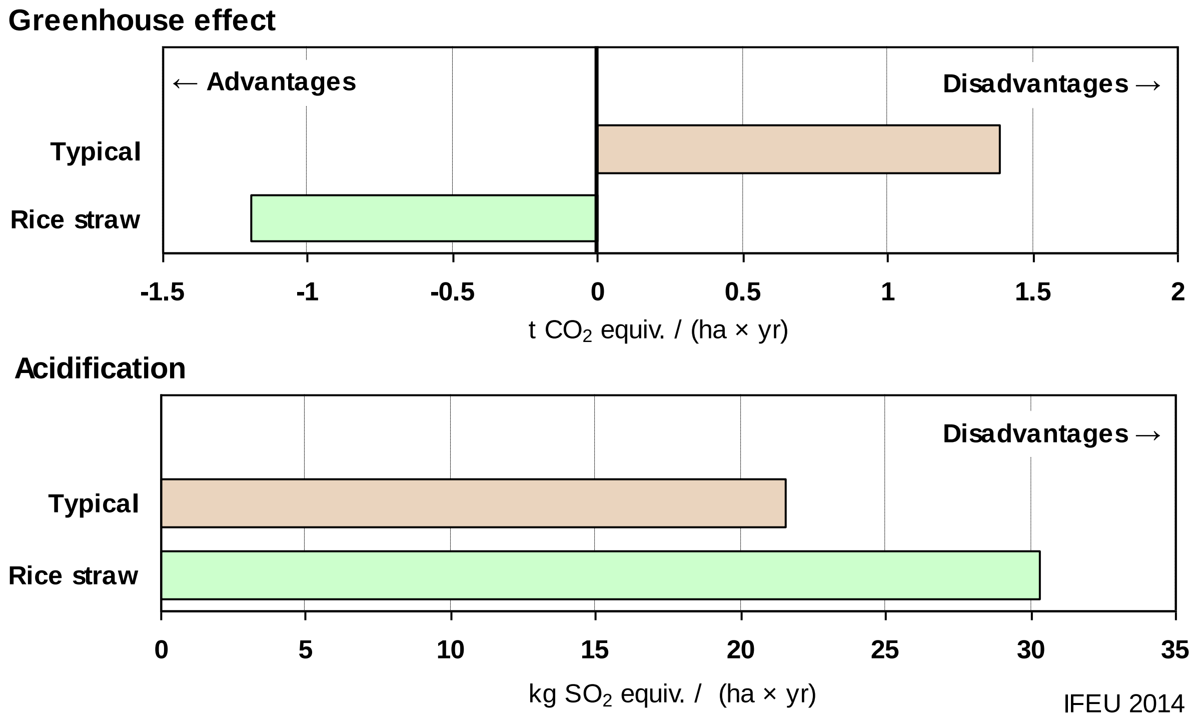


**Fig. 4-24** Comparison of the influence of rice straw as external energy carrier on the net results of sweet sorghum ethanol production with the typical syrup production scenario for the environmental impact categories greenhouse effect and acidification. Results are based on typical cultivation conditions defined for the syrup production scenario.

In the syrup scenario, external energy carriers are needed to produce ethanol from syrup since the bagasse has already been used to boil down the sugar juice into syrup. As shown in Fig. 4-24, the use of rice straw as external energy carrier can influence the balance of the impact category greenhouse effect decisively. If coal and fuel oil as energy carriers for the conversion process are used, as done in the typical scenario, additional burdens are caused. If, however, rice straw is used, greenhouse gases can be even saved since the combustion of rice straw is $CO_2$ neutral. The pattern for the impact category depletion of non-renewable energy carriers looks similar (Annex, Fig. 8-6). Regarding the impact category acidification (see Fig. 4-24, acidification), the use of rice straw causes more additional burdens than the use of fuel oil or coal. This is because the combustion of biomass emits generally more $NO_X$, which contributes strongly to this category, than fossil energy carriers. The same pattern can be observed for the other investigated impact categories except for aquatic eutrophication, which is not affected by rice straw as external energy carrier.

**Conclusions**

In the syrup production scenario external energy carriers are needed to convert sugar juice into ethanol since the bagasse has already been used to concentrate the sugar juice into syrup. Using e.g. rice straw as external energy carrier, affects the results of the category greenhouse effect decisively, thus, from a climate protection point of view a renewable energy resource out of residual products should be used where possible.

### Comparison of reference systems

This paragraph compares the contributions of different reference systems to the overall results for the impact category greenhouse effect (Fig. 4-25).

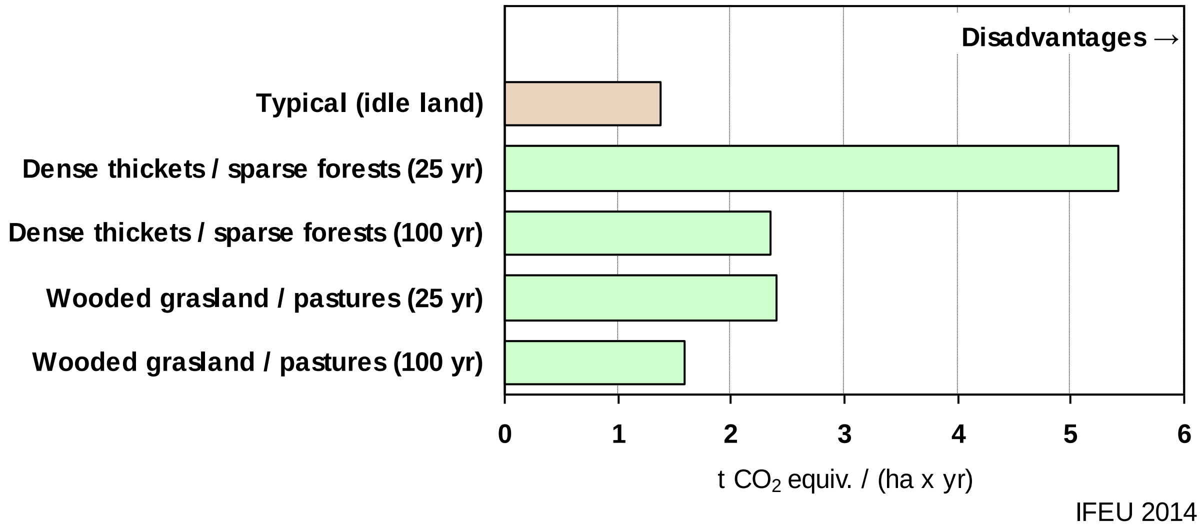


**Fig. 4-25** Comparison of the net results for different reference systems of sweet sorghum ethanol production and use in the syrup production scenario for the environmental impact category greenhouse effect. Carbon change is either amortised after 25 or 100 years. Results are based on typical cultivation and conversion conditions defined for the syrup production scenario.

As already shown for the cane fallow scenario, the choice of the cultivation area has a strong influence on the greenhouse gas balance: the higher the carbon stock of the natural vegetation, the higher are the carbon losses. If sweet sorghum is cultivated, hence, the higher are additional environmental burdens in the category greenhouse effect. Furthermore, compared to the typical scenario, a change in the carbon stock always shows disadvantageous results, no matter the time of amortisation.

**Conclusions**

If land cover changes are involved to cultivate sweet sorghum in the syrup production scenario, the outcome of the greenhouse gas balance of sweet sorghum ethanol compared to gasoline is the worse the higher the carbon stock of the area and the lower the amortisation rate. Thus, if a piece of land is converted for sweet sorghum cultivation, a reduction of the carbon inventory of this area must be prevented.

### 4.1.4 Bandwidths of sweet sorghum scenarios

In this subchapter the bandwidths of the sweet sorghum scenarios cane fallow, grain to food and syrup production are presented. The bandwidths are mainly based on the datasets (typical, low and high) defined in subchapter 3.1.4. Furthermore, the low, typical and high datasets also include additional parameters as specified in Table 4-1.

**Table 4-1** Summary of low, typical and high datasets for the sweet sorghum scenarios cane fallow, grain to food and syrup production.

| | **Cane fallow** | | | **Grain to food** | | | **Syrup** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low | Typical | High | Low | Typical | High | Low | Typical | High |
| **Transport distance** (to ethanol unit; [km]) | 100 | 30 | 30 | 100 | 30 | 30 | 100 | 100 | 30 |
| **By-products** | | | | | | | | | |
| Surplus bagasse | Fe | E | E | Fe | E | E | Fe | Fe | Fe |
| Grains | EtOH | EtOH | EtOH | F / F | F / F | F / F | F / F | F / F | F / F |
| Leaves | Fer | Fer | E | Fer | Fer | Fe | Fe | Fe | Fe |
| **External energy** | - | - | - | - | - | - | Fo | Fo | Rs |

Fe = feed; E = energy; EtOH = ethanol; Fer = fertiliser; F / F = feed or food; Fo = fossil energy carriers; Rs = rice straw

Fig. 4-26 shows a greater bandwidth for the cane fallow scenario than for the grain to food or the syrup production scenario. This is mainly due to greater variation possibilities regarding the use of the by-products (surplus bagasse and leaves to bioenergy) and due to a stronger impact of yield variations on the overall result in the cane fallow than in the other two scenarios. In total, about 15 t of $CO_2$ equivalents per hectare per year can be saved if sweet sorghum cultivation and use is optimised according to the considered measures within the bandwidth definitions.

For the syrup production scenario, a low yield and conversion efficiency not necessarily leads to disadvantageous results compared to the typical scenario since a low yield means the processing of less syrup and, thus, the need of less external energy carriers for conversion. Even a lower conversion efficiency cannot offset this advantage, thus net results are better in the low than in the typical scenario. As already described in subchapter 4.1.3.3, section ‘Comparison of different energy carriers’, the use of renewable residues such as rice straw as external energy carrier helps to save greenhouse gases in this scenario.

**Conclusions**

Compared to the grain to food and the syrup production scenario the highest optimisation potential can be observed for the cane fallow scenario, including high yields and conversion efficiencies as well as a use of leaves and surplus bagasse for bioenergy production. Optimisation potential is lower for the grain to food scenario since here yields are expected to be lower and the alternatives of by-product use are less manifold. For the syrup production scenario, the bandwidth is not as large as for the cane fallow scenario but optimisation measures can be decisive in order to make this scenario feasible from a climate protection point of view.

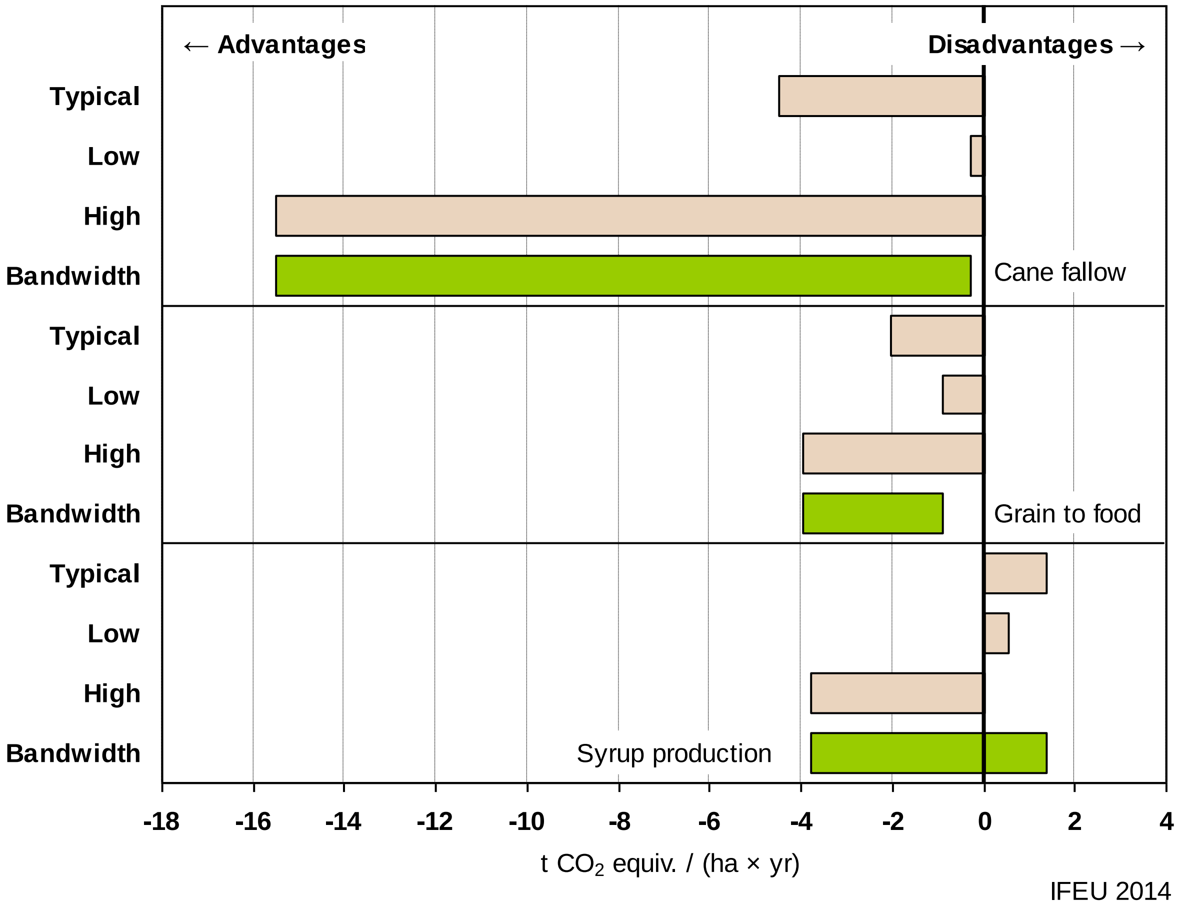


**Fig. 4-26** Bandwidths of net results (typical, low, high) for sweet sorghum bioethanol production in the impact category greenhouse effect for the sweet sorghum scenarios, cane fallow, grain to food and syrup production.

# 4.2 Biomass sorghum scenarios

This subchapter displays the results of the different biomass sorghum production and use systems investigated in this project. First, results of the biogas production scenario are presented (subchapter 4.2.1 and 4.2.2). Afterwards, the results of the alternative biomass use options are demonstrated and compared with the biogas production scenario (see subchapter 4.2.3).

## 4.2.1 Biogas production from biomass sorghum

First, for the biogas production scenario (CHP), the influence of different life cycle stages on the overall result is described exemplarily for one impact category. The results for all environmental impact categories including all sensitivity analyses are displayed afterwards in subchapters 4.2.1.1 to 4.2.1.3. The results of the other biogas use options are presented in subchapter 4.2.1.4.

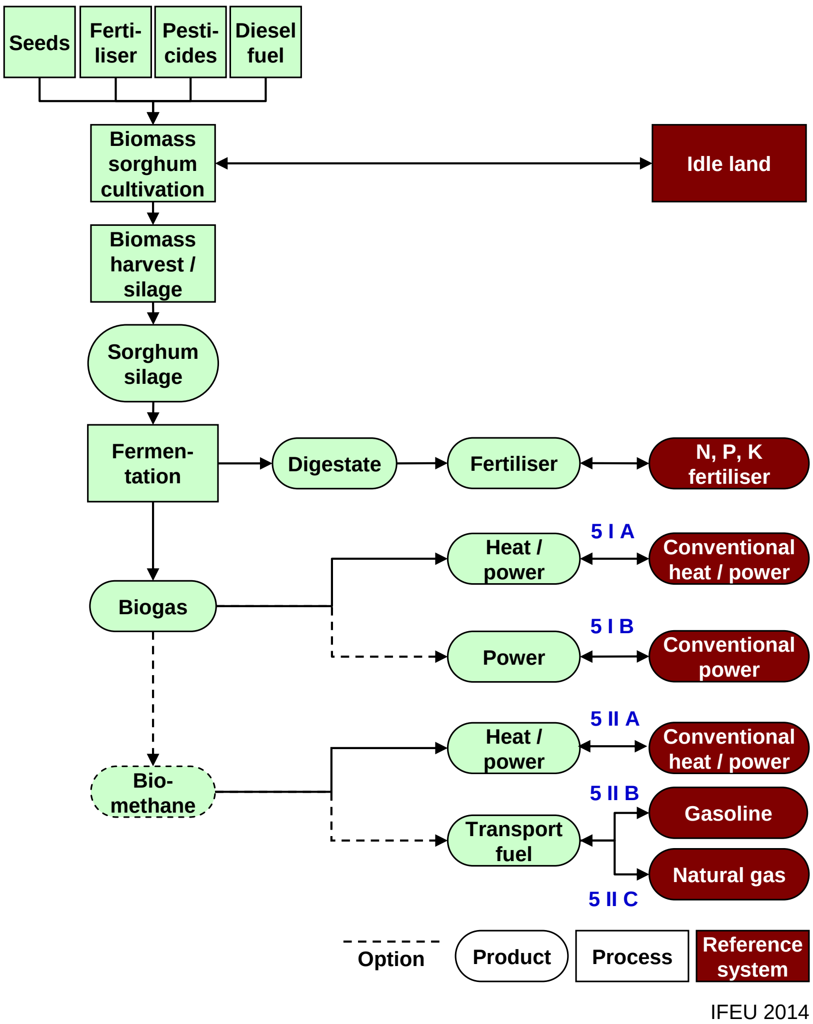


**Fig. 4-27** Schematic overview of biogas and biomethane production from biomass sorghum for the temperate climate; numbers indicate scenario numbers; for further descriptions see subchapter 3.2.1.

Fig. 4-27 depicts the entire life cycle of the biogas production scenario from biomass sorghum (including biomethane production). All light green processes arise if biogas is produced out of biomass sorghum. All brown production steps are conventional processes that are replaced by biogas production from biomass sorghum.

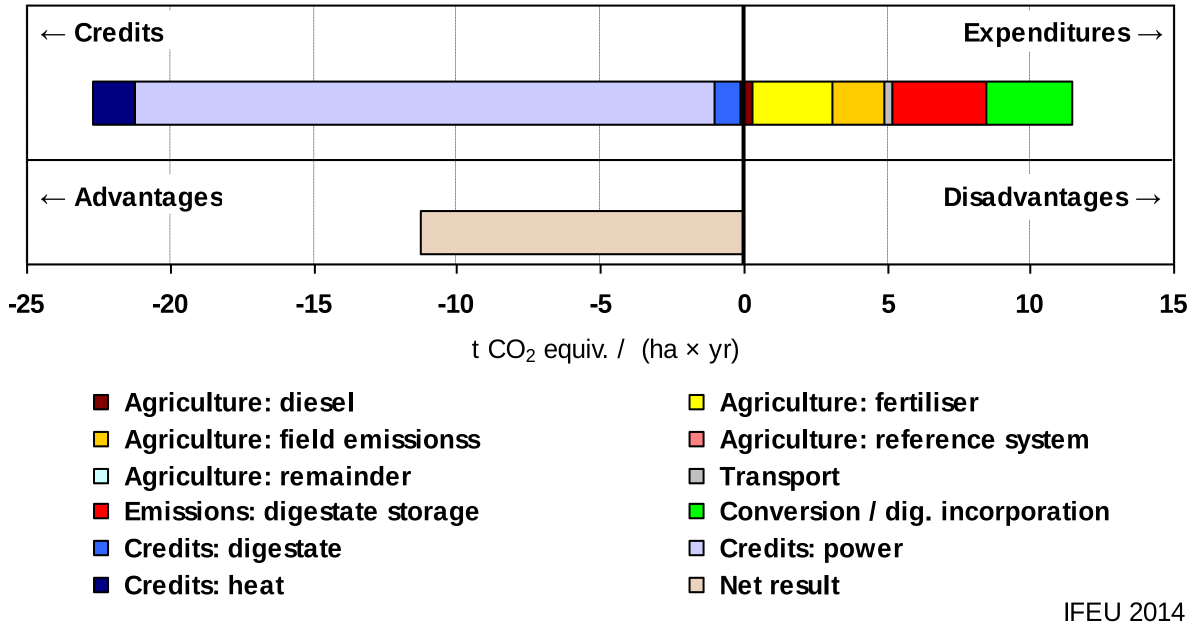


**Fig. 4-28** Contributions of individual life cycle steps (coloured bars) to the overall net result (light brown bar) of biogas production and use from biomass sorghum compared to the production and use of its fossil equivalent for the environmental impact category greenhouse effect. Results are based on typical cultivation and conversion conditions.

**How to read Fig. 4-28:**

If biomass sorghum cultivated on 1 ha is used for biogas production to generate heat and power instead of using fossil fuels, credits (upper left bar) and expenditures (upper right bar) from different life-cycle steps add up to a saving of about 11 tonnes of greenhouse gases per year (lower bar). More details regarding the individual contributions to credits and expenditures are explained in the text (subchapter 4.2.1.2).

The environmental impacts of this scenario are exemplarily shown for the impact category greenhouse effect in Fig. 4-28. Illustrated are impacts of individual life cycle stages (coloured sections of upper bars) and how they contribute to the overall results (brown bars) are illustrated. There are expenditures associated with each life cycle, which are depicted as positive (additional) emissions in Fig. 4-28. They arise from the light green processes in Fig. 4-27 for the production and use of biogas from biomass sorghum. The avoided emissions from the replaced processes (brown in Fig. 4-27) are credited to the biogas production and are thus depicted as negative emissions in Fig. 4-28. The net result is calculated in the way that the credits for the biogas production are subtracted from the expenditures. Thus, the net results show the amount of the impact category which can be saved or is caused by the use of biogas from biomass sorghum instead of a conventional product. For the impact category

greenhouse effect the net result is negative (-11 t $CO_2$ equiv. / ha / yr), which means that about 11 tons of greenhouse gases can be saved per hectare per year.

#### 4.2.1.1 Results of all environmental impact categories

Even though the greenhouse gas balance of biogas production and use from biomass sorghum shows advantageous results, biogas from biomass sorghum is not per se environmentally friendly, but causes also disadvantages for the environment. Thus, under most conditions, additional environmental burdens are caused in the environmental impact categories acidification, terrestrial and aquatic eutrophication and ozone depletion. Besides greenhouse effect, mitigation of environmental burdens is also achieved regarding the category depletion of non-renewable energy resources. Results of the categories human toxicity and photochemical ozone formation (summer smog) are more or less balanced (Fig. 4-29). For photosmog, however, the suggested models aggregating the potential ozone creating substances are still debated on among experts. Due to the complex chemical reactions involved in the troposphere ozone formation, base data in the category photosmog has a high uncertainty – different hydrocarbons have diverse characterisation factors and are very variable between different engines or processes that provide the same products or services. Furthermore, for both photosmog and human toxicity (here: particulate matter), the amounts of given credits and expenditures are very similar, therefore only slight modifications in the base data for either the biogas or the fossil fuel life cycle may change the sign of the net results (versus advantage or disadvantage).

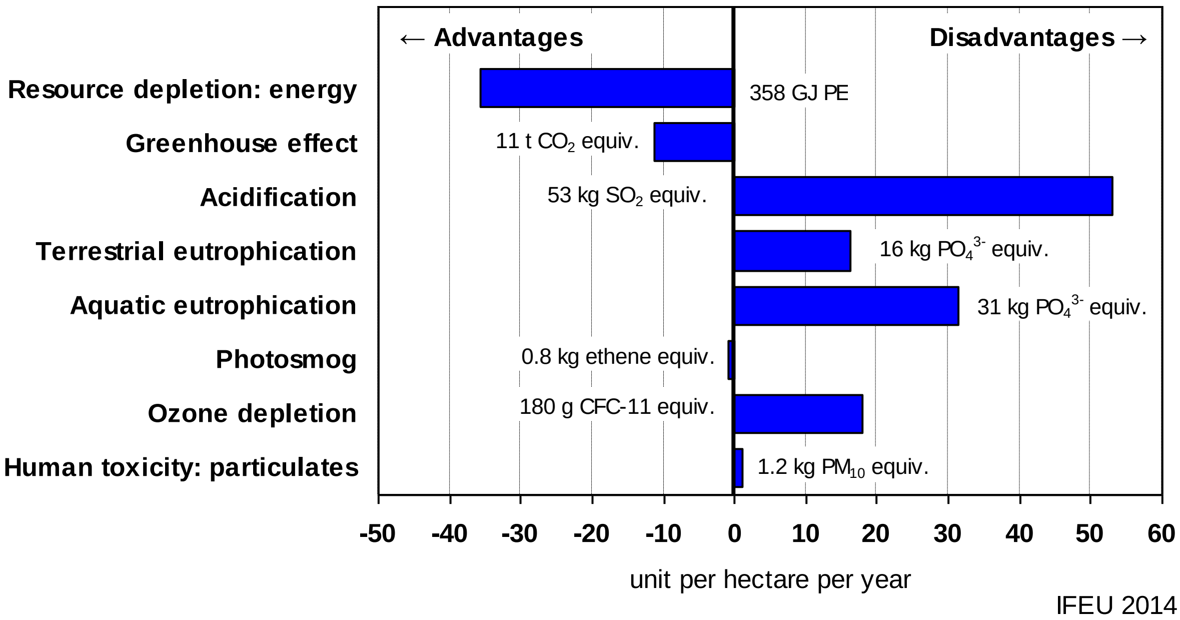


**Fig. 4-29** Net results for biogas production from biomass sorghum per hectare per year compared to gasoline. Results include all investigated environmental impact categories and are based on typical cultivation and conversion conditions.

**Conclusions**

Even though greenhouse gas and energy balances of biogas production and use from biomass sorghum show advantageous results compared to fossil fuels, biogas from biomass sorghum is not per se environmentally friendly, but causes also disadvantages for the environment. Thus, to improve biogas production from biomass sorghum, optimisation is necessary to reduce disadvantages and increase advantages. For the impact categories photosmog and human toxicity (particulate matter), the data basis is in part uncertain and the amounts of given credits and expenditures are very similar. Therefore the results cannot be considered as robust. Thus, the category photosmog is not further presented in the following subchapters.

**Results for decision makers**

If there are conflicts between advantageous results of a scenario in one environmental impact category and disadvantageous results in another category, the question comes up how to compare these figures. As specified in the methodology section (subchapter 2.2.2), a decision to accept certain disadvantages in favour of other advantages requires weighting on the basis of value-choices beyond scientific arguments, which is not done in this study. Nevertheless, a comparison of the magnitude, not the severity, of different impacts on a scientific basis can be done based on inhabitant equivalents. In this case, the impacts per space and time e.g. per hectare per year are compared (normalised) to the average annual impact that is caused by an inhabitant of the reference region (here European Union). For normalisation factors see Annex, subchapter 8.2.

Fig. 4-30 shows that the impact of all presented categories is in the same order of magnitude. In other words, there is no single result in an impact category that is extremely more disadvantageous or advantageous than the others.

**Conclusions**

As already shown in the previous subchapter, the production and use of biogas from biomass sorghum is either advantageous or disadvantageous for the environment compared to its fossil equivalent. Since, however, impacts of all presented categories are in the same order of magnitude, an objective decision for or against biogas from biomass sorghum can therefore not be made. However, based on a subjective value system a decision is possible: If, for example energy savings and greenhouse effect are given the highest priority, biogas from biomass sorghum performs better than its fossil equivalent.

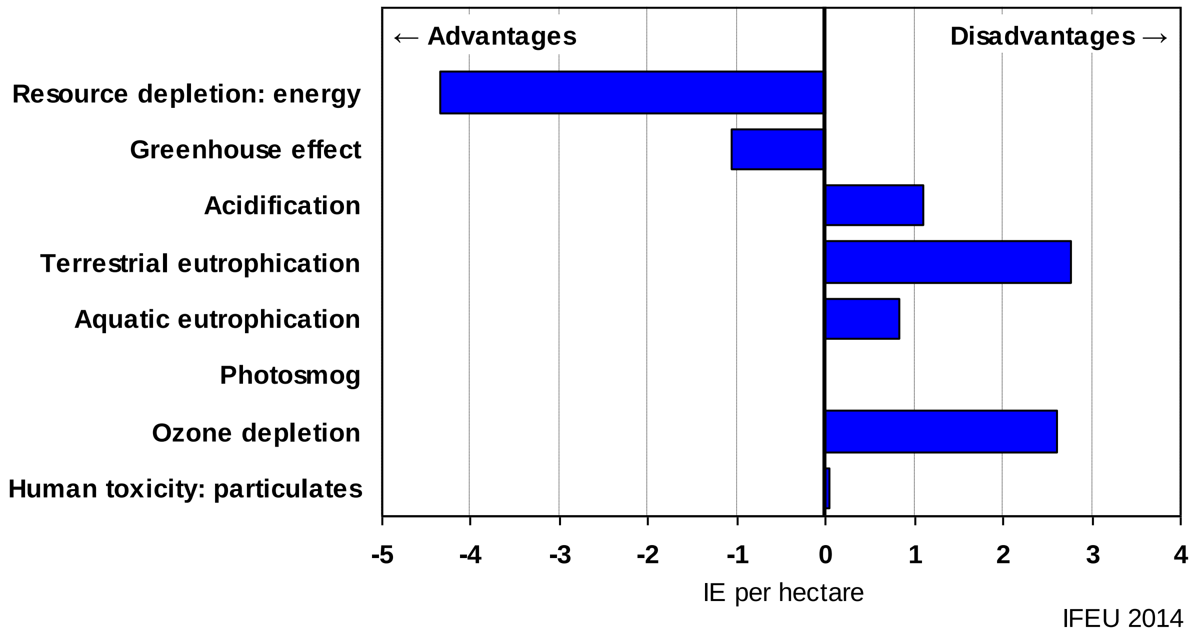


**Fig. 4-30** Overview of net results for the biogas scenario per hectare per year normalised to inhabitant equivalents (IE). Results include all investigated environmental impact categories and are based on typical cultivation and conversion conditions.

**How to read the first bar in Fig. 4-30:**

The production and use of biogas from biomass sorghum instead of fossil fuels saves per hectare as much of non-renewable energy resources as about 4.3 European inhabitants consume each year.

### 4.2.1.2 Influence of single life cycle stages

In order to identify important life cycle steps to optimise biogas production from biomass sorghum, the influence of different production steps on the overall outcome is described in the following.

In the impact category greenhouse effect (Fig. 4-31, greenhouse effect), credits are dominated by avoided environmental impacts which mainly derive from the substitution of conventional products through biogas for power generation ("Credits: power"). Expenditures are dominated by environmental impacts that occur during biomass cultivation ("Agriculture: fertiliser", "Agriculture: field emissions") or during the conversion of biomass into biogas ("Emissions digestate storage", "Conversion / dig. incorporation"). The contributions to the categories acidification (Fig. 4-32, 'Typical'), terrestrial eutrophication and ozone depletion are similar to those of the category greenhouse effect, even though the magnitudes of impacts may differ (Annex, Fig. 8-7, 'Typical'). The patterns of results for the categories depletion of non-renewable energy resources and aquatic eutrophication look slightly different (Fig. 4-31, resource depletion and aquatic eutrophication). For the impact category depletion of non-renewable energy resources, emissions from the field and the digestate storage are not detected. The impact category aquatic eutrophication (Fig. 4-31, aquatic eutrophication) looks different since it is mainly influenced by field emissions (due to $NO_3^-$ emissions, which are

caused by nitrification processes of ammonia by microorganisms in the soil) and the use of the by-product digestate (is used as fertiliser that leads to $NO_3^-$, but also reduces the amount of applied mineral fertilisers, thus saves $NO_3^-$ emissions during mineral fertiliser application).

The dominating life cycle steps are particularly relevant to numerous environmental impacts and therefore represent important starting points for optimising biogas production. The life cycle steps “Transports”, “Agriculture: diesel consumption”, “Agriculture: reference system” and “Agriculture: remainder” have either no or only little influence on the analysed impact categories, thus, the optimisation potential is relatively small.

To illustrate and discuss the potential of the dominating life cycle steps, the following sensitivity analyses are conducted:

- Biomass production specific variations (including variations in yield, fertiliser application, field emissions)
- Conversion plant specific variations (including conversion efficiency, $CH_4$ emissions, heat usage, type of digestate storage and time of digestate incorporation)
- Variation of substituted conventional energy carriers

Furthermore, an excursus shows whether a larger transportation distance influences the net results of the investigated impact categories significantly.

**Conclusions**

Some life cycle stages are particularly relevant to the results of numerous environmental impact categories and therefore represent starting points for optimising biogas production from biomass sorghum. These often include fertilisation (especially nitrogen fertilisation), field emissions (influenced by fertilisation), the storage of the digestate and the time until digestate incorporation. Another optimisation variable in most categories is represented by credits given for the avoided expenses for the production and use of fossil energy carriers. Thus, several sensitivity analyses are conducted to discuss the optimisation potential of the relevant life cycle stages.

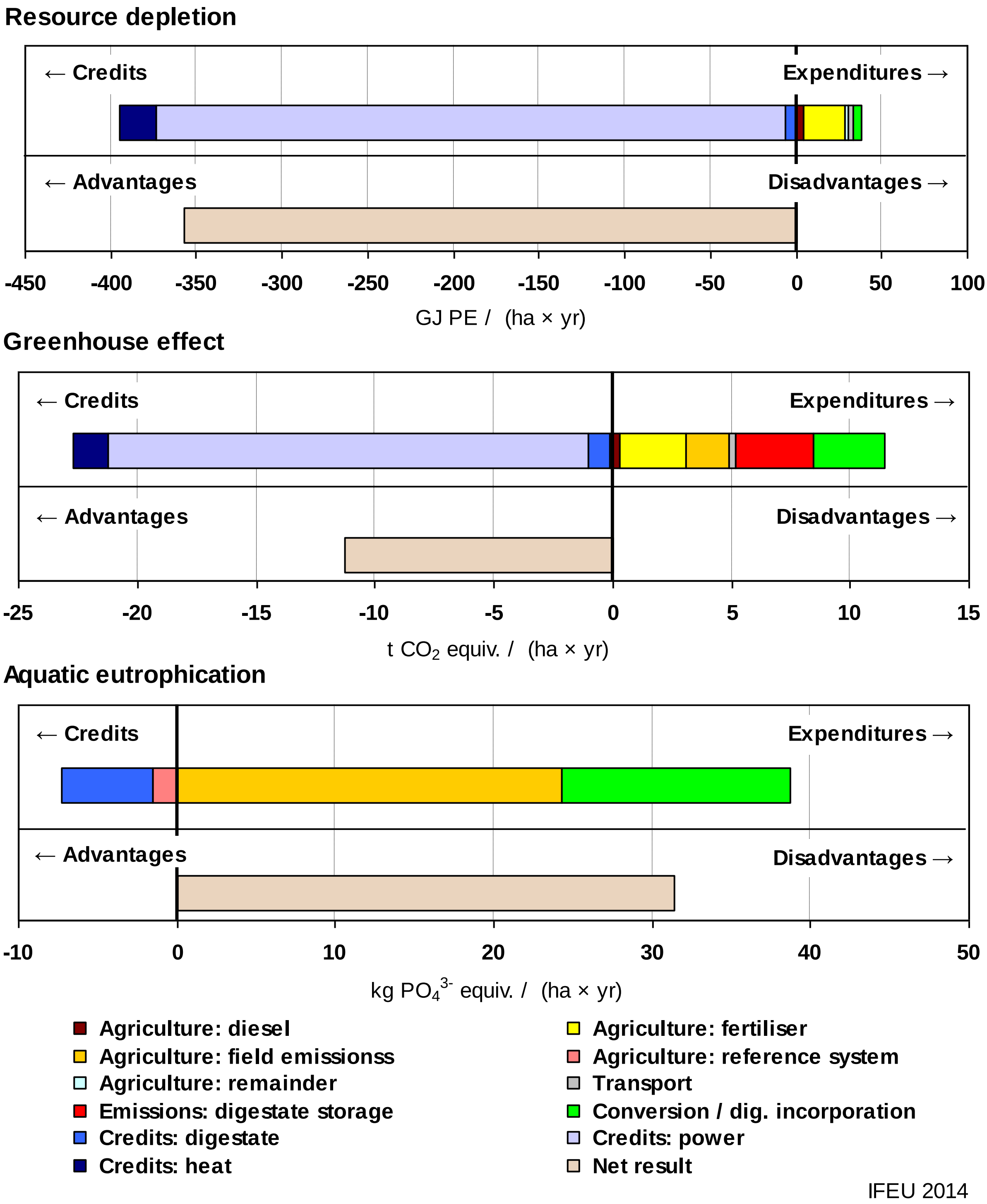


**Fig. 4-31** Contributions of individual life cycle steps (coloured bars) to the overall net result (light brown bar) of biogas production and use from biomass sorghum compared to the production and use of its fossil equivalent for the environmental impact categories depletion of non-renewable energy resources, greenhouse effect and aquatic eutrophication. Results are based on typical cultivation and conversion conditions. For further categories, see Annex, Fig. 8-7, 'Typical'.

#### 4.2.1.3 Sensitivity analyses

This subchapter describes the results of different sensitivity analyses conducted in the biogas scenario.

**Biomass production**

In this section the influence of different biomass yields on the overall results of biogas production is described. Results for the impact categories greenhouse effect and acidification are illustrated in Fig. 4-32. Further results of the other investigated impact categories are shown in the Annex, Fig. 8-7.

Generally, high yielding systems require a higher input of fertilisers; hence induce more emissions that lead to higher expenditures. Furthermore, higher yields also lead to higher expenditures for the conversion process since more biomass needs to be converted. However, as shown in Fig. 4-32, category greenhouse effect, these higher inputs and emissions are far outweighed by higher credits for heat and power generation due to a higher biogas output. The overall result is strongly advantageous. A similar pattern can be found for the category depletion of non-renewable energy resources (Annex, Fig. 8-7, resource depletion). Thus, an increase of biomass yield leads to higher savings of greenhouse gases and fossil energy carriers. In contrast, low biomass yields lead to fewer savings.

For the impact categories acidification, terrestrial and aquatic eutrophication and ozone depletion, however, high yielding systems lead to additional environmental burdens since the extra credits for a higher biogas output still cannot outweigh higher expenditures for cultivation and conversion (exemplarily Fig. 4-32, acidification, other categories: Annex, Fig. 8-7).

**Nutrient content in the harvested biomass**

Since expenditures in general are especially influenced by the amount of applied mineral fertilisers (particularly nitrogen fertiliser) and associated field emissions, one way to reduce expenses could be the reduction of the needed amount of applied fertilisers. However, the amount of fertilisers is calculated according to sustainable cultivation practices (amount of fertiliser = nutrient removal + losses, see Annex, Table 8-1), thus, a reduction can only be reached by decreasing the amount of nutrients removed from the field since then less mineral fertiliser is needed to be applied. Fig. 4-33 shows an example how big the impact of a decreased amount of applied fertilisers, hence of nutrients that are removed from the field can be. A decreased amount of applied fertilisers leads to higher savings of greenhouse gases and energy resources. Particularly strong, however, is the influence of a reduced fertiliser input on the other impact categories, thus, additional burdens can be reduced significantly.

**Conclusions**

The production and use of biogas from biomass sorghum saves more greenhouse gases and fossil energy carriers the higher the biomass yield of biomass sorghum. Thus, one option to optimise biogas production from biomass sorghum includes aiming at higher yields. However, higher yields also lead to additional environmental burdens in the other impact categories investigated. Since all categories are strongly influenced by the amount of applied mineral fertilisers (especially N fertiliser), another optimisation potential is to reduce the nutrient content in the harvested biomass.

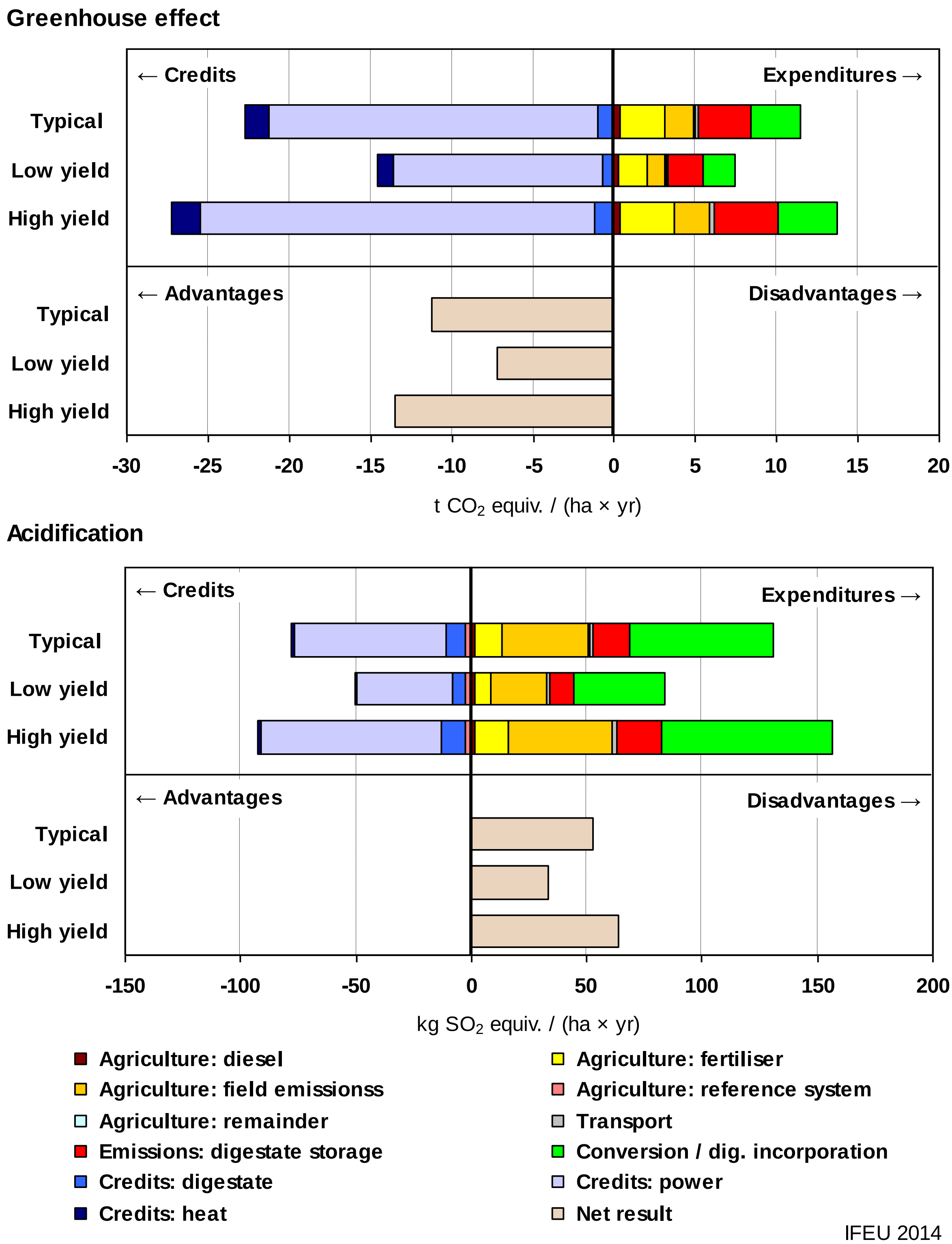


**Fig. 4-32** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) of biogas production and use from biomass sorghum compared with the production and use of its fossil equivalent under different biomass yield assumptions (low, typical, high) for the impact categories greenhouse effect and acidification. For further categories see Annex, Fig. 8-7.

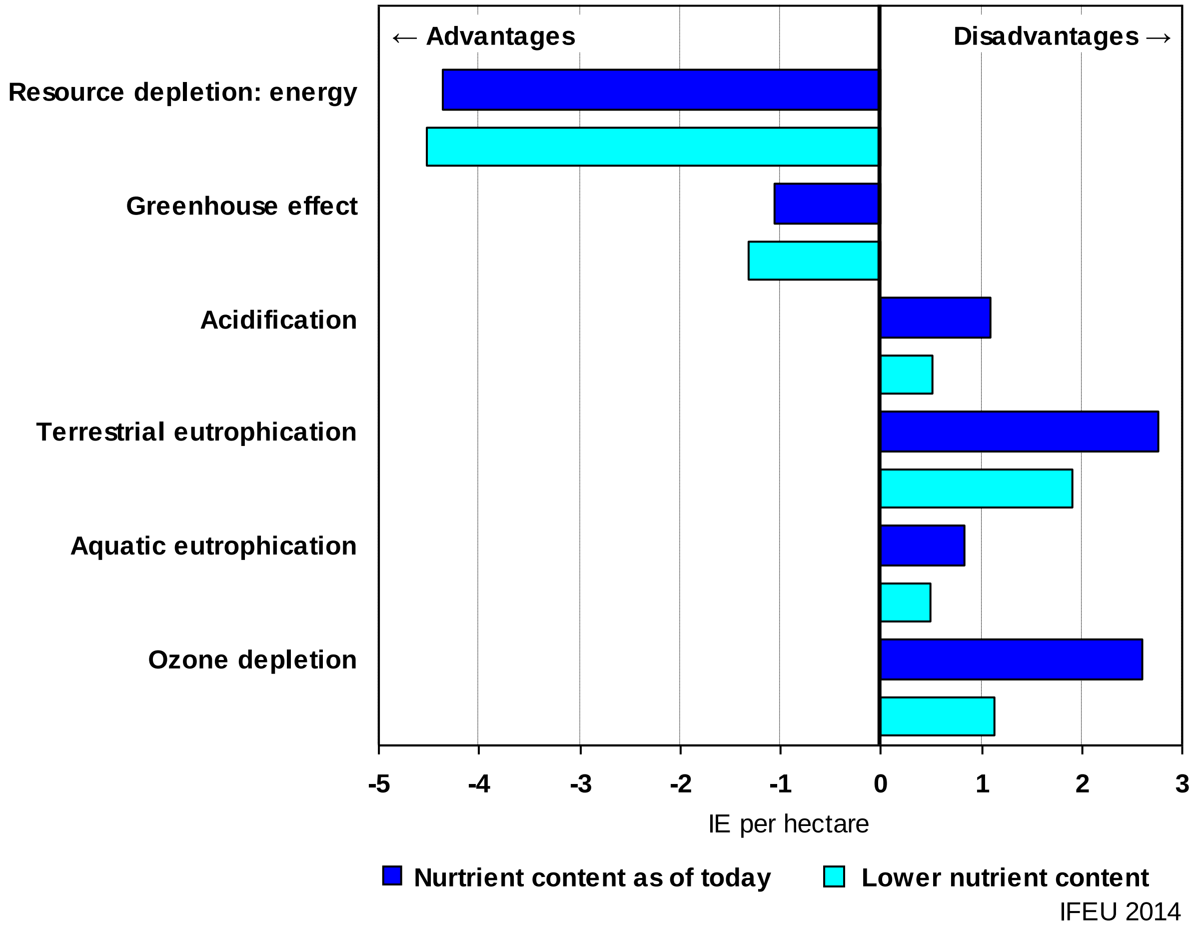


**Fig. 4-33** Net results of the investigated environmental impact categories for biogas production and use from biomass sorghum compared with the production and use of its fossil equivalent separated by different amounts of applied mineral fertilisers, hence a different nutrient content in the harvested biomass. Results are based on typical cultivation and conversion conditions defined for the biogas scenario.

### Conversion plant specific variations

In this section, the influence of conversion plant specific variations on the overall results of biogas production is presented. Results for the impact categories depletion of non-renewable energy resources, greenhouse effect and acidification are illustrated in Fig. 4-34. Further results of the other investigated impact categories are presented in the Annex, Fig. 8-8.

As described in subchapter 3.2.5 and summarised in Table 4-2, typical, low and high datasets were defined to show conversion plant specific variations. The low dataset includes low conversion efficiencies, an open digestate storage tank, high $CH_4$ emissions, an incorporation of the digestate into the soil after 24 hours and a heat utilization rate of 20 %. The high dataset, however, represents high conversion efficiencies, a covered, gas-tight digestate storage tank, thus, no $CH_4$ emissions, an incorporation of the digestate into the soil after 1 hour and a heat utilization rate of 80 %. The typical dataset corresponds to the current state of the art as it is standard e.g. in Germany at the moment.

**Table 4-2** Summary of typical, low and high conversion plant specific variations for biomass sorghum biogas production.

| | **Typical** | **Low** | **High** |
|---|---|---|---|
| Conversion efficiency | $eta_{el}$: 37.5 %<br>$eta_{th}$: 43 % | $eta_{el}$: 32 %<br>$eta_{th}$: 52 % | $eta_{el}$: 41 %<br>$eta_{th}$: 43 % |
| Heat utilisation | 20 % | 20 % | 80 % |
| Digestate storage | open | open | closed |
| CH4-emissions | 2.5 % | 15 % | 0 % |
| Digestate incorporation | 24 h after application | 24 h after application | 1 h after application |

The **conversion efficiency** mostly varies with conversion plant size. Usually, the larger the plant, the better the electrical and thermal efficiency and the higher the biogas output per hectare per year (see Fig. 4-34, especially “Credits: power”). Thus, for almost all investigated impact categories, a higher conversion efficiency also leads to better results. Slightly higher emissions due to bigger gas engines used in larger conversion plants are therefore of no consequence. The only exception is the category aquatic eutrophication since here only biomass cultivation related emissions are of relevance, thus, the conversion efficiency shows no impact on the overall result of this category (Annex, Fig. 8-8, aquatic eutrophication).

The **heat utilisation** rate especially influences the life cycle step “Credits: heat”. Thus, the more heat from a combined heat and power unit can be utilised the more fossil energy carriers can be avoided. This especially affects the overall results of the impact categories greenhouse effect and depletion of non-renewable energy resources (Fig. 4-34). All other categories are either not or only little influenced by the degree of heat utilisation (Annex, Fig. 8-8).

An open **digestate storage** tank emits a great amount of greenhouse gases. A reduction of **$CH_4$ emissions** from 15 % to 2.5 % can already change the overall result of the greenhouse gas balance from negative to positive (Fig. 4-34, greenhouse effect). However, even more greenhouse gases can be saved if the digestate storage tank is closed completely gas-tight so that no $CH_4$ is emitted anymore. For the impact categories terrestrial eutrophication (Annex, Fig. 8-8) and acidification (Fig. 4-34, acidification) a closed digestate storage also affects the balances positively, due to the avoidance of a great amount of ammonium emissions from the digestate. The results of the categories depletion of non-renewable energy resources (Fig. 4-34, resource depletion), aquatic eutrophication and ozone depletion (Annex, Fig. 8-8) are either not or only little influenced by the type of the digestate storage and the amount of $CH_4$ emissions.

The time between **digestate** application and **incorporation** is highly correlated with the amount of $NH_3$ emissions. The earlier the digestate is incorporated after application, the lower are the $NH_3$ emissions. This especially influences the balances of the impact categories acidification (Fig. 4-34, acidification) and terrestrial eutrophication (Annex, Fig. 8-8) since both categories are strongly influenced by $NH_3$ emissions. Furthermore, an earlier incorporation of the digestate also increases credits for the digestate since more mineral fertiliser can be saved if less nutrients are lost before incorporation. Together with the reduction of $NH_3$ emissions through a closed digestate storage the overall result in the category acidification is more or less balanced, thus compared to conventional energy carriers the production and use of biogas out of biomass sorghum shows no additional burdens anymore. The overall

result of all other impact categories are either not or only little influenced by the time of digestate incorporation.

**Conclusions**

To gain optimised conversion conditions for biogas production from biomass sorghum, digestate storage tanks should be covered and closed gas-tight. Additionally, the digestate should be incorporated into the soil within 1 hour. Furthermore, the biomass should be converted in large conversion plants with high electrical and thermal efficiencies. Heat utilisation in the conversion plant should be as high as possible.

**Fig. 4-34** (next page): Comparison of conversion plant specific variations of biogas production and use from biomass sorghum for the impact categories depletion of energy resources, greenhouse effect and acidification. For further categories see Annex, Fig. 8-8. For plant specific variation details see Table 4-2.

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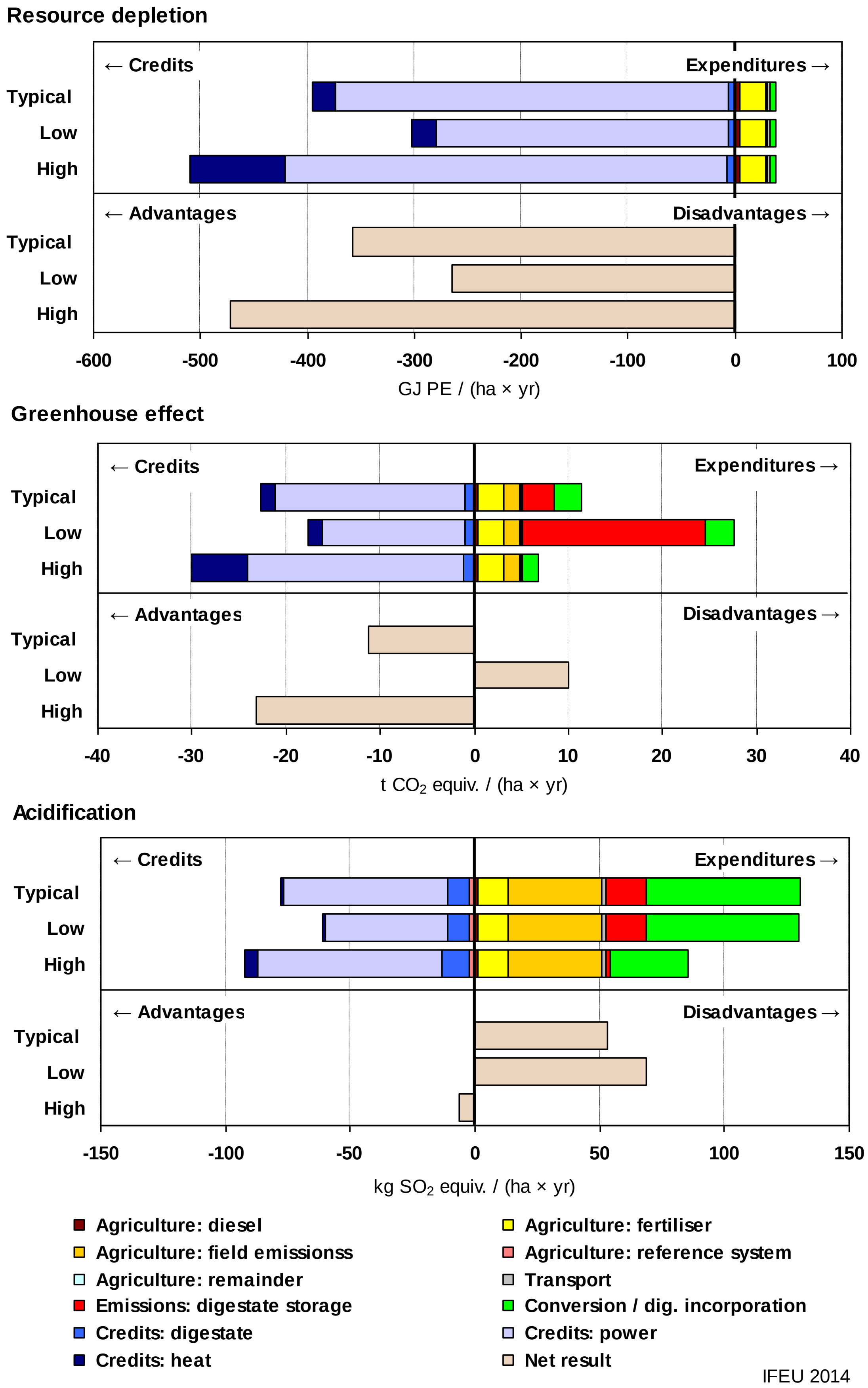
Resource depletion
← Credits
Expendityres →
Typical
Low
High
← Advantages
Disadvantages →
Typical
Low
High
-600 -500 -400 -300 -200 -100 0 100
GJ PE / (ha × yr)
Greenhouse effect
← Credits
Expenditures →
Typical
Low
High
← Advantages
Disadvantages →
Typical
Low
High
-40 -30 -20 -10 0 10 20 30 40
t $CO_2$ equiv. / (ha × yr)
Acidification
← Credits
Expenditures →
Typical
Low
High
← Advantages
Disadvantages →
Typical
Low
High
-150 -100 -50 0 50 100 150
kg $SO_2$ equiv. / (ha × yr)
Agriculture: diesel
Agriculture: fertiliser
Agriculture: field emissionss
Agriculture: reference system
Agriculture: remainder
Transport
Emissions: digestate storage
Conversion / dig. incorporation
Credits: digestate
Credits: power
Credits: heat
Net result
IFEU 2014

### Variation of substituted conventional energy carriers

In this section, the influence of different substituted conventional energy carriers on the overall result of the biogas scenario is presented. Results for the impact categories greenhouse effect and acidification are illustrated in Fig. 4-35.

Depending on the substituted energy carrier and the environmental impact category, the credits for the avoided expenses of the fossil energy carriers can be higher or lower. The differences are almost entirely due to variations of credits given for the power supply. If a higher proportion of coal is replaced, which emits a great amount of $CO_2$ during combustion, the greenhouse gas balance shows more advantageous results than if natural gas is substituted (Fig. 4-35, greenhouse effect). The more fossil carbon is emitted during combustion, the more can be saved if replaced and the better is the greenhouse gas balance. Substituting coal is also advantageous for the net results of the categories depletion of non-renewable energy resources, terrestrial eutrophication and acidification. In the impact category acidification (Fig. 4-35, acidification), substituting coal reduces the additional environmental burdens by decreasing $SO_2$ emissions in a way that the net result is more or less balanced. Thus, compared to conventional gasoline, biogas production from biomass sorghum shows no further environmental harm. For the impact categories ozone depletion and aquatic eutrophication, the type of the energy carrier has either no or only little impact.

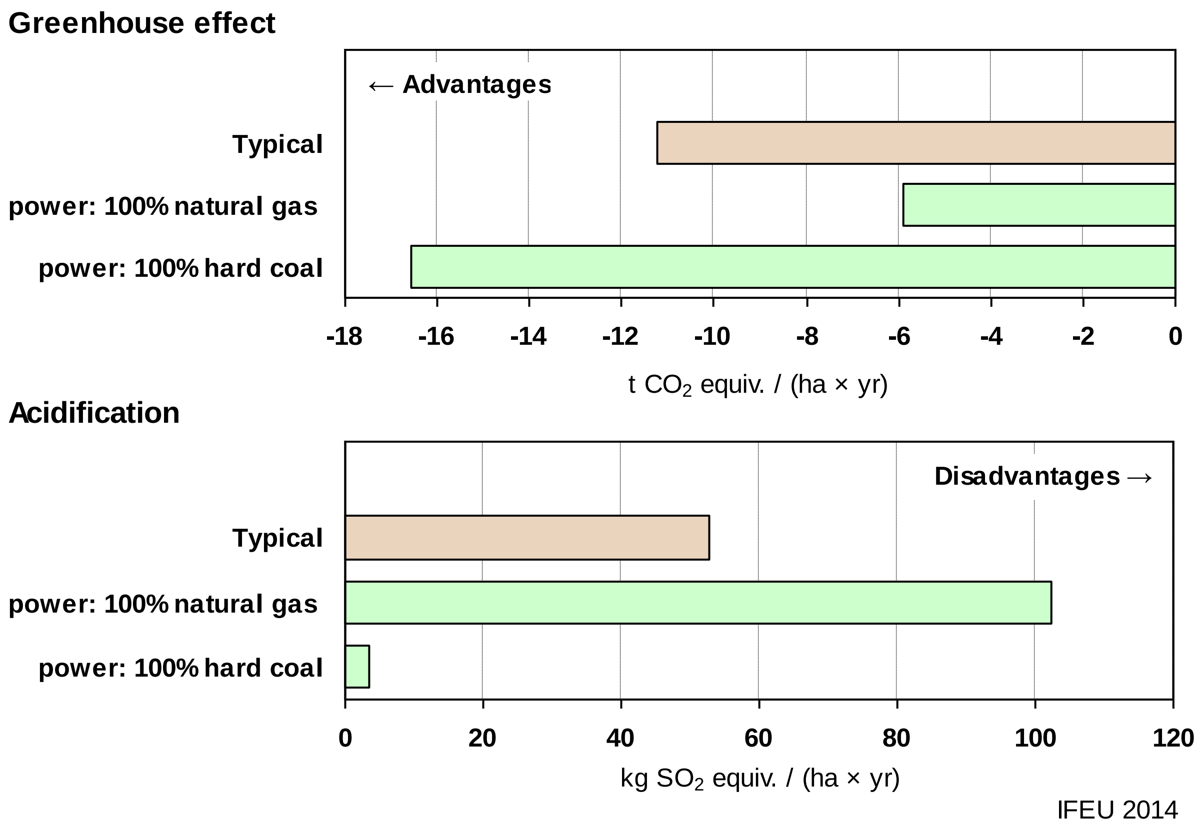


**Fig. 4-35** Comparison of different substituted conventional energy carriers for biogas production from biomass sorghum for the impact categories greenhouse effect and acidification. Results are based on typical cultivation and conversion conditions.

**Conclusions**

The more fossil carbon, emitted during the combustion of the fossil energy carrier, can be saved, the more advantageous is the outcome of the biomass sorghum balances in most investigated impact categories. This means that wherever it is possible to replace coal as a fossil energy carrier, more advantageous results are obtained. However, since the energy carrier can mostly not be influenced by the plant operator, the general optimisation potential to improve biogas production from biomass sorghum is relatively low. Nevertheless, a biogas production shows advantageous results especially in countries where coal is the main source of power supply.

**Excursus: Variation on transport distances**

In the biogas scenario, the mean transport distance from the field to the central biogas production unit is considered as 30 km. However, since this distance could be much longer in some regions, we also analysed if a longer transport distance (100 km) has an impact on the investigated impact categories. However, as depicted in Fig. 4-36, a longer transportation distance has only little influence on the impact category greenhouse effect. A similar pattern can be found for the other investigated categories.

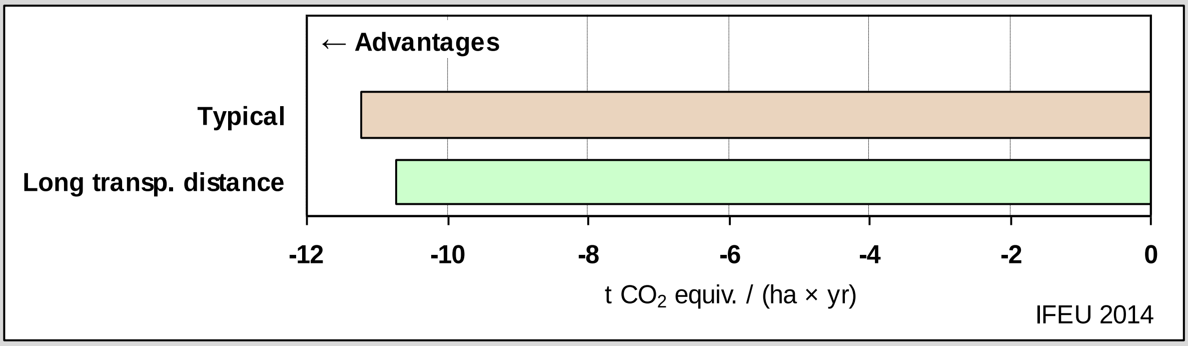


**Fig. 4-36** Comparison of net results for biogas production from biomass sorghum in the typical biogas production scenario with a long transport distance variation.

**Conclusions**

The transportation distance of harvested biomass from field to the central biogas production unit has only little influence on the outcome of all investigated impact categories.

#### 4.2.1.4 Comparison of biogas use options

Besides the production of biogas and its use in a combined heat and power (CHP) production unit, biogas can also be used for power production only. Alternatively, the biogas can be further processed into biomethane and used either for heat and power production, as transport fuel or as a natural gas substitute. A schematic overview of these scenarios is also given in Fig. 4-27. For a detailed scenario description see subchapter 3.2.1.

To make a comparison between biogas and biomethane pathways reasonable, the biogas production scenario was also calculated under the same conversion assumptions as the biomethane scenario. This includes that the digestate storage is covered gas-tight and that 100 % of the produced heat can be used. These assumptions, however, do not necessarily

correspond to typical biogas plants in Europe, thus, the typical scenario, defined before in this report, slightly differs.

Fig. 4-37 exemplarily shows how the different biogas use options affect the impact categories greenhouse effect and acidification. This and additional results in the Annex (Fig. 8-9) show that the pattern of environmental advantages and disadvantages are similar for all use options. Yet, the magnitudes of impacts can differ substantially.

- Most greenhouse gases can be saved if biogas is produced under the same conditions as biomethane, since for the biomethane production less credits for the power production can be obtained. This is because additional energy is needed to refine biogas into biomethane. The energy is covered by using power out of the production process, thus no extra expenses are caused but fewer credits are given for power production.
- If biogas is used for power production only, less greenhouse gases can be saved than if biogas is used in a combined heat and power unit (typical scenario) since no credits for heat production can be given.
- The usage of biomethane in a CHP unit saves more greenhouse gases than a usage of biomethane as natural gas substitute or as fuel since the conversion is less efficient.

The pattern looks similar for the impact category depletion of non-renewable energy resources (Annex, Fig. 8-9, resource depletion). For the impact category acidification biogas production shows less additional environmental burdens compared to the other use options if biogas is produced under the same assumptions as biomethane, mainly due to higher credits for a heat utilisation of 100 %. Additional burdens in this category are particularly high if biomethane is used as natural gas substitute. This is because the substituted natural gas inherently emits comparatively low amounts of $SO_2$ and $NO_X$, thus only little credits are given for avoided expenses (Fig. 4-37, acidification). The patterns for the impact categories terrestrial eutrophication and ozone depletion look similar except for the biomethane as fuel scenario since here less additional burdens are caused due to comparatively high emissions of $NO_X$ and $N_2O$ during fuel combustion (Annex, Fig. 8-9). The different biogas use options have no real impact on the category aquatic eutrophication since the cultivation of biomass sorghum and the amount of the produced digestate are more or less the same for all biogas pathways (Annex, Fig. 8-9, aquatic eutrophication).

**Conclusions**

From an environmental perspective, biogas from biomass sorghum and its use in a CHP unit should be favoured over other biogas use options, as far as biogas from biomass sorghum is produced under the same assumptions as biomethane. In case biogas is further refined into biomethane, the use of biomethane in a combined heat and power unit should be favoured over a use as a natural gas substitute or fuel.

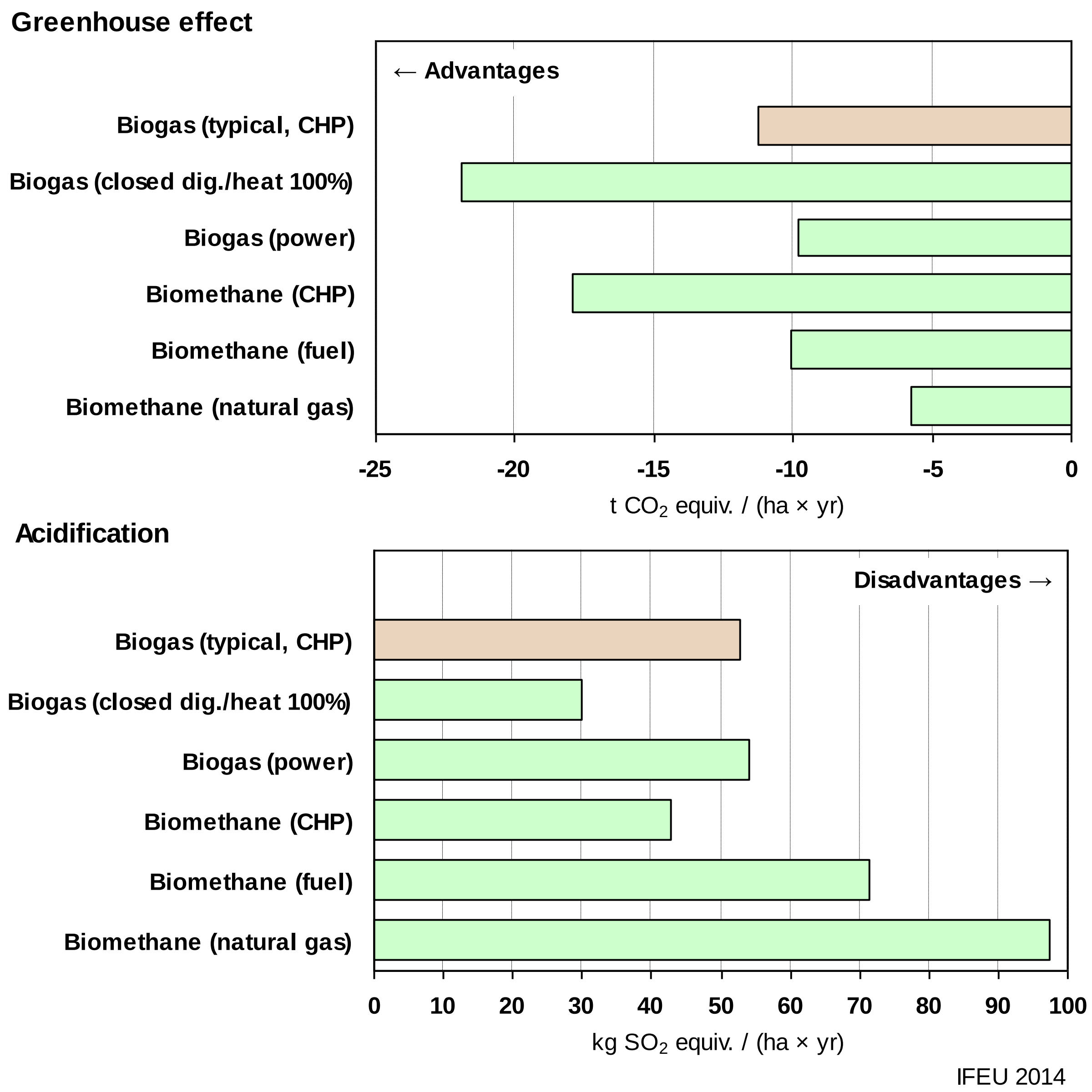


**Fig. 4-37** Comparison of different biogas use options in the impact categories greenhouse effect and acidification. For further categories see Annex, Fig. 8-9. Results are based on typical cultivation and conversion conditions.

### 4.2.2 Bandwidth of biogas production

In this subchapter the bandwidth of the biogas production scenario is presented. The bandwidth is based on the typical, low and high datasets defined in subchapter 3.2.5. Furthermore, for the low dataset also a high transportation distance (100 km) was assumed while in the typical and high datasets a distance of 30 km was set.

Fig. 4-38 shows an enormous bandwidth of net results for the biogas production scenario ranging from additional environmental burdens in the impact category greenhouse effect to savings of up to 28 t of $CO_2$ equiv. per hectare per year in case of the high dataset. Differences are mainly due to variations in the type of the digestate storage and in the time of di-

gestate incorporation. In addition, more greenhouse gases can be saved if the yield is higher and the transportation distance is as short as possible.

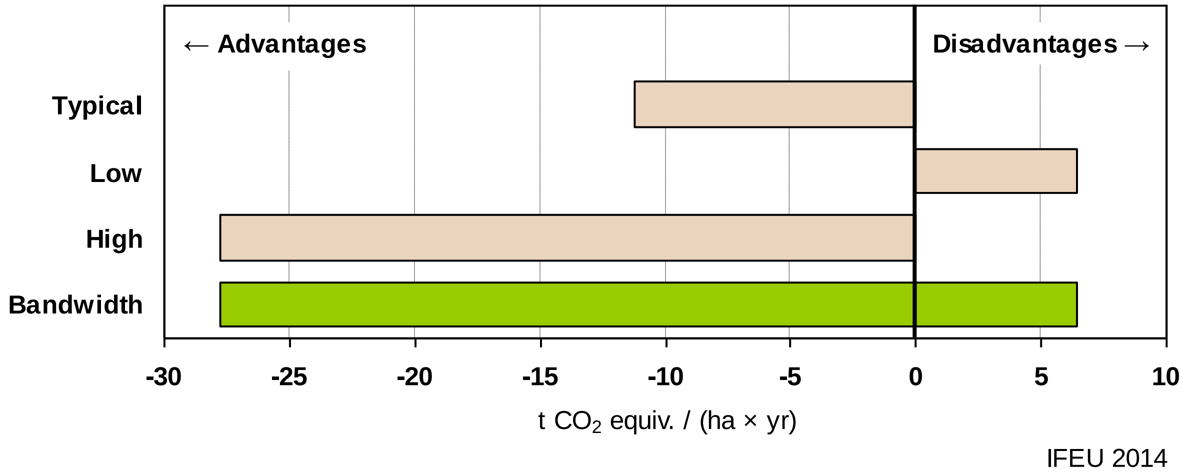


**Fig. 4-38** Bandwidths of net results (typical, low, high) of the biogas production scenario for the impact category greenhouse effect.

**Conclusions**

The bandwidth of net results for the biogas production scenario is enormous. Thus, in total a high optimisation potential and / or measures exist: Most important and easy to implement is a gas tight coverage of the digestate storage tanks and a prompt incorporation of the digestate into the soil after its application.

### 4.2.3 Alternative bioenergies from biomass sorghum

In this subchapter the results of alternative bioenergies from biomass sorghum are presented and compared with biogas production. Alternative bioenergies include the production of ethanol from the lignocellulose fraction of biomass sorghum, the conversion of biomass into energy via direct combustion and the gasification of the biomass either directly or after pyrolysis. The direct combustion process is divided into different subsequent use options: direct combustion combined with a CHP unit or direct combustion combined with power or heat production only. For the direct combustion scenario with heat production only, the substituted heat can also differ: either the substituted heat is generated from the marginal mix (50 % fuel oil) or from 100 % fuel oil. All these alternative bioenergies are illustrated and described in detail in subchapters 3.2.2 to 3.2.4. To see also how biogas production as described in the previous subchapter (closed digestate storage tanks, 100 % heat utilisation) performs in comparison to the alternative bioenergies this biogas production scenario is also included in this section.

Fig. 4-39 exemplarily compares the performance of biogas production with the **direct combustion** scenarios regarding the impact on the category greenhouse effect:

- The direct combustion of biomass and its use in a combined heat and power unit saves more greenhouse gases than the production of biogas even if the digestate

storage is closed and the heat utilisation rate is 100 % (Fig. 4-39, greenhouse effect). This is mainly due to a more efficient conversion that leads to higher energy gain.

- The other direct combustion scenarios perform slightly poorer than the 'optimised' biogas production scenario, except if the substituted energy carrier is pure fuel oil since here more carbon is emitted during combustion compared to the combustion of the typical mix of energy carriers applied in the other scenarios.
- If the typical biogas scenario is considered, direct combustion scenarios perform either similar or better due to higher emissions from the digestate storage during biogas production.

Results for the impact category depletion of non-renewable energy carriers slightly differ in detail due to a different ratio regarding carbon and energy content of different fossil energy carriers (such as natural gas or fuel oil) (Annex, Fig. 8-10, resource depletion).

In the impact category acidification (Fig. 4-39, acidification) the 'optimised' biogas production shows about the same additional environmental burdens than the direct combustion option (CHP). For the category terrestrial eutrophication (Annex, Fig. 8-10, terrestrial eutrophication), however, an 'optimised' biogas production shows slightly higher disadvantages than the direct combustion use options (CHP and power only) since slightly higher $NO_X$ emissions during combustion of the biomass are far outweighed by much higher $NH_3$ emissions from digestate application.

For the impact category ozone depletion, both biogas production scenarios perform better than the direct combustion scenarios, since more $N_2O$ is emitted during the combustion process than during biogas conversion. Furthermore, in the direct combustion scenario, more $N_2O$ emissions are observed, since no digestate occurs that can replace mineral fertiliser (Annex, Fig. 8-10, ozone depletion). For the impact category aquatic eutrophication (Annex, Fig. 8-10, aquatic eutrophication), however, the handling of the digestate in the biogas scenarios leads to higher additional burdens compared to the other scenarios since fertilisation using digestate instead of mineral fertiliser emits a greater amount of $NO_3^-$ that leads to higher expenditures in this category.

If biogas production and direct combustion are compared it should be kept in mind that these results are based on the premise that the biomass is left on the field until the water content of the biomass is low enough to burn the biomass directly without drying step. Results may change significantly if a drying step for the biomass is necessary.

Furthermore, Fig. 4-39 also compares the performance of biogas production with the production of **second generation ethanol** and **Fischer-Tropsch (FT) fuels** regarding the impact on the category greenhouse effect:

- Compared to biogas production, both the production of second generation ethanol and FT fuels, lead to considerably fewer savings of greenhouse gases per hectare of cultivated area (Fig. 4-39, greenhouse effect). The performance is worse mainly due to a more efficient conversion of biomass into biogas than into 2G ethanol or FT fuels.

- Furthermore, both conversion processes need more energy than the biogas production, which leads to higher greenhouse gas emissions.
- In the case of gasification after pyrolysis results are more or less balanced, thus, the environmental harm is similar to using conventional fuels.

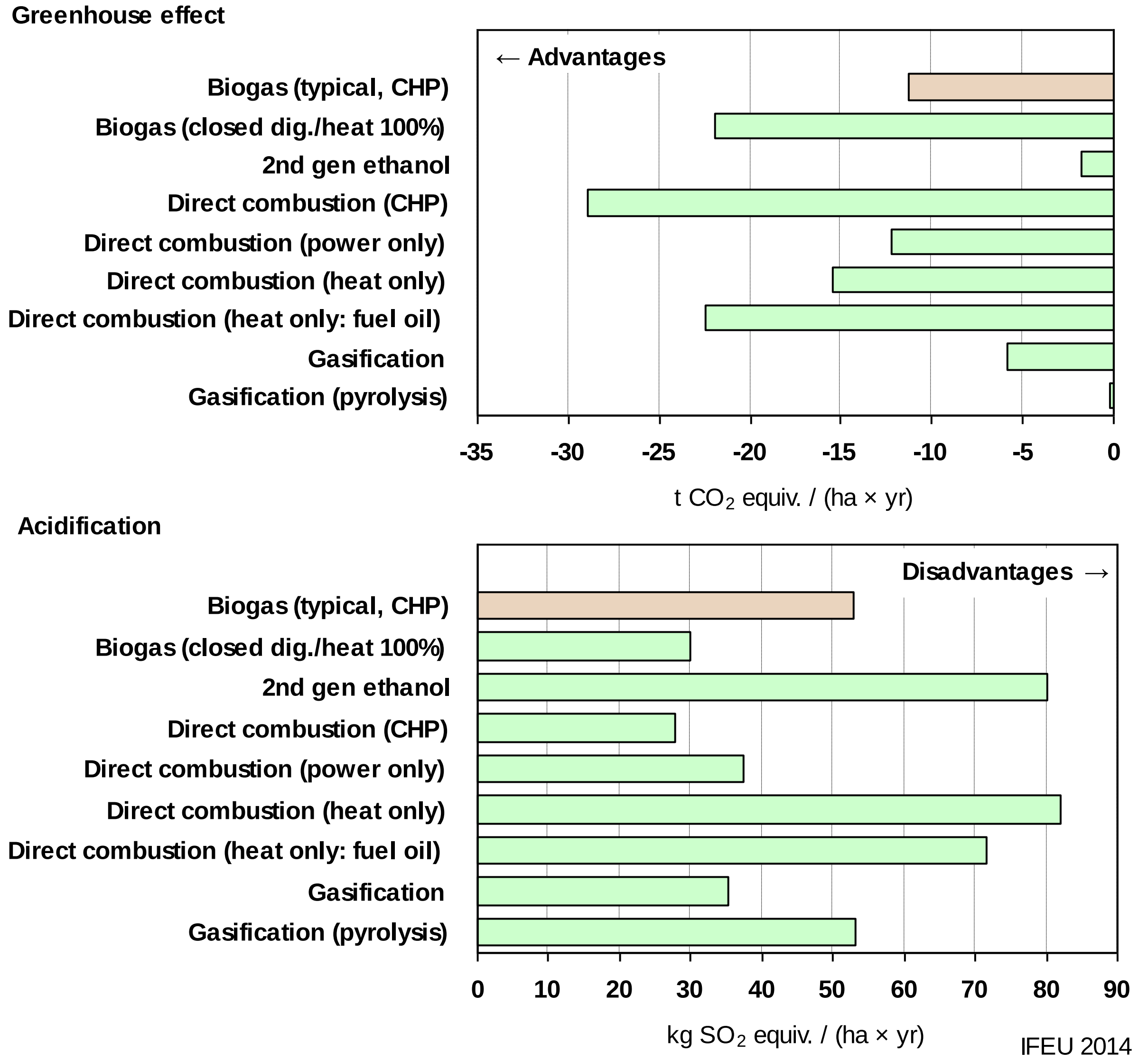


**Fig. 4-39** Comparison of alternative bioenergies from biomass sorghum with the biogas production scenario for the environmental impact categories greenhouse effect and acidification. For further categories see Annex, Fig. 8-10. Results are based on typical cultivation conditions.

Results are similar for the impact category depletion of non-renewable energy carriers (Annex, Fig. 8-10, resource depletion). In the category acidification, biogas production shows lower disadvantages compared to $2^{nd}$ generation ethanol and FT fuels, at least if an 'optimised' biogas production is assumed (Fig. 4-39, acidification). For the category terrestrial eutrophication (Annex, Fig. 8-10, terrestrial eutrophication) disadvantages are mostly bigger for biogas production compared to the other two alternative bioenergies due to high $NH_3$ emissions during digestate application. In the category ozone depletion results of the gasifi-

cation process and the biogas production are similar. Second generation ethanol shows most additional burdens in this category due to the fact that there are no by-products causing $N_2O$ emissions.

For the impact category aquatic eutrophication (Annex, Fig. 8-10, aquatic eutrophication) biogas production from biomass sorghum performs slightly worse compared to second generation ethanol and FT fuel production due to the usage of the digestate.

**Conclusions**

A direct combustion of biomass sorghum followed by a combined heat and power unit performs best compared to all other use options (biogas production, gasification, 2nd generation ethanol) in almost all investigated environmental impact categories. Thus, from an environmental protection point of view the direct combustion of biomass sorghum should be favoured over the processing of biomass sorghum into biogas, but only if both heat and power can be produced and used. A production of Fischer-Tropsch fuel or 2nd generation ethanol from biomass sorghum, however, does not represent an advantageous alternative for biogas production.

## 4.3 Summary: LCA

The results of the life cycle assessment can be summarised as follows:

**General aspects for sweet sorghum and biogas production scenarios**

The production and use of sweet and biomass sorghum as energy crops can cause a wide spectrum of potential impacts ranging from significant environmental benefits to distinctly detrimental environmental impacts compared to conventional energy carriers. In the cane fallow, grain to food and biogas production scenarios, results for the impact categories depletion of non-renewable energy resources and greenhouse effect are mostly advantageous compared to fossil equivalents, whereas the results for the other investigated impact categories (acidification, terrestrial and aquatic eutrophication, ozone depletion and, in case of the sweet sorghum scenarios, human toxicity) cause additional environmental burdens. For the syrup production scenario, however, mostly disadvantageous results can be observed for all investigated impact categories. Thus, to improve the environmental performance of bioethanol and biogas production in all scenarios, optimisation is necessary to reduce disadvantages and increase advantages.

Some life cycle stages are particularly relevant to numerous environmental impact categories and therefore represent starting points for optimising biomass production and use. Most important for sweet sorghum and biomass sorghum scenarios are these life cycle stages:

- **Fertilisation** (especially nitrogen) and **field emissions** (influenced by fertilisation),
- Credits given for the avoided expenses for the **use of conventional energy carriers**.

For most sweet sorghum scenarios also the use of the **by-products** are important life cycle steps. For the biomass sorghum scenario, the **way of storing the digestate** during biogas production and the **time until digestate incorporation** are decisive life cycle aspects.

For both sweet sorghum (except for syrup production) and biomass sorghum scenarios, it holds true that **high biomass yields** can help to save greenhouse gases and fossil energy carriers. Thus, one way to optimise bioethanol and biogas production includes aiming at higher yields. Since all categories in all sweet sorghum and biomass sorghum scenarios are strongly influenced by the amount of applied mineral fertilisers (especially N fertiliser), another optimisation potential is to **reduce the nutrient content** in the harvested biomass while still sustainable cultivation practices are guaranteed.

The **transportation distance** has only little influence on the outcome of the overall results of all investigated impact categories and all sweet sorghum and biomass sorghum gas production scenarios.

**Special aspects for sweet sorghum scenarios**

- The **optimisation potential** is higher for the cane fallow than for the grain to food and the syrup production scenario.
- Since the impact of the **conversion efficiency** on the overall results is relatively small for the sweet sorghum scenarios, the conversion efficiency holds only a small potential for optimising bioethanol production.
- The different use options of the **by-products** represent a huge optimisation potential in the sweet sorghum scenarios (mainly cane fallow). In the future, leaves should be used for bioenergy production. The by-products grains and surplus bagasse (not required for process energy provision) should only be used for bioenergy production if grains are not needed as food and the use of surplus bagasse as feed is not needed to relieve pressure on regional land availability, respectively.
- As long as there are no optimisation arrangements in the **syrup production** scenario to reduce especially the expenditures (e.g. by reducing the nutrient content of harvested biomass or by decreasing expenses from external energy carriers), aiming at higher yields should not be pursued in the first place.
- In the syrup production scenario, **external energy carriers** are needed to convert sugar juice into ethanol since the bagasse has already been used to boil down the sugar juice into syrup. From a climate protection point of view, a renewable energy resource out of residual products such as rice straw should be used for energy provision where possible.
- If **land cover** changes are involved, the outcome of the greenhouse gas balance depends largely on the carbon stocks of the area. If a piece of land is developed for sweet sorghum cultivation, a reduction of the carbon inventory of this area must be prevented.

- If sweet sorghum is cultivated in **traditional grain sorghum cultivation** regions, there is no great difference in the overall results if grain sorghum is totally or only partially replaced.

**Special aspects for biomass sorghum scenarios**

- To gain optimised conversion conditions for biogas production, **digestate storage tanks** should be covered and closed gas-tight. Additionally, the digestate should be incorporated into the soil as soon as possible after application.
- When replacing **fossil energy carriers**, the more carbon dioxide emissions from their combustion can be saved, the more advantageous is the outcome in most of the impact categories investigated. However, since mostly the replaced energy carrier cannot be influenced by the plant operator, the optimisation potential is relatively low.
- From an environmental perspective, **biogas and its use in a CHP** unit is advantageous with respect to the other biogas use options, as far as biogas is produced under the same opportune conditions as biomethane. In case biogas is further refined into **biomethane**, the use of biomethane in a combined heat and power unit should be favoured over a use as a natural gas substitute or fuel.
- A **direct combustion** of biomass sorghum and its use in a CHP unit performs best compared to all other use options in almost all categories. Also 2$^{nd}$ generation ethanol as a fuel cannot reach those levels of environmental advantages. Thus, from an environmental protection point of view the direct combustion should be favoured over the processing of biomass sorghum into biogas, but only if both heat and power can be produced and used.

**Excursus: Net land use**

For the environmental assessment in SWEETFUEL the unit of reference was chosen as "per ha per yr of direct land use" for all impact categories because the used agricultural land is the limiting factor for energy sorghum cultivation since arable land is scarce. The most efficient climate change mitigation is thus achieved by those scenarios, which show the highest greenhouse gas emission savings per area of land used. However, since land use is not only directly affected by the occupation of agricultural land through the cultivation of energy sorghum but also indirectly by the use of the by-products, it is also worth considering the net land use which is defined as the direct land use plus indirect land use for the provision of further inputs (where applicable) minus agricultural land that may not be cultivated anymore elsewhere because the by-products of the assessed process replace commodities produced on a certain area such as dedicated feed crops.

For some sweet sorghum scenarios, net land use deviates strongly from direct land use and even leads to "negative" results in some cases. Negative net land use means that the cultivation of sweet sorghum may overall release land instead of occupying additional land. The reason is that some by-products (surplus bagasse, grains) are used directly or indirectly as feed or food and replace feed / food, which is conventionally cultivated separately. These areas for separate feed / food cultivation are not needed anymore if feed / food are instead provided by sweet sorghum.

This is true specifically,

- if grains are used for ethanol production in the cane fallow scenarios, they are also indirectly used as feed since the vinasse produced by the fermentation process can be used as feed. Thus, although one hectare per year is needed for sweet sorghum cultivation, some land (much less than one hectare) can be saved elsewhere since vinasse replaces conventional feed (here soymeal) that has not to be cultivated anymore. If surplus bagasse is used as feed and replaces feed production elsewhere (in this example around one hectare of wheat), net area occupancy could even become negative. Thus, more area may become available under certain boundary conditions than is effectively needed for the production of sweet sorghum;
- in case of the grain to food scenarios (grains are used as food and sweet sorghum cultivation replaces grain sorghum cultivation), results can even be more distinctive: As sweet sorghum produces almost as much grains as the replaced grain sorghum, about 0.8 hectares per year of grain sorghum can be replaced while maintaining grain production levels in the main scenario (surplus bagasse to energy). This results in a net area occupancy of 0.2 hectares per year. If surplus bagasse is additionally used as feed, no area is effectively needed for the production of sweet sorghum since more than 1 ha can be saved by the use of the by-products (Fig. 4-40).

Considering those results, the optimal use of surplus bagasse is strongly dependent on the specific situation: Per hectare per year of direct land use bioenergy production from surplus bagasse is advantageous compared to a usage as feed. However, based on results per hectare per year of net land use, the use of surplus bagasse as feed is the better option if the land becoming available through replacing separate feed production is used for bioenergy provision or if detrimental land use changes can be avoided. In some scenarios leaves are used as feed, thus, additional area becomes available. However, the dimension is strongly dependent on the replaced source of feed.

However, as the replacement of feed is indirect and subject to market dynamics, those results are very uncertain. Nevertheless, the general conclusion is clear but considerably opposite to what was shown for the direct land use approach: Per 1 hectare net area and year more greenhouse gases and non-renewable energy resources can be saved in the grain to food scenarios than in the cane fallow scenarios. Thus, it is possible to produce the same amounts of food and feed, which are currently produced separately, on a smaller total area and to additionally obtain fuel from the same land on top. A similar potential for net land use reductions has already been observed for few other biofuel production systems such as sugar beet ethanol /Rettenmaier et al. 2008/. However, intensification of agriculture also has downsides, which are observed for most biofuels: Environmental impacts such as acidification and eutrophication increase e.g. through higher yields and thus increased fertiliser use. Thus, where agricultural land is highly competed for and feed production contributes to this competition, surplus bagasse should be used as feed. The more land is available the better performs the use of surplus bagasse for energy production in combination with less intensive separate feed production. (Continued on next page.)

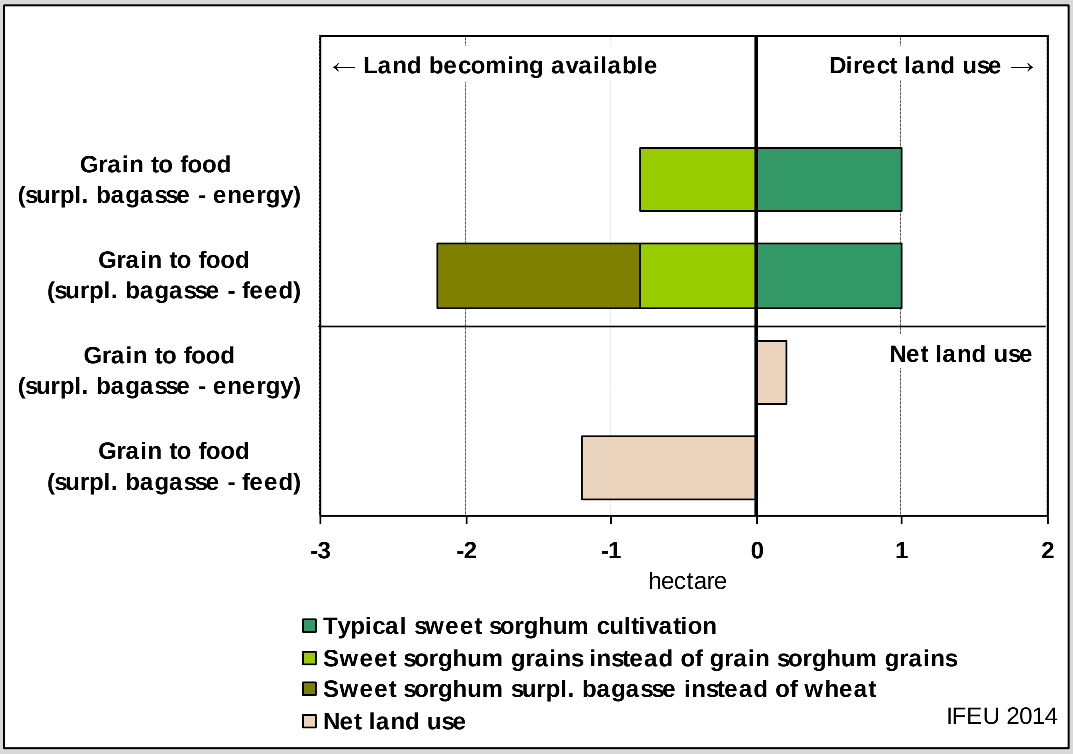


**Fig. 4-40** Overview on direct land use and net land use in the grain to food scenarios.

(Continued) Overall, replacement of grain sorghum is an option for sweet sorghum cultivation if (little) additional land is available to maintain food production levels or can be made available e.g. through substitution of local feed cultivation by surplus bagasse.

Technically, the expression of results per net area and year is thus more useful in a situation of high land use competition because it takes indirect effects on other forms of land use into account. Nevertheless, an expression of results per directly used area yields more robust results as most indirect effects are caused by volatile and variable markets. Furthermore, direct land use is sufficient in many cases and should thus be used as a basic unit of reference supplemented by net land use where appropriate and informative. For the biomass sorghum scenarios direct land use and net land use are the same, since here no by-products occur that can directly or indirectly be used as feed or food.

**Conclusions**

As shown in this excursus, substantial amounts of agricultural land may be set free if by-products of sweet sorghum cultivation and use such as grains or surplus bagasse are used as feed or food and separate feed or food production becomes obsolete. Depending on regional market conditions, this may even exceed the area needed for sweet sorghum cultivation. Thus, increased sweet sorghum cultivations with a smart and regionally adapted use of by-products can be realised without occupying additional agricultural land.

# 5 Results: Life cycle environmental impact assessment

In this section the results of the life cycle environmental impact assessment are presented. In subchapter 5.1 the local environmental impacts of the sweet and biomass sorghum scenarios and the conventional systems are described. Subchapter 5.2 includes a comparison of the sorghum scenarios with the conventional systems. A summary of the life cycle environmental impact assessment is given in subchapter 5.3.

## 5.1 Sorghum scenarios and conventional systems

In the following, the local environmental impacts are summarized for all sorghum scenarios (subchapters 5.1.1 and 5.1.2) and the conventional systems (subchapter 5.1.3).

### 5.1.1 Sweet sorghum scenarios

In this section the results of the life cycle environmental impact assessment for the sweet sorghum scenarios are presented. The subchapter is divided into the provision of biomass (subchapter 5.1.1.1), necessary material inputs (subchapter 5.1.1.2), relevant aspects of transportation and logistics (subchapter 5.1.1.3) and the conversion of the biomass (subchapter 5.1.1.4).

#### 5.1.1.1 Biomass provision

The cultivation of energy crops includes both risks as well as opportunities, dependent on the type of crop. The assessment of crop-specific impacts primarily depends on the comparison with alternative land uses i.e. on the agricultural reference system. Alternative types of land use could be e.g. idle land, forest areas or areas reserved for nature conservation. In the following subsections the local environmental impacts of the three scenarios for sweet sorghum compared to the respective reference systems are summarised.

**Cane fallow scenarios**

As outlined in subchapter 3.1.1 this scenario encompasses the cultivation of sweet sorghum as an intermediate crop between two sugar cane cycles replacing crops like soy or peanuts.

Regarding local environmental impacts it can be stated that the replacement of soy or peanuts by sweet sorghum leads to a more uniform landscape since sweet sorghum very much resembles sugar cane in terms of physiognomy, whereas soy or peanuts offer different habitats and contribute to a more heterogeneous landscape. Thus, the cultivation of sweet sorghum leads to higher risks regarding the loss of landscape elements, the loss of habitat types and the loss of species and to negative impacts on plants / biotopes, animals and biodiversity. Contrarily, lower risks regarding soil erosion can be expected because of the improved ground coverage compared to soy / peanuts. This comparison is very relevant if the impacts of sweet sorghum introduction into a *specific* cultivation area are to be evaluated.

However, this is not the goal of the LC-EIA in SWEETFUEL. Here, the aim is to evaluate the impacts of sweet sorghum introduction into the agricultural system in a larger regional context. Since the demand for soy and peanuts is assumed to be constant, the displaced former intermediate crops need to be grown on additional land which often needs to be transformed into arable land prior to cultivation. From a methodological point of view (see also Fig. 3-1), it is therefore not necessary to compare sweet sorghum to the displaced former intermediate crop, i.e. its cultivation can therefore directly be compared to the respective alternative land use options (idle land, wooded grassland / pastures, dense thickets / sparse forests).

If the cultivation of sweet sorghum is compared to the reference system “idle land”, the following environmental impacts are expected: there is a higher risk of erosion due to the lower soil coverage compared to idle land. Due to the annual export of biomass the carbon balance of the soil as well as the balance of nutrients has to be compensated by fertiliser and / or input of organic material which leads to an increased risk of eutrophication. The stress on soil in combination with chemical weed control might also negatively affect animals, plants and biodiversity. Additionally, the land transformation usually leads to a loss of habitats. The impact on the environmental factors climate / air, landscape and human health and recreation is relatively low and no differences are expected compared to the reference system. Table 5-1 summarises the risks associated with cultivation of sweet sorghum on the environmental factors compared to the reference system idle land.

**Table 5-1** Risks associated with the cultivation of sweet sorghum compared to the reference system idle land.

| Type of risk | Affected environmental factors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Soil | Ground water | Surface water | Plants/ Biotopes | Animals | Climate/ Air | Land-scape | Human health and recreation | Bio-diversity |
| Soil erosion | negative[1]/ neutral[2] | | negative[1]/ neutral[2] | | | | | | |
| Soil compaction | negative | negative | | negative | negative | | | | negative |
| Loss of soil organic matter | negative[1]/ neutral | | | negative[1]/ neutral[2] | negative[1]/ neutral[2] | | | | negative[1]/ neutral[2] |
| Soil chemistry / fertiliser | negative | negative | | | | | | | |
| Nutrient leaching | | negative | | | | | | | |
| Eutrophication | negative | negative | negative | negative | negative | | | | negative |
| Water demand | | negative | | neutral | neutral | | | | neutral |
| Weed control / pesticides’ | | negative | negative | negative | negative | | | | negative |
| Loss of landscape elements | | | | neutral | neutral | neutral | neutral | neutral | neutral |
| Loss of habitat types | | | | neutral/ negative | neutral/ negative | | | | neutral/ negative |
| Loss of species | | | | neutral/ negative | neutral/ negative | | | | neutral/ negative |

Foot notes:

1: Negative if sweet sorghum leaves are removed from field after harvest

2: Neutral if sweet sorghum leaves are left on the field after harvest

The displacement of soy / peanuts might also lead to a transformation of wooded grassland / pasture or dense thickets / sparse forests into arable land. The comparison of sweet sorghum cultivation and wooded grassland / pasture or dense thickets / sparse forests generally leads to higher environmental risks than the comparison of sweet sorghum and idle land. Wooded grasslands / pastures as well as dense thickets / sparse forests provide a more varied habitat for plants and animals, possess a greater value in terms of landscape elements and have a greater share in the regulation of the local climate than arable land. Hence the cultivation of sweet sorghum leads to more negative impacts on plants / biotopes, animals, climate / air, landscape, human health and recreation and biodiversity. Since the clearing of trees, thickets or even forests might become necessary the cultivation of sweet sorghum also leads to a higher burden regarding the carbon dioxide balance. The risks associated with the cultivation of sweet sorghum compared to the reference systems wooded grassland / pasture and dense thickets / sparse forests are summarised in Table 5-2.

**Table 5-2** Risks associated with the cultivation of sweet sorghum compared to the reference systems wooded grassland / pasture and dense thickets / sparse forests.

| Type of risk | Affected environmental factors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Soil | Ground water | Surface water | Plants/ Biotopes | Animals | Climate/ Air | Land-scape | Human health and recreation | Bio-diversity |
| Soil erosion | negative | | negative | | | | | | |
| Soil compaction | negative | negative | | negative | negative | | | | negative |
| Loss of soil organic matter | negative | | | negative | negative | | | | negative |
| Soil chemistry / fertiliser | negative | negative | | | | | | | |
| Nutrient leaching | | negative | negative | | | | | | |
| Eutrophication | negative | negative | negative | negative | negative | | | | negative |
| Water demand | | negative | | negative | negative | | | | negative |
| Weed control / pesticides' | | negative | negative | negative | negative | | | | negative |
| Loss of landscape elements | | | | negative | negative | negative | negative | negative | negative |
| Loss of habitat types | | | | negative | negative | | | | negative |
| Loss of species | | | | negative | negative | | | | negative |

## Grain to food scenarios

In the grain to food scenarios, sweet sorghum is grown on land that was originally used for grain sorghum. For the purpose of this analysis it is assumed that grain yields of sweet sorghum are lower than grain yields of grain sorghum. Thus, to further guarantee food / feed security the yield difference needs to be balanced by cultivating additional grain sorghum (see subchapter 3.1.2).

Methodologically two qualitative land use changes need to be assessed:

- Land that was used for the cultivation of grain sorghum turns into land that is used for the cultivation of sweet sorghum
- Idle land turns into land that is used for the cultivation of grain sorghum

With respect to the first aspect it can be postulated that the local environmental impacts are negligible. The cultivation of sweet and grain sorghum is similar in terms of sowing, growth, nutrient and water demand, appearance and habitat type.

Regarding the second qualitative land use change, the same applies as described in Table 5-1.

**Syrup production scenario**

The third sweet sorghum scenario comprises a decentralised pre-treatment of the sweet sorghum stalks at village level. The cultivation of sweet sorghum is assumed to take place on land that was originally used for the cultivation of other crops which in turn need to be grown on alternative land (idle land, wooded grassland / pastures, dense thickets / sparse forests). Methodologically that case can be subsumed by comparing the cultivation of sweet sorghum to the alternative land use options listed above. This comparison has already been conducted in the previous subsections and thus is not repeated here.

#### 5.1.1.2 Material inputs

Following a life cycle-oriented approach, the provision of fertiliser, pesticides and fuel for agricultural vehicles has to be taken into consideration as well.

**Fertiliser**

Essential factors for soil fertility in agricultural soils used for intensive feedstock production are carbon, nitrogen and phosphorus as well as calcium, potassium, magnesium and sulphur. Micronutrients contribute to the health of feedstock plants as well and can generally be provided with the application of mineral fertiliser.

The most important factor for soil fertility in intensive agriculture is carbon, which has to be provided in form of biomass, either as

- Harvesting residues
- Manure from livestock farming
- Green manure in form of cover crops (e.g. legumes)
- Residues from biological conversion processes e.g. vinasse from sugar cane and sweet sorghum or residues from anaerobic digestion. Organic fertiliser has the advantage to cover parts of other essential nutrients as well.

In intensive agricultural areas additional application of fertiliser is necessary providing e.g. nitrogen, phosphorus, potassium and calcium. This can either be provided as mineral fertiliser coming from the chemical industry (e.g. nitrogen fertilisers via the Haber-Bosch process) or from mining (phosphorus in form of Apatite [e.g. from Morocco], nitrogen in form of potassium nitrate [e.g. from China]).

Especially due to long-term changes in landscape affecting soil, water, flora, fauna and biodiversity, the application of mineral fertiliser has negative implications on the environment.

### Pesticides

Intensive agricultural production goes along with establishing monocultures, in order to minimise efforts for maintenance and harvesting. Agricultural profits are often impacted by different kinds of pests, either herbal diseases (fungi, bacteria, virus) or herbivorous animals (beetles, moths etc.). In order to minimise damage from diseases or any kind of pests various pesticides are available.

Especially due to long-term changes in landscape affecting soil, water, flora, fauna and biodiversity, the application of pesticides has negative implications on the environment.

### Fuel

Fuel is necessary to move agricultural machinery. The provision of petroleum-based fuels has negative implications on the environment.

Table 5-3 summarises potential impacts from value chains of providing fertiliser, pesticides and fuel for feedstock production.

**Table 5-3** Potential impacts on the environment related to the value chains of material inputs for feedstock provision.

| Element | Mineral fertiliser | Mineral fertiliser | Pesticides | Fuel |
|---|---|---|---|---|
| Source / Type of risk | Mining | Chemical industry | Chemical industry | Crude oil refinery |
| Prospection | C | n/a | n/a | C |
| Drilling / Mining | E | n/a | n/a | E |
| Waste production | D | D | D | D |
| Demand of water | C | D | D | D |
| Emissions (exhaust fumes, water, metal) | C | D | D | D |
| Land requirements | E | C | C | D |
| Demands for steel (equipment) | C | B | B | D |
| Transportation | D | D | D | D |
| Refining / processing | D | E | E | D |
| Accident (e.g. traffic, leakage, etc.) | C | C | E | E |

Impacts are ranked in five comparative categories (A, B, C, D, E); “A” is assigned to the best options concerning the respective factor, “E” is assigned to unfavourable options concerning the respective factor; reference scenario: “no action” alternative

High impacts on the environment are expected from the provision of mineral fertiliser, both from mining and the chemical industry, pesticides and fuels. Emissions to air of greenhouse gases and ozone depleting substances from these processes ($N_2O$ from N fertiliser production) deploy at global level, which means that they are diluted and thus contribute relatively little to local environmental impacts elsewhere. Other emissions to air and water have more local implications, i.e. around the point of production of these products. These emissions are well covered by LCA. In contrast to that, land use-related impacts on soil, water and biodiversity which also occur around the point of production (e.g. mining of minerals), are not covered in state-of-the-art LCA studies yet. These impacts can be very high at local level.

However, since only a small fraction of the total production volume of these products is used for the cultivation of sorghum, only a small fraction of their local environmental impacts can be allocated to the products obtained from it.

#### 5.1.1.3 Transport and logistics

Concerning the local environmental impacts resulting from transport and logistics the cane fallow and the grain to food scenarios can be assumed to be similar to each other but different to the syrup production scenario. Impacts of logistics are expected from:

- Transportation infrastructure
- Refuelling traffic
- Transportation and storage facilities

**Transportation infrastructure**

Transportation of feedstock and distribution of fuel products will most of all be based on trucks with need of roads. In each of the sweet sorghum scenarios the cultivation of sweet sorghum displaces other crops. Hence for the cultivation of sweet sorghum an existing transportation infrastructure is accessible. However the compensatory cultivation of soy / peanuts (scenario “cane fallow”), grain sorghum (scenario “grain to food”) or other crops (scenario “syrup production”) might necessitate the construction of roads or the expansion of existing roads. In order to minimise transportation it would make sense from an economic point of view to build conversion units close to feedstock production. As far as it is necessary to build additional roads, environmental impacts are expected on soil (due to sealing effects), water (reduced infiltration), plants, animals and biodiversity (loss of habitats, individuals and species).

**Refuelling traffic**

Impacts on the environment are expected to result from the lower energy content of ethanol compared to conventional fossil fuels resulting in increased traffic due to an increased need of refilling the tank. In addition, the traffic due to distribution of fuel products (from the ethanol plant / refinery to the filling stations) increases for the same reason (lower energy content). This might increase emissions of noise and exhaust fumes affecting soil, animals, plants, air and human health. Depending on the surroundings and the already existing impacts the significance of additional emissions and traffic can be diverging. The risk of emissions in comparison with wide-scale-emissions and high traffic loads of industrial areas will be below de-

tection limits. In sensitive areas mitigation measures might be necessary (e.g. reduced speed for transportation traffic).

**Transportation and storage facilities**

Unlike biomass / grain sorghum yields the juice of the sweet sorghum stalks cannot be stored longer than a few days since the sugar degrades rapidly after harvest. Therefore the sweet sorghum stalks have to be processed soon after harvest.

The cane fallow and the grain to food scenarios encompass direct delivery of unprocessed feedstock to the central ethanol plants. Due to the limited storage tolerance, the processing of the stalks at the ethanol plant has to take place more or less “just in time”. However, small intermediate storage facilities at the bioethanol plants are needed to buffer supply gaps leading to clearing, sealing and compaction of soil, loss of habitats (plants, animals) as well as reduced groundwater infiltration.

The syrup production scenario encompasses a pre-treatment step of the sweet sorghum stalks at village level directly after harvest. The pre-treatment includes the production of syrup through concentration of juice. The syrup is transported to the central ethanol plant afterwards. Small storage containers are needed in order to store the syrup both at village level and at the central ethanol plant.

With respect to the transportation volumes necessary this implies that in total less biomass weight needs to be transported to the ethanol plant in the scenario “syrup production”. However, as a result of the assumption that the average distance between the sweet sorghum cultivation and the ethanol plant is greater in the scenario “syrup production” than in the scenarios “biogas and biomethane production” and “grain to food”, the product of the transported mass and the distance might be equal or similar in each of the sweet sorghum scenarios.

With respect to the storage facilities needed this implies that in the cane fallow and the grain to food scenarios somewhat smaller storage capacities are necessary than in the scenario “syrup production”. As to the scenario “syrup production” the construction of new storage containers (tanks) would cause sealing and compaction of soil, loss of habitats (plants, animals) as well as reduced groundwater infiltration. However the containers needed at village level are small compared to industrial storage facilities for storable biomass.

#### 5.1.1.4 Biomass conversion

Feedstock processing and ethanol production in the cane fallow and the grain to food scenarios are conducted in a centralised ethanol production unit while in the syrup production scenario first processing steps are conducted on a decentralised level.

The local environmental impact assessment is done as a benefit and risk assessment, based on the investigation of potential effects on the environmental factors compared to reference scenarios.

Following impact identification and prediction, impact evaluation is the formal stage at which the significance is determined. Impact significance depends on the joint consideration of its characteristics (quality, magnitude, extent, duration) and the importance (or value) that is attached to the resource losses, environmental deterioration or alternative uses.

Impacts can be

1. related to the construction phase
2. project-related: buildings, infrastructure and installations
3. related to the operation phase

Table 5-4 summarises the local environmental impacts associated with sweet sorghum conversion in the cane fallow and grain to food scenario (centralised conversion) and the syrup scenario (decentralised syrup production and centralised ethanol production).

Both scenarios perform rather similar, except for the impacts related to buildings, infrastructure and installations (i.e. soil sealing) and the emissions of gases and fine dust which are very high in the case of low-tech processes used fort the decentralised syrup production which are associated with higher emissions.

**Table 5-4** Potential impacts on the environment related to different technologies regarding sweet sorghum feedstock conversion and transport.

| Technology / Product<br>Technology related factor | Sweet sorghum conversion | |
|---|---|---|
| | Centralised ethanol production | Decentralised syrup production |
| | Ethanol | Ethanol |
| **Impacts resulting from construction phase** | | |
| Construction works | C | C |
| **Impacts related to buildings, infrastructure and installations** | | |
| Buildings, infrastructure and installations (size and height) | **E** | **E** |
| **Impacts resulting from operation phase** | | |
| Emission of noise (conversion unit) | D | D |
| Emission of gases and fine dust (conversion unit) | C | C[1] / E[2] |
| Emission of light (conversion unit) | C | C |
| Drain of water resources for production (conversion unit) | D | D |
| Waste water production and treatment (conversion unit) | D | D |
| Traffic (collision risk, emissions) | C | C |
| Electromagnetic emissions from high-voltage transmission lines | n/a | n/a |
| Disposal of wastes/residues | B | B |
| Risk of accidents<br>- explosion<br>- fire in the plant<br>- fire in the storage areas | C | C |

Impacts are ranked in five comparative categories; "A" is assigned to the best options concerning the respective factor, "E" is assigned to unfavourable options concerning the respective factor; reference scenarios: "no action" alternatives. Foot notes: 1: Centralised ethanol plant. 2: Decentralised syrup production.

### 5.1.2 Biomass sorghum scenarios

In this section the results of the life cycle environmental impact assessment for the biomass sorghum scenarios are presented. The subchapter is divided into the provision of biomass (subchapter 5.1.2.1), necessary material inputs (subchapter 5.1.2.2), relevant aspects of transportation and logistics (subchapter 5.1.2.3) and the conversion of the biomass in the respective plants (subchapter 5.1.2.4).

#### 5.1.2.1 Biomass provision

The cultivation of energy crops includes both risks as well as opportunities, dependent on the type of crop. The assessment of crop specific impacts primarily depends on the comparison with alternative land uses i.e. on the agricultural reference system. Alternative types of land use could be e.g. idle land, forest areas or areas reserved for nature conservation. Since both forest and grassland conversion are forbidden in Europe, the agricultural reference system for the assessment of annual crops such as biomass sorghum is idle land.

**Biomass sorghum**

Table 5-5 summarises the risks associated with cultivation of biomass sorghum on the environmental factors.

**Table 5-5** Risks associated with the cultivation of biomass sorghum compared to the reference system idle land.

| Type of risk | Affected environmental factors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Soil | Ground water | Surface water | Plants/ Biotopes | Animals | Climate/ Air | Land-scape | Human health and recreation | Bio-diversity |
| Soil erosion | negative | | negative | | | | | | |
| Soil compaction | negative | negative | | negative | negative | | | | negative |
| Loss of soil organic matter | negative | | | negative | negative | | | | negative |
| Soil chemistry / fertiliser | negative | negative | | | | | | | |
| Nutrient leaching | | negative | | | | | | | |
| Eutrophication | negative | negative | negative | negative | negative | | | | negative |
| Water demand | | negative | | neutral | neutral | | | | neutral |
| Weed control / pesticides' | | negative | negative | negative | negative | | | | negative |
| Loss of landscape elements | | | | neutral | neutral | neutral | neutral | neutral | neutral |
| Loss of habitat types | | | | neutral/ negative | neutral/ negative | | | | neutral/ negative |
| Loss of species | | | | neutral/ negative | neutral/ negative | | | | neutral/ negative |

Compared to idle land, the cultivation of biomass sorghum has a higher impact on soil: The danger of erosion is high, especially after planting the seeds and after harvesting, when soil cover is low. Due to the annual export of biomass the carbon balance of the soil as well as the balance of nutrients has to be compensated by fertiliser or / and input of organic material / green manuring, which means that the potential impact on groundwater by leaking and on superficial water by runoff is quite high. Animals, plants and biodiversity might be impacted as well, as the stress on soil in combination with chemical weed control might cause a decrease in species diversity. The cultivation of biomass sorghum might lead to a loss of habitats and plant species compared to idle land affecting flora, fauna and biodiversity, although the impact could be minimised by providing additional habitats, e.g. nesting areas for birds and hiding places for deer. So the impact might not be that negative. The impact on the environmental factors climate / air, landscape and human health and recreation is relatively low and compared to the reference system no differences are expected.

#### 5.1.2.2 Material inputs

Since the sustainability assessment of SWEETFUEL focuses on a comparative evaluation of potential technological sorghum use paths, the need for fertiliser, pesticides and fuel for the intensive agricultural production of biomass sorghum is postulated to be identical to sweet sorghum. An assessment of the environmental impacts related to the value chains of material inputs for feedstock provision is given in subchapter 5.1.1.2 and Table 5-3.

#### 5.1.2.3 Transport and logistics

Impacts of logistics are expected from:

- Transportation infrastructure
- Refuelling traffic
- Transportation and storage facilities

**Transportation infrastructure**

Transportation of feedstock and distribution of fuel products will most of all be based on trucks with need of roads. Since the geographical reference of the biomass sorghum scenarios focuses on temperate regions the need of roads is expected to be low. However depending on the location of potential conversion units there might be impacts resulting from the implementation of additional transportation infrastructure. In order to minimise transportation it would make sense from an economic point of view to build conversion units close to feedstock production. As far as it is necessary to build additional roads environmental impacts are expected on soil (due to sealing effects), water (reduced infiltration), plants, animals and biodiversity (loss of habitats, individuals and species).

**Refuelling traffic**

The biogas and biomethane as well as the direct combustion scenario do not produce biofuels and thus are not discussed within this paragraph. The second generation ethanol scenario produces ethanol which is used as a substitute for conventional gasoline and the gasification scenario produces e.g. FT diesel which is used as a substitute for conventional diesel.

While the energy content of diesel produced via gasification is comparable to conventional diesel, the energy content of ethanol is lower than the energy content of conventional gasoline. As described in subchapter 5.1.1.3 the lower energy content of ethanol leads to increased traffic volumes since the tank needs to be refilled more frequently. For further impacts caused by this factor see subchapter 5.1.1.3.

**Transportation and storage facilities**

Again a distinction between the biomass sorghum scenarios is necessary. Solely in the biogas and biomethane scenario the biomass sorghum yields are processed in a wet state while in the second generation ethanol, the direct combustion and the gasification scenarios dry biomass is processed. The processing of wet biomass necessitates the construction of clamp / bunker silos (close to the agricultural production). On the other hand the processing of dry biomass necessitates huge storage capacities to minimise damage due to humidity (mould) or vermin. In case additional buildings are needed the construction would cause sealing and compaction of soil, loss of habitats (plants, animals) as well as reduced groundwater infiltration.

#### 5.1.2.4 Biomass conversion

Feedstock processing and the provision of the respective products (methane, ethanol, FT fuels as well as heat and power) is done in four different conversion units. The local environmental impact assessment is done as a benefit and risk assessment, based on the investigation of potential effects on the environmental factors compared to reference scenarios.

Following impact identification and prediction, impact evaluation is the formal stage at which the significance is determined. Impact significance depends on the joint consideration of its characteristics (quality, magnitude, extent, duration) and the importance (or value) that is attached to the resource losses, environmental deterioration or alternative uses.

Impacts can be

1. related to the construction phase
2. project-related: buildings, infrastructure and installations
3. related to the operation phase

**Construction phase**

Impacts related with the construction of a plant are temporary and not considered to be significant.

**Buildings, infrastructure and installations (size and height of the plant)**

Any biomass sorghum conversion unit needs processing facilities, energy generation, administration buildings, waste water treatment etc., which usually goes along with clearing and sealing of soil. Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Scaling up plants from different technologies to comparable outputs and yields might further minimise the differences in land consumption. Significant impacts are expected on water, soil, plants, animals and landscape.

**Operation phase**

Impacts from operating a conversion plant are expected from:

- Emission of noise
- Emissions of gases and fine dust
- Emission of light
- Drain of water resources for production
- Waste water production and treatment
- Traffic (collision risks, emissions)
- Electromagnetic emissions
- Disposal of wastes/residues
- Risk of accidents (explosion, fire in the plant or storage areas or release of GMO)

The significance of impacts might vary with the type of technology and the location of a potential plant. A decision on a case-by-case-basis is necessary anyway.

Each type of conversion unit emits noise, gases, fine dust and light, needs water resources and releases waste water. Most impacts on the environment are comparable on a generic level. As long as legal thresholds and state-of-the-art technologies are provided, qualitative differences are not expected.

However, differences between the four types of biomass conversion can be identified:

- Solely in the scenario "second generation ethanol" genetically modified micro-organisms are applied during the processing steps. Hence, in this scenario a potential risk to release GMO is given.
- The operating temperature and pressure are higher in the scenario "gasification" than in the other biomass sorghum scenarios. For this reason a higher risk of hazardous accidents is recognized.
- Solely in the scenario "biogas and biomethane production" and the scenario "direct combustion", significant amounts of power are generated. Thus, for these scenarios higher environmental impacts due to electromagnetic emissions are expected.
- Compared to other potential biomass sorghum conversion units, the need to dispose ashes in landfills that accrue during the combustion of biomass sorghum leads to higher environmental impacts in the scenario "direct combustion".

The potential impacts of the four biomass conversion units on the environment are summarised in Table 5-6.

**Table 5-6** Potential impacts on the environment related to different technologies regarding biomass sorghum feedstock conversion and transport.

| Technology related factor \ Technology / Product | Biogas and biomethane | | Direct combustion | 2G ethanol | Gasification |
|---|---|---|---|---|---|
| | Heat and power | Methane | Heat and power | 2G ethanol | FT fuels |
| **Impacts resulting from construction phase** | | | | | |
| Construction works | C | C | C | C | C |
| **Impacts related to buildings, infrastructure and installations** | | | | | |
| Buildings, infrastructure and installations (size and height) | E | E | E | E | E |
| **Impacts related to operational phase** | | | | | |
| Emission of noise (conversion unit) | D | D | D | D | D |
| Emission of gases and fine dust (conversion unit) | C | C | C | C | C |
| Emission of light (conversion unit) | C | C | C | C | C |
| Drain of water resources for production (conversion unit) | D | D | D | D | D |
| Waste water production and treatment (conversion unit) | D | D | D | D | D |
| Traffic (collision risk, emissions) | C | C | C | C | C |
| Electromagnetic emissions from high-voltage transmission lines | D | C/D | D | C | C |
| Disposal of wastes/residues | B | B | C | B | C |
| Risk of accidents<br>- explosion<br>- fire in the plant<br>- fire in the storage areas<br>- release of GMO | C[2] | C | C | C/D[1] | C/D[2] |

Impacts are ranked in five comparative categories; “A” is assigned to the best options concerning the respective factor, “E” is assigned to unfavourable options concerning the respective factor; reference scenarios: “no action” alternatives

Foot notes:
1: Increased impact potential expected due to operating with GMO (risk of release)
2: Increased potential of accidents due to potentially hazardous production conditions

### 5.1.3 Conventional systems

Following a life cycle-oriented approach, the objective of the environmental assessment is to compare potential impacts of sweet and biomass sorghum scenarios with other conventional (fossil-driven) reference systems. Reference technologies considered include:

- Provision of fuels:
  - Crude oil refinery (production of fuels)

For the later comparison of competing biomass-based systems with their conventional (fossil-driven) reference systems, the following energy-providing systems are evaluated:

- Provision of energy:
    - Oil-/gas-fired power plant (heat and power generation)
    - Coal-fired power plant (heat and power generation)
    - Nuclear power plant (heat and power generation)

**Crude oil refinery (provision of fuels)**

Oil refineries process crude oils into useful products e.g. naphtha, diesel or kerosene. The crude oil comes from oil production platforms (via pipelines or tankers) and is separated into fractions by fractional distillation. The fractions at the top of the fractionating column have lower boiling points than the fractions at the bottom. The heavy bottom fractions are often cracked into lighter, more useful products. All of the fractions are processed further in other refining units. The majority of the products are used for energy purposes, both in mobile (= transport) or stationary applications.

**Oil-/gas-fired power plant (provision of heat and power)**

For the provision of power, fuel oil / natural gas is burnt to produce heat in order to generate electric power. In general this is done via an electric generator driven by combustion turbines or steam. Modern plants can act as CHP plants if in addition to power generation a heat sink is available.

**Coal-fired power plant (provision of heat and power)**

Coal is burnt to produce heat in order to generate electric power. In general this is done via an electric generator driven by steam. Modern coal plants can act as CHP plants if in addition to power generation a district heating system is attached.

**Nuclear power plant (provision of heat and power)**

Nuclear fission produces energy which is used to generate electric power via a generator. Heat is usually left over as dead energy as distances towards settlements or industries are too long to establish a cost-effective transportation.

#### 5.1.3.1 Raw material production / extraction

According to the life cycle-oriented approach, an assessment of feedstock provision i.e. value chains in conventional reference systems is applied. Considered conventional feedstock provision includes crude oil, natural gas, coal and uranium ore. Each is related with different types of risks causing potential impacts on the environment. Impacts of transportation are taken into consideration as well.

**Crude oil / natural gas provision**

Impacts of crude oil / gas provision are expected to affect all environmental factors. The impacts are classified as unfavourable for the environment. Drilling processes especially in combination with the production of oil and water based mud and the huge demand of water /Ziegler 2011/ bear significant risks for the environment. Further significant impacts are expected from transportation, especially due to the implementation of pipelines.

Both value chains (crude oil / gas provision) include high risks of environmental impacts related with accidents, which in case of crude oil provision exceed the risks of gas provision by far (see e.g. /Wikipedia 2014/ for a list of spills). Basically the environmental factors soil, water, plants / biotopes, animals and biodiversity are affected. Table 5-7 summarises potential impacts on environmental factors on the value chains for both crude oil provision and natural gas provision as exploitation and refining are very often done simultaneously.

**Table 5-7** Impacts on the environmental factors related with the value chains of crude oil / natural gas provision; potentially significant impacts are marked with thick frames; reference scenario: no use.

| Technological factor | Affected environmental factors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Soil | Ground water | Surface water | Plants/ Biotopes | Animals | Climate/ Air | Land-scape | Human health and rec-reation | Bio-diversity |
| Prospection | | | | negative | negative | | | | negative |
| Drilling / mining | negative | negative | negative | negative | negative | | negative | | negative |
| Waste (oil based and water based mud) | negative | negative | negative | negative | negative | | | | negative |
| Demand of water (process water) | | negative | negative | negative | negative | | negative | | negative |
| Emissions (exhaust fumes, water, metal) | | negative | negative | negative | negative | negative | | negative | |
| Land requirements | negative | negative | negative | negative | negative | negative | negative | | negative |
| Demands of steel (tubes, equipment) | negative | | | negative | negative | | negative | | |
| Transportation | negative | negative | negative | negative | negative | negative | negative | negative | negative |
| Refining / processing | negative | negative | negative | negative | negative | | negative | negative | negative |
| Accidents (traffic, pipeline leakage) | negative | negative | negative | negative | negative | | negative | negative | negative |

### Coal provision

Coal is a soil resource and available in two main types:

- Hard coal is usually provided with deep mining; major sources are found in the United States, China and Russia.
- Lignite is usually exploited in surface mining; the largest deposits are found in the United States and in Russia.

The intensity of impacts summarised in Table 5-8 is varying with the type of mining, both causing severe impacts on the environment:

- Impact on ground water: deposits beneath the groundwater level require huge draining efforts with further consequences for the groundwater table on a regional scale; in addition huge amounts of water are needed for dust prevention in open pits.

- The leaching of burden piles might cause environmental problems due to polluted surface water and ground water.
- Air pollution: surface mining causes fine dust and can release radioactive substances (e.g. radon) associated with coal deposits.
- The major impact of surface mining is the loss of land. Huge areas with habitats and wildlife including human settlements are dug away causing impacts on soil, water, plants / biotopes, animals, landscape, human beings and biodiversity. Even renaturation measures cannot restore the original status.

**Table 5-8** Impacts on environmental factors related with the value chains of coal provision; potentially significant impacts are marked with thick frames; reference scenario: no use.

| Technological factor | Affected environmental factors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Soil | Ground water | Surface water | Plants / Biotopes | Animals | Climate / Air | Land-scape | Human health and recreation | Bio-diversity |
| Prospection | | | | negative | negative | | | | negative |
| Mining | negative | negative | negative | negative | negative | | negative | | negative |
| Waste (excavated material) | negative | | | negative | negative | | | | negative |
| Demand of water (process water) | | negative | negative | negative | negative | | | | negative |
| Emissions (exhaust fumes, water, metal) | | negative | negative | negative | negative | negative | | negative | |
| Land requirements | negative | negative | negative | negative | negative | | negative | negative | negative |
| Demands of steel (tubes, equipment) | | | | negative | negative | | negative | | |
| Transportation (carriers) | negative | | negative | negative | negative | negative | negative | negative | negative |
| Refining / processing | | | | | | | negative | negative | |
| Accidents (traffic) | negative | negative | negative | negative | negative | | negative | negative | |

## Provision of uranium ore

Uranium as the main driver of nuclear power plants is a widely spread soil resource generally low concentrated. As a heavy metal it is toxic and it is radioactive. Most of the uranium ore is found in Australia, Canada, Kazakhstan and Africa.

Uranium mining goes along with significant impacts on the environment (e.g. /UNSCEAR 1993/), basically related with mining, production of waste, water depletion, emissions and land requirements.

- Mining: as the concentration of uranium in the ore is relatively low, huge amounts of rocks have to be moved causing major land consumption with severe impacts on soil, water, wildlife and landscape.

- Uranium is chemically extracted leaving huge amounts of waste (tailings) contaminated with heavy metals (associated with uranium ore) and other radio nuclides, basically impacting water and wildlife.
- Dried tailings cause toxic and radioactive dusts impacting huge areas used for stock breeding or agriculture, thus causing negative impacts on soil, wildlife, and human beings /Schramm 2012/.
- An important impact on local societies arises from massive expropriations and displacements.

Table 5-9 summarises major impacts of uranium mining on the environment.

**Table 5-9** Impacts on environmental factors related with the value chains of provision of uranium ore; potentially significant impacts are marked with thick frames; reference scenario: no use.

| Technological factor | Affected environmental factors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Soil | Ground water | Surface water | Plants / Biotopes | Animals | Climate / Air | Land-scape | Human health and recreation | Bio-diversity |
| Prospection | | | | negative | negative | | | | negative |
| Mining | negative | negative | negative | negative | negative | | negative | | negative |
| Waste (excavated material) | negative | negative | negative | negative | negative | | negative | | negative |
| Demand of water (process water) | | negative | negative | negative | negative | | | | negative |
| Emissions (exhaust fumes, dust, metal) | negative | negative | negative | negative | negative | negative | | negative | |
| Land requirements | negative | | | negative | negative | | negative | | negative |
| Demands of steel (tubes, equipment) | | | | negative | negative | | negative | | |
| Transportation (carriers) | negative | | | negative | negative | | | | |
| Enrichment | negative | | | | | | negative | negative | |
| Accidents (traffic) | negative | | | negative | negative | | | | |

## Comparison of conventional value chains

Although impacts might vary in details, the provision of different fossil energy carriers on a generic level has similar impacts on the environment. Major impacts are caused by land requirements that might in case of mining (provision of coal, especially lignite, and uranium ore) exceed land consumption in the context with crude oil provision or the provision of natural gas, even if the construction of pipelines affords a huge amount of land. The considered value chains have significant impacts on water, either by draining (coal), washing (uranium) or the use of process water (crude oil). Transportation from overseas resource areas produces considerable emissions affecting air quality and thus wildlife environment and human

health. Significant impacts are expected from dusts in case of coal and uranium provision showing high intensities in open pit mining and because of toxic and radioactive dusts in uranium mining as well. The risk combined with accidents might be highest in crude oil and gas provision as these value chains are dealing with hazardous substances. Table 5-10 summarises major implications of the considered value chains in comparison with the no action alternative.

**Table 5-10** Potential impacts on the environment related to different value chains regarding the provision of heat and power in conventional systems; reference scenario: no use.

| Technological factor | Crude oil / gas provision | Coal provision | Uranium provision |
|---|---|---|---|
| Prospection | C | C | C |
| Drilling / Mining | E | E | E |
| Waste | D | D | E |
| Demand of water (process water) | C / D[3] | D / E[2] | D |
| Emissions (exhaust fumes, dust, water, metal) | C / D[3] | C / E[2] | E |
| Land requirements | C / D[1] | C / E[2] | E |
| Demands of steel (tubes, equipment) | D | C | C |
| Transportation (carriers, pipelines) | D | D | D |
| Refining / processing / enrichment | D | D | D |
| Accidents (traffic, pipeline leakage) | E | C | C |

Impacts are ranked in comparative categories; "A" and B" are assigned to the best options concerning the respective factor, but are not used in this case; "E" is assigned to unfavourable options concerning the respective factor; reference scenario: "no action" alternative

Foot notes:
1: Increased land requirements in on-shore production
2: Increased impacts with open pit mining
3: Increased impact in crude oil provision

### 5.1.3.2 Raw material conversion

Impacts from implementing conventional conversion plants and use of conventional (fossil and nuclear) feedstock are expected from:

1. The construction of the plant

2. Buildings, infrastructure and installations on-site

3. The operation of a prospective plant

#### Construction phase

Impacts related with the construction of a plant are temporary and not considered to be significant.

**Buildings, infrastructure and installations (size and height of the plant)**

Any conventional conversion plant needs processing facilities, energy generation, administration buildings, waste water treatment etc., which usually goes along with clearing and sealing of soil. Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Scaling up plants from different technologies to comparable outputs and yields might further minimise the differences in land consumption. Significant impacts are expected on water, soil, plants, animals and landscape.

**Operation phase**

Impacts from operating a conversion plant are expected from:

- Emission of noise
- Emissions of gases and fine dust
- Emission of light
- Drain of water resources for production
- Waste water production and treatment
- Traffic (collision risks, emissions)
- Electromagnetic emissions
- Disposal of wastes/residues
- Risk of accidents (explosion or fire in the plant or storage areas)

Significance of impacts might vary with the type of technology and the location of a potential plant. A decision on a case-by-case-basis is necessary anyway.

Each type of refinery / heat and power plant emits noise, light, needs water resources and releases waste water. Most impacts on the environment are comparable on a generic level. As long as legal thresholds and state-of-the–art technologies are provided, qualitative differences are not expected.

*Emission of gases and fine dust*

Gases (e.g. odours) in most of the considered technologies are expected to be equal, whereas unfavourable gases are often linked to crude oil refineries in combination with chemical refineries.

In nuclear power plants emissions of radioactive substances is verifiable. The effect of low radiation doses on the environment are still under investigation and not yet completely clear. For instance, a study done by the Federal office of radiation protection /BfS 2007/ in Germany confirms a significant correlation between the distance of residence from the nearest nuclear power plant at the time of the diagnosis and the risk of developing cancer (leukaemia) before the 5$^{th}$ birthday.

*Traffic (emissions, collision risk)*

The provision of fossil driven refineries goes along with long distance transportation by ship / railway and / or pipelines with little impacts on local traffic.

Nuclear power plants provide a special risk due to transportation of high-level radioactive waste such as sending nuclear fuel to reprocessing plants in special CASTOR-containers (CASTOR = **ca**sk for **s**torage and **t**ransport **o**f **r**adioactive material). The substances are radioactive and radiation is detectable outside the castor-containers. In addition some of the transported radionuclides are highly poisonous (e.g. Plutonium) and potentially dangerous to the environment.

*Disposal of waste materials / residues*

All types of refinery / heat and power plants produce solid waste during operation. Taking into account statutory frameworks for the operation of plants non-biodegradable solid waste should be collected and provided for correct disposal. Considerable risks are expected in crude oil refineries especially when combined with chemical refineries as a number of dangerous substances are produced.

A potentially high risk to the environment are nuclear wastes from nuclear power plants, as an ultimate waste disposal is still pending, causing a long-term threat to the environment and society including human health.

*Risk of accidents and explosion or fires in plant and storage areas*

Chemical-technical production processes are often related with high temperatures, high pressure, use of organic solvents as well as the existence of pollutants. Dealing with a higher hazard potential on substances and processing techniques both the risk of accidents and the potential consequences for the environment from chemical technical processes are significant.

Nuclear technology bears an enormous risk as consequences from the core meltings of Chernobyl (26 April 1986) and Fukushima (11 March 2011) could proof. Radioactive releases and the toxicity of radionuclides have severe and enduring impacts on the environment as well as the total biosphere. Consequences of these disastrous accidents are still under investigation.

**Comparison of conversion technologies**

The comparison of the conversion technologies on technological related factors is summarised in Table 5-11.

**Table 5-11** Potential impacts on the environment related to different technologies regarding conventional feedstock conversion and transport.

| Technology related factor \ Technology / Product | Fuel provision | Energy provision | | |
|---|---|---|---|---|
| | Crude oil refinery | Crude oil/ Gas plant | Coal plant | Nuclear power plant |
| | Fuels | Heat and power | Heat and power | Heat and power |
| **Impacts resulting from construction phase** | | | | |
| Construction works | C | C | C | C |
| **Impacts related to buildings, infrastructure and installations** | | | | |
| Buildings, infrastructure and installations (size and height) | E | E | E | E |
| **Impacts resulting from operation phase** | | | | |
| Emission of noise (conversion unit) | D | D | D | D |
| Emission of gases and fine dust (conversion unit) | D | C | D | C[1] |
| Emission of light (conversion unit) | C | C | C | C |
| Drain of water resources for production (conversion unit) | D | D | D | D |
| Waste water production and treatment (conversion unit) | D | D | D | D |
| Traffic (collision risk, emissions) | C | C | C | E[2,3] |
| Electromagnetic emissions from high-voltage transmission lines | n/a | C | C | C |
| Disposal of wastes/residues | D[2] | C | C | E[2,3] |
| Risk of accidents<br>- explosion<br>- fire in the plant<br>- fire in the storage areas | E[1,2] | E[1,2] | E[1,2] | E[1,2,3] |

Impacts are ranked in five comparative categories; "A" is assigned to the best options concerning the respective factor, "E" is assigned to unfavourable options concerning the respective factor; reference scenarios: "no action" alternatives

Foot notes:
1: Increased potential of accidents due to potentially hazardous production conditions
2: Increased impact potential expected due to potentially hazardous substances
3: Increased impact potential expected due to radioactive substances; although the emission level during normal operation is low, the toxicity can be quite high.

## 5.2 Comparison: Sorghum scenarios versus conventional systems

This subchapter comprises a comparison of the sorghum scenarios and the conventional systems, divided into feedstock provision (subchapter 5.2.1) and conversion (subchapter 5.2.2).

### 5.2.1 Feedstock provision

The provision of feedstock is linked to local environmental impacts varying according to the type of feedstock and the technology. Both types of feedstock (renewable / non-renewable) can be used for energy production as well as for further processing (e.g. chemical industry). However, there are fundamental differences in provision technologies which in case of bio-based feedstock are linked with different management types for soil and cultivation.

Since type of risks associated with these technologies are completely different in quality and quantity, a direct comparison is not possible. Nevertheless, Table 5-12 summarises impacts on local environmental factors assuming a reference system of no use on a sustainability level, choosing three different impact categories: heavy, medium and low.

The types of risks expected from provision of fossil feedstock are fundamentally different and in general are based on extraction technologies focussing on components below the surface. A restoration of the original status is normally impossible.

From a sustainability point of view, impacts related with the provision of bio-based feedstock are expected to be mostly reversible. For instance, the depletion of soil organic matter (SOM) due to agricultural cultivation or management, depletion of water due to use of fertiliser and pesticides or loss of habitats and species due to changes in land use can be compensated over a certain period of time if risk factors responsible for the impact will be abandoned. However, most of the impacts from conventional fossil feedstock provision especially on soil, flora, fauna and landscape are expected to be long-term changes and non-reversible.

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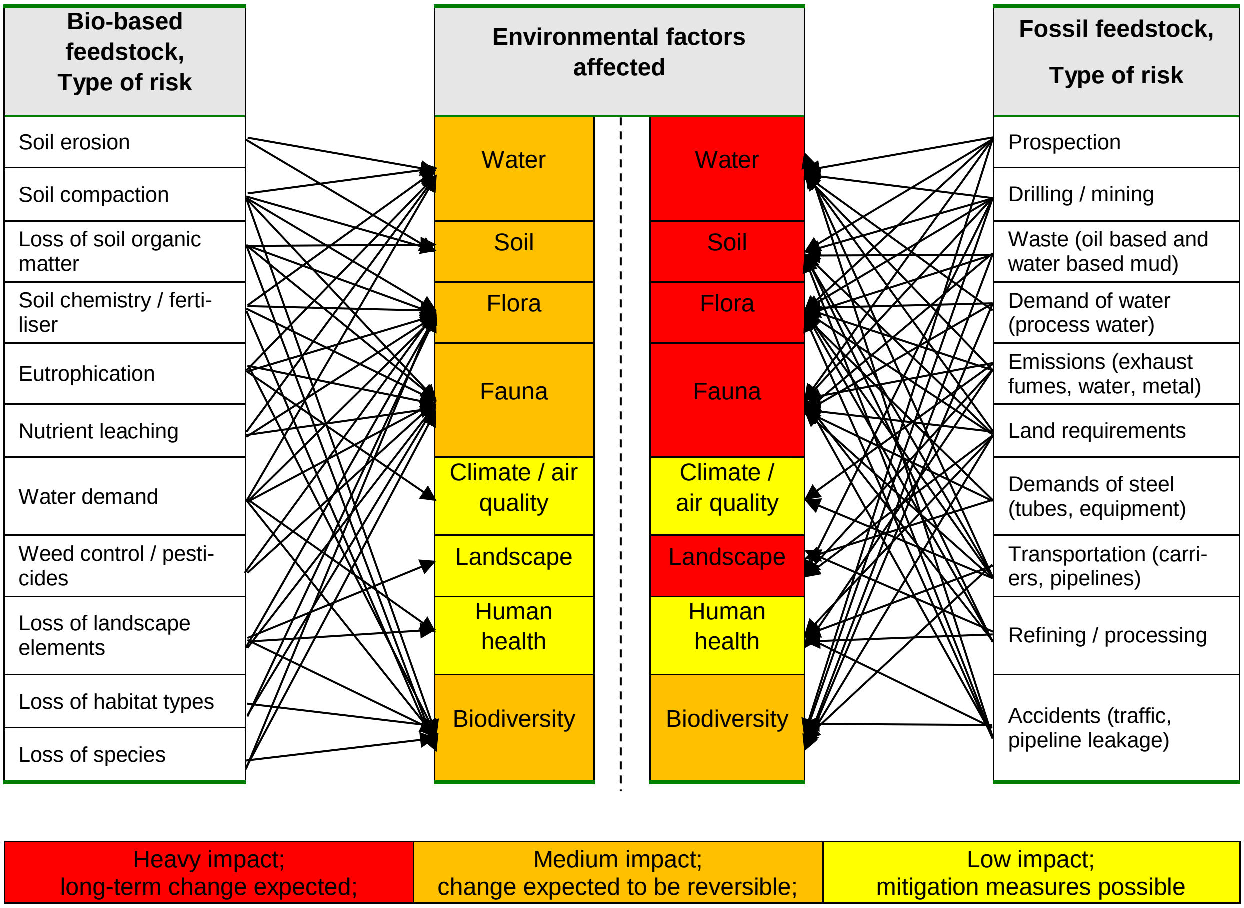
**Table 5-12** Comparison of impact on environmental factors due to provision of sweet and biomass sorghum and conventional feedstock regarding impact sustainability in three different categories; reference system: no use.




### 5.2.2 Feedstock conversion

The challenges during the implementation of biomass conversion units and reference technologies are similar. According to the applied methodology there are impacts related to

1. the construction of the plant
2. buildings, infrastructure and installations on-site
3. the operation of the plant

**Construction phase**

Compared to the respective biomass conversion units significant differences from impacts related with the construction of conventional conversion units are not expected.

**Buildings, infrastructure and installations (size and height of the plant)**

No differences are expected from impacts related to buildings, infrastructure and installations. All technologies considered need processing facilities, energy generation, administration buildings, waste water treatment etc. Impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is

negligible. Scaling up plants from different technologies to comparable outputs and yields might further minimise the differences in land consumption. For both sorghum as well as conventional conversion units significant impacts are expected on water, soil, plants, animals and landscape due to the construction of buildings, infrastructure and installations.

**Operation phase**

When comparing the respective sorghum conversion units to the conventional conversion units no differences are expected from

- emission of noise
- emission of light
- waste water production and treatment

Each type of refinery / plant emits noise and light and releases waste water. Most impacts on the environment are comparable on a generic level. As long as legal thresholds and state-of–the-art technologies are provided qualitative differences are not expected.

Additional significant impacts are expected during operation of the plant, due to risks of explosions and fire in the plant or the storage areas, accidents and production / treatment of waste. Depending on the location of the plant, additional impacts might occur due to

- drain of water resources for production (environmental factor: water),
- waste water production / treatment and release to the environment (environmental factors: water, plants, animals, biodiversity),

which might be lower in case of conventional refineries as they are usually associated with water reservoirs (sea, big rivers) due to facilitate cooling and transportation.

*Emission of gases and fine dust (refinery)*

Gases (e.g. odours) in most of the considered technologies are expected to be equal, whereas unfavourable gases are often linked to crude oil refineries in combination with chemical refineries.

In nuclear power plants, emissions of radioactive substances are verifiable. The effect of low radiation doses on the environment are still under investigation and not yet completely clear. For instance a study done by the Federal office of radiation protection /BfS 2007/ in Germany confirms a significant correlation between the distance of residence from the nearest nuclear power plant at the time of the diagnosis and the risk of developing cancer (leukaemia) before the 5th birthday.

*Drain of water resources for production*

The need for water especially in conventional refineries (very often situated along navigable rivers in order to benefit from lower transportation costs) might be of less concern. According to /Jungbluth 2007/ the average demand for process water in a conventional oil refinery is projected at 0.6 $m^3$ of water / t of crude oil plus 4 $m^3$ of water / t crude oil of cooling water. This has impacts on environmental factors water (superficial water) and the life associated

with it (e.g. aquatic animals, plants). Impacts on the surrounding might be less due to locations associated with water (big rivers, lakes, sea).

Sorghum conversion units would be situated close to areas with feedstock production, due to the minimisation of transportation routes and costs. The water demand in sorghum conversion units can even be higher than in a conventional conversion unit. In case of water scarcity especially in water-scarce regions during dry periods this might lead to enormous risks, affecting environmental factors like water, animals, plants, landscape and human beings.

*Traffic (emissions, collision risk)*

Differences are expected from traffic related with feedstock provision. Emissions from the provision of a sorghum conversion unit driven with local feedstock will concentrate around the plant, resulting basically in an increase of vehicle movements (delivery of feedstock and products) in combination with an increase in emissions and the risk of accidents. Impacts are expected to be local. The provision of fossil driven refineries and power plants goes along with long distance transportation by ship / railway and / or pipelines with little impacts on local traffic. From a life cycle-oriented point of view, differences in impacts might be lower especially if risks of accidents (e.g. oil spills) are taken into account but this goes beyond the scope of the applied methodology.

Crude oil as well as coal or “yellow cake” is brought to European refineries with huge tank ships. Long-distance transportation increases exhaust fumes (cargo ship, lories) with potential impacts on water (ocean), related organisms (plants, animals, biodiversity), air quality and landscape. Natural gas is provided in pipelines with additional impacts on the environment. The distribution in Central Europe basically runs over pipelines and vessels. Nevertheless in general transportation impacts of fossil feedstock imports exceed impacts from sorghum conversion units with local feedstock production.

As the range of impact is expanded to intercontinental scale there is, with means of EIA methodology designed for site-specific impacts, hardly any affection detectable due to dilution. Enlarged ranges of impact reduce its local significance. The effect might be clearer from an LCA point of view.

Nuclear power plants provide a special risk due to transportation of high-level radioactive waste such as sending nuclear fuel to reprocessing plants in special CASTOR-containers (CASTOR = **ca**sk for **s**torage and **t**ransport **o**f **r**adioactive material). The substances are radioactive and radiation is detectable outside the castor-containers. In addition, some of the radionuclides transported are highly poisonous (e.g. plutonium) and potentially dangerous to the environment.

*Electromagnetic emissions*

Power generation plants driven by fossil fuels are usually large scale constructions. Accordingly high electromagnetic emissions are to be expected. Contrarily within the biomass sorghum scenarios “biogas and biomethane production” and “direct combustion” small scale plants are used for biomass conversion and power generation while within all other sorghum scenarios no power is generated at all. For this reason conventional systems lead to higher

environmental impacts due to electromagnetic emissions from high-voltage transmission lines.

*Disposal of waste materials / residues*

All types of refineries / plants produce solid waste during operation. Except for the ashes produced in the biomass sorghum scenario “direct combustion”, the residues from sorghum conversion units are biodegradable (potential use of fertiliser) or combustible (potential use in CHP) with potentially lower impacts on the environment than the residues from the conventional conversion units. Taking into account statutory frameworks for the operation of plants, non-biodegradable solid waste should be collected and provided for correct disposal. Considerable risks are expected in crude oil refineries especially when combined with chemical refineries as a number of dangerous substances are produced.

A potentially high risk to the environment are nuclear wastes from nuclear power plants, as an ultimate waste disposal is still pending, causing a long-term threat to the environment and society including human health.

*Risk of accidents and explosion, fires in plant and storage areas, release of GMO*

Biotechnical production plants have advantages regarding the quality of the processes and the substances used as they usually operate under relatively soft conditions such as lower temperature, relatively low pressure and very often in aquatic ambience. Chemical-technical production processes are often related with high temperatures, high pressure, use of organic solvents as well as the existence of pollutants. Otherwise the biotechnical production can have a specific risk due to possible releases of organisms being ecologically (genetically modified) and hygienically relevant, although the “related hazardous potential is classified at the most as ‘low’ and probably as ‘negligible’” /Hoppenheidt et al. 2004/.

Dealing with a higher hazardous potential on substances and processing techniques both the risk of accidents and the potential consequences for the environment from chemical technical processes exceed sorghum conversion units by far as historical and latest news could demonstrate (e.g. Switzerland, fire in the Sandoz plant in November 1986; Venezuela, fire in the Amuay refinery, in August 2012).

Nuclear technology bears an enormous risk as consequences from the core meltings of Chernobyl (26 April 1986) and Fukushima (11 March 2011) could proof. Radioactive releases and the toxicity of radionuclides have severe and enduring impacts on the environment as well as the total biosphere. Consequences of these disastrous accidents are still under investigation.

**Comparison of conversion technologies**

The comparison of the conversion technologies on technological related factors is summarised in Table 5-13.

**Table 5-13** Potential impacts on the environment related to different technologies regarding feedstock conversion and transport.

| Technology / Product — Technology related factor | Sorghum conversion | | | | | | | Conventional conversion | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fuel | | Energy | | | Fuel | | Fuel | Energy | | |
| | Centralised | Decentral syrup prod. | Anaerobic digestion | Anaerobic digestion | Direct combustion | 2G ethanol | Gasification | Crude oil refinery | Crude oil/ Gas plant | Coal plant | Nuclear power plant |
| | 1G ethanol | 1G ethanol | Heat and power | Methane | Heat and power | Ethanol | FT fuels | Fuels | Heat and power | Heat and power | Heat and power |
| **Impacts resulting from construction phase** | | | | | | | | | | | |
| Construction works | C | C | C | C | C | C | C | C | C | C | C |
| **Impacts related to buildings, infrastructure and installations** | | | | | | | | | | | |
| Buildings, infrastructure and installations (size & height) | E | E | E | E | E | E | E | E | E | E | E |
| **Impacts resulting from operation phase** | | | | | | | | | | | |
| Emission of noise (conversion unit) | D | D | D | D | D | D | D | D | D | D | D |
| Emission of gases and fine dust (conversion unit) | C | C | C | C | C | C | C | D | C | D | C[4] |
| Emission of light (conversion unit) | C | C | C | C | C | C | C | C | C | C | C |
| Drain of water resources for production (conv. unit) | D | D | D | D | D | D | D | D | D | D | D |
| Waste water production and treatment (conv. unit) | D | D | D | D | D | D | D | D | D | D | D |
| Traffic (collision risk, emissions) | C | C | C | C | C | C | C | C | C | C | E[3,4] |
| Electromagnetic emissions from high-voltage transmission lines | C | C | D | C/D | D | C | C | C | D | D | D |
| Disposal of wastes/residues | B | B | B | B | C | B | C | D[3] | C | C | E[3,4] |
| Risk of accidents<br>- explosion<br>- fire in the plant<br>- fire in the storage areas<br>- release of GMO | C | C | C | C | C | C/D[1] | C/D[2] | E[2,3] | E[2,3] | E[2,3] | E[2,3,4] |

Impacts are ranked in five comparative categories; “A” is assigned to the best options concerning the respective factor, “E” is assigned to unfavourable options concerning the respective factor; reference scenarios: “no action” alternatives

1: Increased impact potential expected due to operating with GMO (risk of release)
2: Increased potential of accidents due to potentially hazardous production conditions
3: Increased impact potential expected due to potentially hazardous substances
4: Increased impact potential expected due to radioactive substances; although the emission level during normal operation is low, the toxicity can be quite high.

## 5.3 Summary: LC-EIA

The methodological approach developed for the assessment of local environmental impacts in SWEETFUEL is labelled a Life Cycle - Environmental Impact Assessment (LC-EIA). The main idea of this approach is to apply major elements of EIA to a complete life cycle on a generic basis. Due to this approach, it is possible to supplement the Life Cycle Assessment (LCA) by elements of EIA.

The main features of the LC-EIA approach can be summarised as follows:

- The intensity and resolution of the environmental effects can be arranged between the classical project-related EIA and the strategic environmental assessment (SEA).
- The outcomes of the LC-EIA are fully compatible to LCA. Results of the LC-EIA give a new quality to the environmental impact category "land use" within the standardised methodology of LCA, by not only balancing the area needed for the application of a new technology but additionally giving information on the quality of the land use change and its possible impacts on local environmental factors.
- LC-EIA is broadening the scope of EIA (as well as SEA) in terms of assessment of a whole life cycle. The local approach of classical EIA usually prevents the inclusion of local environmental effects outside of certain administrative boundaries and thus possibly neglects important environmental effects, e.g. on biodiversity.
- Due to the generic, technology-focussed approach, different scenarios can be assessed and compared more quickly and easily.
- Therefore, an assessment of overall sustainability of a new technology can be carried out more easily and the optimisation of technology-implementation by finding the best options or possibilities to remedy environmental effects can be done more effectively.
- Within the framework of SWEETFUEL and other related projects a comparable methodology for the analysis of biomass production and conversion can be used.

In the following the main results of the LC-EIA conducted in subchapters 5.1 and 5.2 are summarised. Subchapter 5.3.1 focuses on the main results regarding the cultivation und use of sweet sorghum while subchapter 5.3.2 presents the main results regarding the cultivation and use of biomass sorghum. An overall conclusion and a reflection of the LC-EIA results in the broad context of the SWEETFUEL project is given in subchapter 6.1.2.

### 5.3.1 Sweet sorghum scenarios

Local environmental impacts are primarily dominated by 'biomass provision'. The other life cycle stages such as the provision of fertilisers or biomass conversion in ethanol facilities play only a subordinate role. Where sweet sorghum is cultivated on what was previously agricultural land, field crops are displaced. Assuming constant demand they must then be cultivated elsewhere. From an accounting perspective, for this purpose only land comes into question that has not been used agriculturally yet (see subchapter 3.1). These areas are referred to as the agricultural reference system. During the conversion and subsequent agri-

cultural exploitation of these areas a variety of local environmental impacts occur, depending on the agricultural reference system. Sweet sorghum cultivation therefore indirectly leads to field conversion, which is thus also referred to as indirect land use change (iLUC).

- If the reference system is based on 'idle land', land use changes and land cultivation can negatively impact the soil (e.g. erosion, compaction, nutrient extraction), the hydrologic balance (for example nutrient input, pesticide input, water demand), and flora, fauna and biodiversity (e.g. habitat destruction, soil compaction, pesticides).
- If the reference system is based on habitats with a comparatively high ecological value such as pastures or wooded areas, for example, the local impacts on flora, fauna and biodiversity can be much more serious, whereby additional negative impacts on local climate regulation and the landscape may occur.

From a purely qualitative perspective, the environmental impacts caused by sweet sorghum cultivation are very similar across all the investigated sweet sorghum scenarios (given the same reference system). In comparison, from a quantitative perspective, the local environmental impacts of the 'grain to food' scenario are substantially less grave than the local environmental impacts of the other two scenarios ('cane fallow' and 'syrup production'). The reason for this is the considerably lower coverage of cultivated area by the indirect land use change: only approximately 0.2 ha of compensation area are required to cultivate 1 ha of sweet sorghum in the 'grain to food' scenario compared to 1 ha respectively in the 'cane fallow' and 'syrup production' scenarios.

In order to fundamentally reduce the local environmental impacts of sweet sorghum cultivation, the following demand arises: care should be taken that the substitute areas for field crop cultivation (for example soya or peanuts in the 'cane fallow' scenario, grain sorghum in the 'grain to food' scenario and a variety of field crops in the 'syrup production' scenario) are of comparatively low ecological value. Under no circumstances sweet sorghum should be cultivated on areas classified as biodiversity hot spots, or on land that has a high carbon inventory, performs a special hydrologic balance function, or is characterised by a remarkable landscape.

As already noted briefly above, less grave local environmental impacts arise from other life cycle stages, for example from the use of agricultural materials and fuels or from transport infrastructure conditions:

- Local environmental impacts created by sweet sorghum cultivation's material and fuel demand at the material and fuel production location comprise, among other things, the water demand at that location, exhaust gas emissions, disposable wastes and wastewaters. Because only a small proportion of the overall production at the respective material and fuel production locations is used for sweet sorghum cultivation, the local environmental impacts occurring at those locations are only of subordinate relevance to the analysis of sweet sorghum cultivation.
- Because in all three scenarios sweet sorghum is cultivated on land previously used agriculturally, it can be assumed that sufficient road infrastructure already exists and can be utilised, so that no local environmental impacts occur in these areas. Depending on the location of the substitute area, where either soya / peanuts ('cane fallow'),

grain sorghum (‘grain to food) or possibly other field crops (‘syrup scenario’) are cultivated, additional road infrastructure must be built. Inasmuch as additional road infrastructure must be built, local environmental impacts on flora, fauna and biodiversity (habitat destruction and fragmentation), as well as on the soil and the hydrologic balance (surface sealing), must be anticipated.

- Due to the sugar content in the sweet sorghum stalks their storage tolerance is strongly limited which requires immediate processing. In contrast to the central ethanol plant ("cane fallow" and "grain to food" scenarios, respectively), in the syrup production scenario additional - however insignificant - impacts are expected caused by the need for syrup storage facilities. The construction of the small tanks to store the syrup produced at village level imposes negative impacts on soil, water, animals and plants due to clearing, sealing and compaction of soil. On the other hand, due to the concentration of the sweet sorghum juice in the scenario “syrup production”, less biogenic material needs to be transported to the central ethanol plant compared to the scenarios “cane fallow” and “grain to food”, which both encompass direct delivery of sweet sorghum stalks to the ethanol plant.
- Compared to conventional gasoline, the energy content of ethanol is significantly lower. The consequence of this is an overall increase in refuelling frequency and thus an increase in traffic volume, which is in turn associated with a greater noise nuisance and exhaust emissions that might lead to local environmental impacts on the soil, flora, fauna, air quality and human health.

Life cycle stage „biomass conversion“: With respect to the construction of the central bioethanol plant major impacts on soil, water, flora, fauna, biodiversity and landscape are to be expected due to clearing, sealing and material inputs needed. During operation of the bioethanol plant, environmental impacts on water, soil and air are to be expected due to the water demand and the wastewater discharge, the release of gases and fine dust as well as potential accidents. Since ethanol substitutes for conventionally produced gasoline, the sweet sorghum conversion can be compared to the conversion of crude oil in a crude oil refinery. Greater emissions of unfavourable gases as well as a higher risk of hazardous accidents due to the production of dangerous substances, the long-distance transportation of oil and the processing at high pressure and temperature conditions can be identified.

It can be summarised that, depending upon life cycle stages, different local environmental impacts develop that differ in their respective intensity – from less serious to extremely unfavourable. The individual conclusions and recommendations derived from this are given in subchapter 6.1.2.

### 5.3.2 Biomass sorghum scenarios

In Europe, conversion of forest areas is prohibited by law and conversion of grasslands only possible to a small degree. 'Idle land' is therefore adopted exclusively as the agricultural reference scenario for biomass sorghum cultivation (see subchapter 3.2).

As discussed above for the sweet sorghum scenarios, the local environmental impacts in the biomass sorghum scenarios are essentially determined by the cultivation of the biomass. These are cultivation-related impacts on the soil (for example erosion, compaction, nutrient extraction), the hydrologic balance (for example nutrient input, pesticide input, water demand) and flora, fauna and biodiversity (for example habitat destruction, soil compaction, pesticides). In addition, extra local environmental impacts, some quite serious, may occur, in particular with regard to soil quality and local biodiversity, as a result of increasing land pressure or monocultures. Developments in this direction are likely to occur in two cases:

- Increase in conversion efficiency with the consequence that larger facilities are built as a general rule. Since larger facilities require more charging material, more biomass sorghum must be cultivated. However, due to logistical and cost reasons this should occur within a given radius around the facility.
- Biomass sorghum is harvested comparatively wet for biogas and biomethane production, meaning that from an economical perspective the harvested crop displays only low transportability. For large, and therefore efficient, biogas facilities, large quantities of biomass sorghum must therefore be cultivated spatially close to the biogas facility.

In contrast to this, less grave local environmental impacts arise from other life cycle steps, in particular from the use of agricultural materials and fuels, as well as from transport infrastructure conditions:

- Among other things, the local environmental impacts ensuing from the production of materials and fuel comprise water demand, exhaust gas emissions, disposable wastes and wastewaters. However, these local environmental impacts are of only subordinate relevance.
- Because Europe represents the spatial context for biomass sorghum production, it is assumed that sufficiently well-developed transport infrastructure already exists, meaning that no local environmental impacts occur as a result of road building.
- If biogas or biomethane are produced from biomass sorghum, the relatively wet-harvested biomass is ensilaged in bunker silos and then transported as needed to the biogas facility. Relatively little infrastructure is associated with this process. The situation is different if second generation ethanol or synthetic fuels are produced, or biomass sorghum is exploited for energy production (scenarios: '2G ethanol', 'direct combustion' and 'gasification'). Here, biomass sorghum is harvested dry and large warehouses or stores are required. Their construction leads to environmental impacts on flora and fauna (habitat destruction), as well as on the soil and the hydrologic balance (soil compaction, sealing).
- If second generation ethanol is produced from biomass sorghum ('2G ethanol' scenario), the result is an overall increase in refuelling frequency and thus an increase in traffic volume as a result of the lower energy content of ethanol compared to conventional gasoline. This is associated with a greater noise nuisance and exhaust emissions that might lead to local environmental impacts on the soil, flora, fauna, air quality and human health.

In contrast to this, the 'biomass conversion' life cycle stage displays greater local environmental impacts: When building the various biomass sorghum exploitation technologies (a biogas and a 2G bioethanol facility, a CHP plant for direct combustion and a BtL facility for the gasification scenario), (serious) impacts, on the soil, the hydrologic balance, flora, fauna, biodiversity, and the landscape must be anticipated. As a result of the operation of these facilities also local environmental impacts on the soil, the hydrologic balance and air quality can be expected due to the water demand, the production of wastewater, waste disposal, exhaust gas and particulate emissions as well as the possibility of accidents.

Thus, it can be summarised that, depending upon life cycle phase, different local environmental impacts develop that differ in their respective intensity – from less serious to extremely unfavourable. The individual conclusions and recommendations derived from this are given in subchapter 6.1.2.

# 6 Conclusions and recommendations

Based on the results of the previous subchapters, the conclusions of the life cycle assessment (LCA) and the life cycle environmental impact assessment (LC-EIA) are presented in subchapter 6.1. Recommendations for decision makers are given in subchapter 6.2.

## 6.1 Conclusions

In this subchapter the conclusions of the life cycle assessment (LCA) and the life cycle environmental impact assessment (LC-EIA) are given separately in subchapters 6.1.1 and 6.1.2. Subchapter 6.1.3 concludes on the combination of both sets of findings.

### 6.1.1 Life cycle assessment

In this subchapter the conclusions of the life cycle assessment for sweet and biomass sorghum are presented.

**I. Conclusions: Ethanol from sweet sorghum**

The most important differences between the sweet sorghum scenarios considered for this study are listed here once again for the benefit of the hurried reader. A more detailed description can be found in subchapter 3.1:

- **Cane fallow**: sweet sorghum is cultivated as an intermediate crop, for example between two sugar cane cycles.
- **Grain to food**: sweet sorghum is cultivated on land previously used to cultivate grain sorghum.
- **Syrup production**: the sweet sorghum sugar juice is first concentrated into syrup on a decentralised basis at village level. The syrup is then processed further to ethanol in a centralised ethanol plant.

**Environmental benefits and drawbacks:** Compared to conventional gasoline, both environmental benefits and drawbacks can be observed in all sweet sorghum scenarios, depending on the environmental impact category considered. In the 'cane fallow' and 'grain to food' scenarios, the production and use of bioethanol from sweet sorghum contributes to conserving non-renewable energy sources and reducing greenhouse gases. However, additional burdens are created in the environmental impact categories acidification, terrestrial and aquatic eutrophication, human toxicity (particulate matter) and stratospheric ozone. In the 'syrup production' scenario additional burdens ensue in all environmental impact categories under the majority of boundary conditions. The production of bioethanol from sweet sorghum does not have any relevant impact on the environmental impact category photosmog in any of the three scenarios.

**Specific conclusions:** Because some of the specific conclusions for the 'syrup production' scenario differ considerably from the other two scenarios, they are described separately from them.

***'Cane fallow' and 'grain to food' scenarios***

In principle, the majority of expenditures and credits are influenced by the stalk yield and the amount of sugar they contain. A high yield per hectare therefore leads to both greater greenhouse gas savings and greater non-renewable energy resource savings. In addition, it increases the land use efficiency, contributing to a reduction in conflicting objectives between fuel and food plants. From this it can be derived that optimisation of the cultivation conditions with the aim of increasing yields is a high priority objective. This can be achieved e.g. by cultivation on fertile soils and under good climatic conditions, usage of cultivars adapted to the location with high sugar yields, and optimised cultivation methods.

In addition, different life cycle stages influence the expenses and credits of bioethanol production from sweet sorghum to varying degrees. In many of the environmental impact categories the following life cycle steps dominate:

- **Fertiliser:** In many categories the fertiliser applied for sweet sorghum cultivation and the associated field emissions represent a large proportion of expenses. Basically, cultivating sweet sorghum variants which contain fewer nutrients in their harvested biomass presents a large optimisation potential, since then less mineral fertiliser needs to be applied in the future. This means that not only fewer resources are required for fertiliser production, but also that fertiliser-induced field emissions (for example nitrous oxide) are simultaneously reduced.
- **Credit for fossil fuels:** The greater the conversion efficiency, the more ethanol can be extracted from a tonne of sugar and the less bagasse is required to provide the same amount of energy for the conversion process. Both parameters predominantly influence the credits for avoided expenses for gasoline production and the amount of excess power arising from the provision of the process energy.
- **Utilising by-products:** Depending on the environmental impact category and scenario, utilisation of the by-products can have a highly beneficial impact on the overall result and therefore represents a particularly large optimisation potential. This includes:
    - **Surplus bagasse:** Surplus bagasse shows high savings of greenhouse gases if used for bioenergy production; however it should only be used for bioenergy production if the use as feed is not needed to relieve pressure on regional land availability. This is especially important if limited land availability would otherwise lead to conversion of valuable ecosystems into cropland. If land that becomes available through reduction of conventional feed production would be used for more sorghum cultivation, preferences may depend on exact conditions and a further quantification is required.
    - **Leaves:** If the leaves are utilised as a bioenergy source, considerably better results are achieved comparing leaving the leaves on the field – with a corre-

sponding fertiliser effect. However, attention should be paid that leaf removal is sustainable, i.e. the organic substance of the soil is not negatively impacted. The maximum sustainable removable quantity varies according to the site and must be determined on a case-by-case basis.

- **Grains**[1]: Better results are achieved if the grains are processed to ethanol, instead of being left on the field – with a corresponding fertiliser effect.

- Land use change: If land use changes occur as a result of sweet sorghum cultivation, the result of greenhouse gas balancing depends heavily on the original carbon stock (surface and subsurface) of the area under cultivation. The larger the original carbon stock, the worse is the greenhouse gas balance (but depending on the period of amortisation). Sweet sorghum for ethanol production should therefore be cultivated on land with as low a carbon stock as possible as long as it is not required for food cultivation.

In contrast, other life cycle stages display no, or only minor, impacts on the results, meaning that no significant optimisation options are presented here. This includes:

- **Transport:** The transport distance has only a minor impact on the overall result. This applies to both the transport of sweet sorghum to the ethanol plant – even for relatively large, economically unviable distances – and for transporting ethanol to the consumer – even across oceans.
- **Conversion efficiency:** It can be shown that the overall results are improved slightly the higher the conversion efficiency. However, because the influence of conversion efficiency in the ethanol plant is relatively small, there is only a very minor optimisation potential.

**In summary**, sweet sorghum cultivation and its utilisation as bioethanol displays, compared to conventional energy carriers, large environmental potentials and opportunities for optimisation in terms of saving greenhouse gases and non-renewable energy resources or minimising negative environmental impacts.

***'Syrup production' scenario***

In principle, the majority of expenses and credits in the 'syrup production' scenario are influenced by the stalk yield and the amount of sugar they contain, similar to the 'cane fallow' and 'grain to food' scenarios. However, in the 'syrup' scenario higher biomass yields per hectare cultivated land compared to conventional gasoline lead to a greater environmental burden in all environmental impact categories. Where decentralised sugar juice processing is aimed for, higher biomass yields should therefore not be in the foreground, inasmuch as no additional optimisation measures are implemented.

Further conclusions and optimisation options include:

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[1]Note: In the grain to food scenario no grains are available for ethanol production by definition.

- **Optimisation of cultivation conditions** (cultivation on fertile soils and under good climatic conditions, usage of cultivars adapted to the location with high sugar yields, optimised cultivation methods).
- In many categories the **fertiliser** applied for sweet sorghum cultivation and the associated **field emissions** represent a large proportion of expenses. Basically, cultivating sweet sorghum variants which contain fewer nutrients in their harvested biomass presents a large optimisation potential, since then less mineral fertiliser needs to be applied in the future. This means that not only fewer resources are required for fertiliser production, but also that fertiliser-induced field emissions (e.g. nitrous oxide) are simultaneously reduced.
- The greater the **conversion efficiency**, the more ethanol can be extracted from a tonne of sugar and the less bagasse is required to provide the same amount of energy for the conversion process (syrup production). Both parameters predominantly influence the credits for avoided expenditures of gasoline production and the conversion expenses for syrup production. On the whole, it can be shown that the overall results in all environmental impact categories are improved slightly the higher the conversion efficiency. However, because the influence of conversion efficiency is relatively small, there is only a very minor optimisation potential.
- In the 'syrup production' scenario **external energy** must be provided for the conversion process, because the bagasse is already used to concentrate the sugar juice and is no longer available as an internal energy source. Coal, fuel oil or rice straw can be used as external energy sources, for example. Compared to conventional energy sources the use of rice straw impacts very positively on the greenhouse gas and energy balances. However, the use of rice straw impacts negatively on the majority of other environmental impact categories. From an environmental perspective, therefore, decentralised processing of sugar juice to syrup should only be considered if it is possible to exploit a renewable energy source, if possible comprising residual substances, to provide the primary process energy.
- **Land use changes:** If land use changes occur as a result of sweet sorghum cultivation in the 'syrup production' scenario, the greenhouse gas balance is worse the higher the original carbon stock (but depending on the period of amortisation). Sweet sorghum for ethanol production should be cultivated on land with as low a carbon stock as possible, similar to the other two scenarios.

**In summary**, a decentralised syrup production with a subsequent centralised processing of the syrup to ethanol only displays environmental benefits under very stringent boundary conditions. The focus lies primarily on two areas: the efficiency of sugar concentration to form syrup using bagasse and therefore the availability of surplus bagasse for other purposes, and, secondly, the provision of energy for ethanol production from syrup.

**II. Conclusions: Sorghum biomass**

Conclusions with regard to the production of biogas from biomass sorghum and its utilisation in a combined heat and power unit are presented first. The conclusions of the alternative biogas use options and alternative biomass sorghum use options (direct combustion, second generation ethanol, FT fuels) are described afterwards.

**Environmental benefits and drawbacks:** As a result of the production of biogas from biomass sorghum and its utilisation in a CHP, both environmental benefits and environmental drawbacks occur compared to conventional energy resources for generating power and heat, (e.g. coal or fuel oil), depending on the environmental impact category being considered. Under the majority of boundary conditions biogas from biomass sorghum contributes to saving fossil energy resources and reducing greenhouse gases. Additional burdens are generally created in the environmental impact categories acidification, terrestrial and aquatic eutrophication, and stratospheric ozone. In the human toxicity (particulate matter) and photochemical ozone formation (photosmog) categories the balances are predominantly well- balanced.

**Optimisation of cultivation conditions:** The results of the majority of environmental impacts are essentially determined by the biomass yield. A higher yield, for example achieved by optimising the cultivation conditions (cultivation on fertile soils and under good climatic conditions, usage of cultivars adapted to the location with high sugar yields, optimised cultivation methods), leads to greater greenhouse gas savings and enhanced savings of non-renewables, for a simultaneously heavier burden imposed by the remaining environmental impacts. In addition, higher yields are clearly favourable due to the fact that the land use efficiency rises, contributing to a reduction in conflicting aims between the production of bioenergy and food plants.

Different life cycle stages influence the expenses and credits to varying degrees depending on the environmental impact category and therefore respectively display differing optimisation options. The following life cycle stages dominate many of the environmental impact categories:

- **Fertiliser:** In many categories the fertiliser applied for sweet sorghum cultivation and the associated field emissions, in particular of nitrous oxide and nitrate, impact substantially on the results of many environmental categories. Basically, cultivating sweet sorghum variants which contain fewer nutrients in their harvested biomass presents a large optimisation potential, since then less mineral fertiliser needs to be applied in the future. This means that not only fewer resources are required for fertiliser production, but also that fertiliser-induced field emissions (e.g. nitrous oxide) are simultaneously reduced.
- **Digestate storage:** An additional element of the expenses in various environmental impact categories is determined by the mode of digestate storage. If the digestate storage is not covered, the impact on the greenhouse effect is particularly unfavourable as a result of the increased methane emissions. Moreover, an uncovered digestate store leads to increased ammonia emissions, which impact negatively on the terrestrial eutrophication and acidification impact categories. Optimal results can there-

fore be achieved by ensuring that the digestate storage is provided with a gas-tight cover.

- **Digestate application:** The amount of nitrous oxide and ammonia emissions resulting from digestate application and affecting several environmental impacts, such as the greenhouse effect or acidification, is primarily dependent on the time of digestate incorporation into the soil. Incorporating into the soil within an hour reduces the nitrous oxide and ammonia emissions compared to an incorporation period of 24 hours by around 70 %. The digestate should therefore be incorporated into the soil immediately after application.
- **Fossil fuels savings**: By using biogas from biomass sorghum, expenses incurred during the production and use of fossil fuels can be avoided:
  - The **conversion efficiency** generally increases with the size of the conversion plant. The larger the plant, the more biogas per hectare per year can be produced and the larger are the electrical and thermal efficiency in general. This impacts positively on the credits in almost all environmental impact categories. Biomass processing in a large plant therefore proves to be advantageous.
  - The utilisation of biogas impacts positively on the balances if both the electricity and as much as possible of the heat produced can be utilised. Maximum utilisation with a high thermal efficiency should therefore be aimed for.
  - Depending on the **energy comparison system** and the environmental impact, the avoided expenses for the production and utilisation of fossil fuels may be larger or smaller. The differences are almost exclusively determined by the variations in the credits for power production. If a large proportion of coal is replaced, whose utilisation is associated with large $CO_2$ emissions, substantial benefits result in almost all categories compared to natural gas. The more carbon released during the combustion of the substituted energy source, the more can be saved and therefore the better is the overall result. However, because the choice of substituted energy source cannot generally be influenced, the optimisation potential is relatively small.

In contrast, other life cycle steps display no, or only minor, impacts on the results, meaning that no significant optimisation options are presented here. Among others, these include the transport distances.

### Biogas utilisation options

In principle, biogas can be exploited on-site using a variety of technologies. Otherwise, it may be processed to biomethane, fed into a natural gas network and be utilised elsewhere – here, too, with a variety of technologies and uses: for example as fuel or as combustible for power or heat generation. The following results and conclusions are given:

- **Power generation:** Compared to utilisation in CHP, the alternative utilisation of biogas from biomass sorghum for pure power generation displays the same or only slightly worse results in all environmental impact categories.

- **Compared to biomethane:** Direct generation of biogas in CHP reveals substantial benefits in the energy and greenhouse gas balance compared to biomethane, if biogas is produced under the same conditions as biomethane (covered digestate storage, 100 % heat utilisation). Optimised direct utilisation of the biogas should therefore be pursued.
- **Biomethane:** From an environmental perspective, if biogas has to be processed to biomethane, biomethane utilisation in CHP is far more preferable to utilisation as a natural gas substitute or as a fuel.

**Alternative biomass utilisation options**

In addition to utilising biogas in CHP, the biomass can also be utilised in other ways. Some of the differences in the results are considerable:

- **Direct combustion:** If biomass sorghum is directly combusted to generate bioenergy, it displays the greatest life-cycle assessment benefits compared to biogas production. This is because the biomass is left on the field until the water content has dropped to a level to allow the biomass to be directly combusted without the necessity for a drying step. Under these conditions, direct combustion and utilisation in CHP should be preferred over fermentation to biogas.
- **Pure power or heat generation:** These utilisation options provide poorer results compared to utilisation in CHP, in almost all environmental impact categories.
- **$2^{nd}$ generation ethanol and FT fuels:** From an environmental perspective the production and utilisation of biogas should be preferred over the conversion of lignocellulose-based biomass into the innovative biofuel $2^{nd}$ generation ethanol or into FT fuel (with and without pyrolysis).

**In summary**, biomass sorghum cultivation and its utilisation as biogas displays a large environmental potential and a number of opportunities for optimisation in terms of saving greenhouse gases and non-renewable energy resources and minimising negative environmental impacts compared to conventional energy carriers.

### 6.1.2 Life cycle environmental impact assessment

Concerning local environmental impacts, results of the comparison between the SWEETFUEL scenarios and conventional reference systems vary depending on the life cycle stage. Due to the fact that the individual associated risks differ considerably between the bio-based and conventional life cycles in both qualitative and quantitative terms, a meaningful comparison may be drawn at the level of the affected environmental factors only.

Generally, the local environmental impacts are primarily dominated by the biomass cultivation life cycle stage. The downstream phases (biomass conversion), in contrast, play a more subordinate role.

**Biomass provision:** With regard to raw materials provision, biomass tends to be advantageous compared to fossil reference products, as long as the biomass in question is produced

sustainably. To what degree this is guaranteed for the sweet sorghum scenarios primarily depends on the agricultural reference system. As long as sweet sorghum is cultivated on idle land, the consequences of biomass production are – at least to some extent – reversible. On the other hand, if land with a high ecological value, for example grasslands or wooded areas, is converted to arable land to cultivate the displaced field crops, this has grave negative consequences for biodiversity, water and the soil, which may even be irreversibly damaged. This danger exists to a lesser degree in the biomass sorghum scenarios, because in Europe, at least, effective instruments exist to limit direct land use changes. This means it is essential to reduce direct land use changes, for example converting grassland into arable land, as far as possible.

**Conversion:** With regard to the conversion of raw materials, the differences between conversion units for sweet and biomass sorghum and fossil raw material are negligible in terms of impacts resulting from construction phase or related to buildings, infrastructure and installations. Actual differences observed are rather associated with operation-related impacts. In this context, biomass conversion units may show both advantages (e.g. regarding waste generation) and disadvantages (e.g. high specific water consumption, potential increase in traffic). Thus, the specific outcome depends on the chosen pathway. In contrast to the sweet sorghum scenarios, different conversion facilities were studied in the biomass sorghum scenarios investigated here. The respective biomass sorghum conversion units are similar in terms of the local environmental impacts. There is only a minor difference inasmuch as in some of the pathways the biomass sorghum is harvested late and dry and regional trading may become established as a result of the higher transportability of the biomass. In contrast to this, the biomass sorghum is harvested comparatively wet for the 'biogas production' scenario, meaning that the harvested crop displays only low transportability. In order to guarantee economical biogas/biomethane plant operation, it should be assumed that large quantities of biomass sorghum must be cultivated spatially close to the biogas facility. In terms of the local environmental impacts, this increased land use pressure may lead to cumulative impacts at the landscape level.

**In summary**, the LC-EIA adopted here currently represents a practical method for taking local environmental impacts not previously covered by life cycle assessments into account. The results demonstrate that biomass provision, in particular, can display large local environmental impacts, while conversion displays comparatively less, but nonetheless significant, impacts in contrast.

**Excursus for experts: LC-EIA as a supplement of the LCA**

The life cycle environmental impact assessment (LC-EIA) has been successfully established as a supplement to LCA methodology. It allows capturing vital factors influencing local environmental impacts. In this context, LC-EIA provides robust answers on questions that currently cannot be given by LCA methods despite constant evolution. The main distinction stems from the fact that LC-EIA is able to include data in qualitative form that are not currently available for exact quantification, whereas quantitative data remains a requirement for LCAs. The purpose of LC-EIA is the identification of environmental risks and their subsequent evaluation for significance. Further, mitigation measures are recommended to inform pending decisions. This identification of relevant risks does not depend on the summing up of effects across the entire life cycle, the method applied in LCAs, which is superior in principal. However, this is not possible for qualitative differences between individual life cycle stages and their respective reference systems. Thus, a combination of LCA and LC-EIA may reveal additional insights relevant for decision makers. Supplemental LC-EIAs are particularly recommended for life cycle comparisons that include biomass utilisation as long as quantitative LCA methods remain immature, or the data the for rigorous application of these methods are unavailable. In addition, LC-EIAs provide a standard that may act as a gauge for the applicability and validity of novel quantitative methods.

To avoid confusion, please note carefully that LC-EIAs do not qualify as appropriate substitutes for formal environmental impact assessments (EIAs). The methodology may be similar; however, EIAs always address a specific project.

### 6.1.3 Synopsis of LCA and LC-EIA conclusions

The life cycles of the SWEETFUEL scenarios are associated with distinct local, regional and global environmental impacts. A combination of screening LCA and LC-EIA showed that modifications of the life cycle may significantly influence all environmental indicators in complex ways. However, the consequences of decisions or changing circumstances follow a general trend: Local as well as global environmental impacts are especially influenced by the production of the biomass. From a local point of view it is especially important where the biomass grows: As long as sweet and biomass sorghum is cultivated on idle land, the consequences of biomass production are – at least to some extent – reversible and the production counts as sustainable. From a global point of view, biomass production of sweet and biomass sorghum is especially influenced by the amount of applied mineral fertiliser. A reduction should therefore be pursued.

Detailed conclusions from subchapters 6.1.1 and 6.1.2 may be summarised as follows:

With respect to **global and regional environmental impacts**, the main advantage of sweet and biomass sorghum cultivation and use in comparison with the conventional production of energy is that usually a conservation of non-renewable carbon sources is realised. However, in the syrup production scenario the need of external energy carriers can also lead to an additional use of non-renewable energy resources and thus to extra emissions. Therefore, depending on the individual implementation of the scenarios, a wide spectrum of outcomes occur which can range from very favourable to distinctly detrimental environmental impacts in

comparison with the conventional products. Thus, several aspects were considered in matters of optimisation. Optimisation potential is mainly given with respect to reduce the amount of applied mineral fertiliser and increase biomass yields. In case of biomass sorghum production and use, optimisation can be additionally reached by improving conversion plant specific parameters regarding digestate storage or by adjusting agronomic production principles such as the time of digestate incorporation.

For **local environmental impacts**, results of the comparison between the SWEETFUEL scenarios and conventional production practices vary depending on the life cycle stage. Due to the fact that the individual associated risks differ considerably between the two life cycles in both qualitative and quantitative terms, a meaningful comparison may be drawn at the level of the affected environmental factors only. With regard to raw materials supply, biomass tends to be advantageous compared to fossil reference products, as long as the biomass in question is produced sustainably.

For the supply of biomass, please note:

- Try to prevent major land use change such as the conversion of grasslands.
- Endeavour to cultivate crops appropriate to the local growing conditions.

With regard to the conversion of raw materials, the differences between conversion units for sweet and biomass sorghum and fossil raw material are negligible in terms of impacts resulting from the construction phase or related to buildings, infrastructure and installations. Actual differences observed are rather associated with operation-related impacts. In this context, biomass conversion units may show both advantages (e.g. regarding waste generation) and disadvantages (e.g. high specific water consumption, potential increase in traffic). Thus, the outcome depends on the chosen pathway.

**In summary**, the production and use of sweet and biomass sorghum in the SWEETFUEL project carries the potential for a distinct reduction of greenhouse gas emissions and the use of non-renewable energy resources whilst local environmental impacts are negligible to advantageous in comparison with conventional (reference) products as long as the biomass in question is produced sustainably. Specific options for the realisation of this potential have been identified.

## 6.2 Recommendations

Based on the results of the environmental assessments, as well as the conclusions discussed above, a number of recommendations for individual stakeholders, especially decision makers in science, industry and politics, can be derived. Some of these recommendations are specific to the energy sorghum variants investigated here: biomass and sweet sorghum, which are discussed first. Recommendations for both energy sorghum variants then follow.

**Specific recommendations for sweet sorghum**

The following specific recommendations refer to various areas of the entire life cycle:

- Because especially large environmental benefits are associated with the use of the by-products, care should be taken that as much of the plant as possible is machine-harvestable. Technical advances in **harvesters** should therefore be supported, with a focus on harvesting both by-products, the grains and the leaves.
- In order to ensure that the **leaf harvest** is sustainable, i.e. the organic soil substance is not negatively impacted, an appropriate research project should be established with the aim of identifying how the maximum sustainable leaf harvest can be determined across a variety of sites. In addition, a process for implementing the results in the field must be developed.
- The cultivation of sweet sorghum on land with natural vegetation often influences the carbon stock and biodiversity of the land negatively and should therefore be avoided. Initiatives and programmes supporting the establishment of sweet sorghum as an energy crop should therefore promote **integration in existing cultivation systems, or cultivation on low-carbon soils, or soils of relatively little ecological value** and to this end raise incentives and query farmers and investors about convincing concepts. This also applies to the case of sweet sorghum cultivation in sugar cane cycles or, even more so, instead of grain sorghum, because indirect land use changes are here in practise, whose negative impacts must be minimised.
- When planning new ethanol plants, **a concept for full energy utilisation of the leaves** should be compiled as the use of this by-product improves environmental impacts. To increase incentives, ethanol plants with an integrated use of the by-product should e.g. be given priority consideration in funding and authorisation practice. **Syrup processing**: If decentralised syrup production from sweet sorghum should still be pursued further, particular attention should be paid to the concept of energy provision for the centralised processing of the syrup to ethanol. Only those concepts should be promoted or approved that can demonstrate a positive energy and greenhouse gas balance.

### Specific recommendations for biomass sorghum

Specific recommendations for the cultivation and use of biomass sorghum apply predominantly to the following two areas:

*Biogas production:*

- Combined production and utilisation of **power and heat** should be preferred over power production only.
- Biogas plants are often built in areas where there are no noteworthy heat consumers. However, because a high level of heat utilisation is positive from an environmental perspective, a **heat utilisation concept** should be taken into account at the planning stage. To increase incentives, biogas plants with a conclusive heat use concept should be given priority consideration in authorisation practice.
- In terms of the production of biogas from biomass sorghum, a legal obligation should be introduced to cover the digestate storage gas-tight.

*Incorporation of the digestate:*

- An appropriate research project should be established with the aim of identifying whether nitrification inhibitors can be added to the digestate in order to reduce nitrous oxide emissions during digestate application to the field.
- The digestate should be worked into the soil in the shortest possible time (e.g. one hour) after application, in order to prevent unnecessarily high ammonia and nitrous oxide emissions. Legal regulations and monitoring of this practise should be introduced where not yet in place.

*Alternative use options*

- **Direct combustion** of biomass sorghum for combined heat and power production is the environmentally most beneficial use option. As this scenario was not in the primary focus of this study, further research should be supported on implementation barriers, issues of nutrient recycling from ashes and long term perspectives in a changing energy system.
- As **2$^{nd}$ generation ethanol and synthetic FT fuels** are rather medium to long term options, biomass sorghum should not be developed with high priority as feedstock for such fuels but may find an additional market in this use option later.

### General recommendations for energy sorghum

The general recommendations for the investigated energy sorghum variants are relevant to a variety of areas of the entire life cycle:

- Support of breeding programmes for general **yield** optimisation differentiated by geographical, climatic and soil conditions, in order to reap the full benefits of the sorghum variants.
- Promotion of techniques for optimising cultivation methods (e.g. improved fertiliser and pesticide application) for **yield stability or the optimised use of resources**.

- Reduction in applied **mineral fertiliser**:
  - Continuation of appropriate breeding programmes for reducing the nutrient content in the harvested biomass that is intended for energy use.
  - Establishing research projects for optimising suitable cultivation methods (e.g. optimising the time of harvesting) for reducing the nutrient content in the harvested biomass that is intended for energy use.
  - Integration of sweet sorghum and biomass sorghum cultivation respectively in existing, established crop rotation systems should be aimed for, because sorghum are capable of utilising nutrients from deeper layers, which remained unused in the previous cultivation systems. Appropriate research projects should be established, in particular with the aim of identifying promising multi-crop rotations.
  - Research projects should also be established with the aim of investigating the overall environmental impacts of organic farming on energy sorghum cultivation.

*Recommendations in terms of local environmental impacts*

- In the mid- to long-term, **biomass and land use allocation plans** should be developed at national and pan-national level. Due to the fact that environmental implications including resource scarcity in particular do not possess an adequate price, market mechanisms cannot replace these plans.
- Based on these national plans, **regional plans** which include regulations for project planning should be developed. In this context, the cultivation of crops adapted to local conditions should be supported. For instance, the environmental impacts of the cultivation of a crop with a high water demand depend on water availability at the specific location. Furthermore, regional planning is vital due to the fact that also public funds to date have created market actors with considerable local demand for biomass and significant market power. Ethanol producing facilities could potentially exacerbate the process. This can create distortion of competition and thus displacement effects that can be the cause for unsustainable development. With appropriate planning, unfavourable developments can be, and must be, avoided.
- As long as no appropriate planning is in place, preventive measures should include binding land use and cultivation-related sustainable environmental criteria for uniform application across all purposes, i.e. for bio-based materials, chemicals, fuel and energy carriers as well as feed/food production.
- Biomass potentials at the proposed biorefinery site should exceed projected demands. In all likelihood, the demand for biomass from several sectors, including bioenergy production, will increase considerably in the near future.

*Further aspects*

- **Knowledge transfer:** Promote knowledge transfer in terms of experience in cultivating energy sorghum.

- **Quality control:** All appropriate support programmes or implementation concepts and programmes should be accompanied scientifically in order to identify the environmental impacts based on both LCA and LC-EIA and to facilitate optimisation in the course of the running project.

**Outlook**

Overall, it can be shown that the production of bioenergy, such as bioethanol or biogas from energy sorghum, is not ecologically compatible in all cases. However, it can also be shown that it can be presented as being ecologically compatible and that there are numerous possibilities for optimising the environmental benefits and minimising the drawbacks.

The environmental analysis applied here, based on the life cycle assessment (LCA) and supplemented by the life cycle environmental impact assessment (LC-EIA), therefore represents a practical method for comprehensively analysing and evaluating global and local environmental impacts. However, in order to represent the entire sustainability spectrum, other sustainability aspects (in particular economic, social, political and legal aspects) should be taken into consideration. For example, this can be realised by an application of a so called integrated life cycle sustainability assessment (ILCSA) described by /Keller et al. 2014/, which allows a joint evaluation of all aspects with the aid of multi-dimensional comparison matrices (see /Reinhardt et al. 2014/). This helps decision-makers to understand the overall complexity of a system and to initiate appropriate steering measures.

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# 8 Annex

The annex contains various supplementary material including input data, extended methodological descriptions and further results.

## 8.1 Scenario data

This subchapter contains an overview of important agricultural and conversion data for the environmental assessment. The cultivation of biomass and sweet sorghum is assessed in the way that full expenditures of crop cultivation are ascribed to the harvested crop based on a sustainable cultivation practise. This includes that as many nutrients are replaced by fertilisation as are lost by harvesting and emissions to air and water and exceed the deposition of nutrients from the atmosphere (in case of nitrogen) /Müller-Lindenlauf et al. 2014/.

**Table 8-1** Selected data used for SWEETFUEL scenario calculations and certain outputs for the typical dataset.

| | Units (per ha per yr) | Sweet sorghum Cane fallow | Sweet sorghum Grain to food | Sweet sorghum Syrup | Biomass sorghum |
|---|---|---|---|---|---|
| **Agricultural inputs** | | | | | |
| Seeds | kg | 7 | 7 | 7 | 8 |
| Pesticides | kg | 5 | 5 | 2.5 | 5 |
| Fertiliser[2] N | kg | 350 | 260 | 350 | 356 |
| Fertiliser $P_2O_5$ | kg | 120 | 90 | 120 | 125 |
| Fertiliser $K_2O$ | kg | 380 | 285 | 380 | 450 |
| Diesel fieldwork | L | 90 | 85 | 90 | 110 |
| **Yields** | | | | | |
| Biomass | t (dry matter) | 20 | 15 | 20 | 25 |
| Extraction efficiency | % | 95 | 95 | 85 | - |
| Sugar | t | 3.1 | 2.0 | 2.8 | - |
| **Outputs** | | | | | |
| Ethanol (from stalks) | t | 1.6 | 1.0 | 1.2 | - |
| Ethanol (from grains) | t | 1.2 | - | - | - |
| Surplus bagasse | t | 3.7 | 4.5 | 5.5 | |
| Biogas – power | kWh | - | - | - | 23,300 |
| – heat | MJ | - | - | - | 17,100 |

[2] The N-fertiliser demand was calculated as follows: (nutrient content in biomass) × (biomass yield) / (1 - losses through ammonia emissions, denitrification & nitrate leaching) - (atmospheric deposition$_{netto}$). Nutrient contents in biomass and yields for sweet and biomass sorghum are based on experimental data. Deposition$_{netto}$ includes already losses due to ammonia emissions, denitrification & nitrate leaching. Losses are based on model calculations and statistics and atmospheric deposition is based on literature sources /Müller-Lindenlauf et al. 2014/. The following losses were used for nitrogen emissions: Ammonia 3.29 %, nitrate leaching 15 % for annual crops, denitrification losses 10 %. The losses relate to typical agricultural practise expected for 2020. This methodological approach results in higher fertiliser values compared to field trials, but delivers a realistic description of a sustainable agricultural practise.

## 8.2 Parameters for LCA

The required normalisation factors for the EU27 can be found in Table 8-2. For details, please refer to subchapter 2.2.2.

**Table 8-2** Environmental impact categories and the respective inhabitant equivalent (the average impact caused by one inhabitant per year; base year: 2005), (/IFEU 2014/ on the basis of /Eurostat 2007/ and /CML 2009/). Inhabitants EU27 2005: 491,153,644 /Eurostat 2013/.

| Impact category | Unit | EU27 inhabitant equivalent |
|---|---|---|
| Resource depletion: energy | GJ / yr | 82 |
| Greenhouse effect | t $CO_2$ equivalent / yr | 11 |
| Acidification | kg $SO_2$ equivalent / yr | 49 |
| Terrestrial eutrophication | kg $PO_4^{3-}$ equivalent / yr | 6 |
| Aquatic eutrophication | kg $PO_4^{3-}$ equivalent / yr | 38 |
| Photochemical ozone formation | kg ethene equivalent / yr | 20 |
| (Stratospheric) ozone depletion | g CFC-11 equivalent / yr | 69 |
| Human toxicity | kg $PM_{10}$ equivalent / yr | 40 |

## 8.3 Further LCA results of sweet sorghum

This subchapter contains further detailed LCA results, which cannot be shown in subchapter 4.1 due to space constraints.

### 8.3.1 Cane fallow scenarios

#### Biomass production

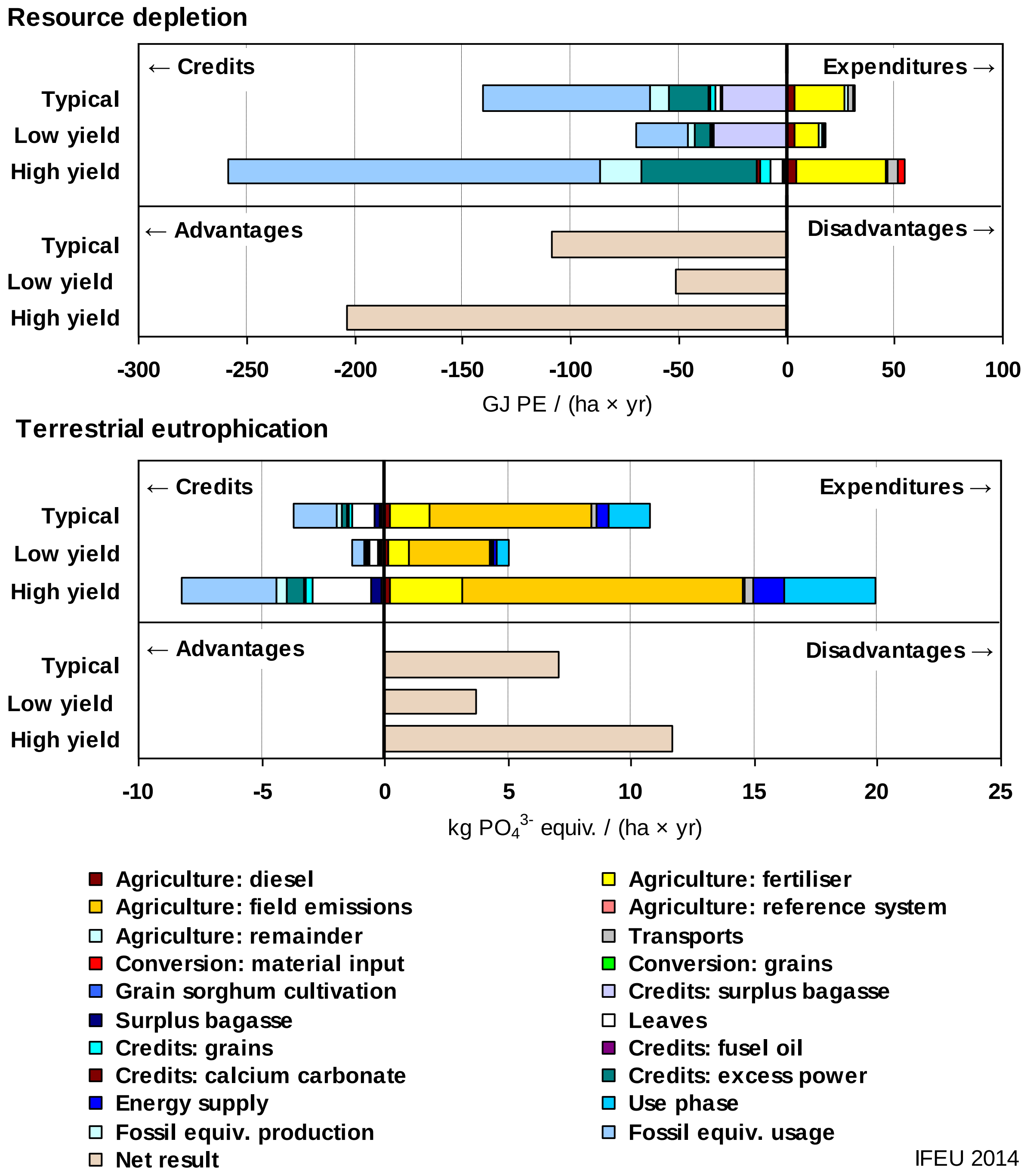



**Fig. 8-1** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) for sweet sorghum ethanol production of the cane fallow scenario and different biomass yields (low, high) in the impact categories resource depletion, terrestrial and aquatic eutrophication, ozone depletion and human toxicity. For further details see section 'Biomass production' in subchapter 4.1.1.3.

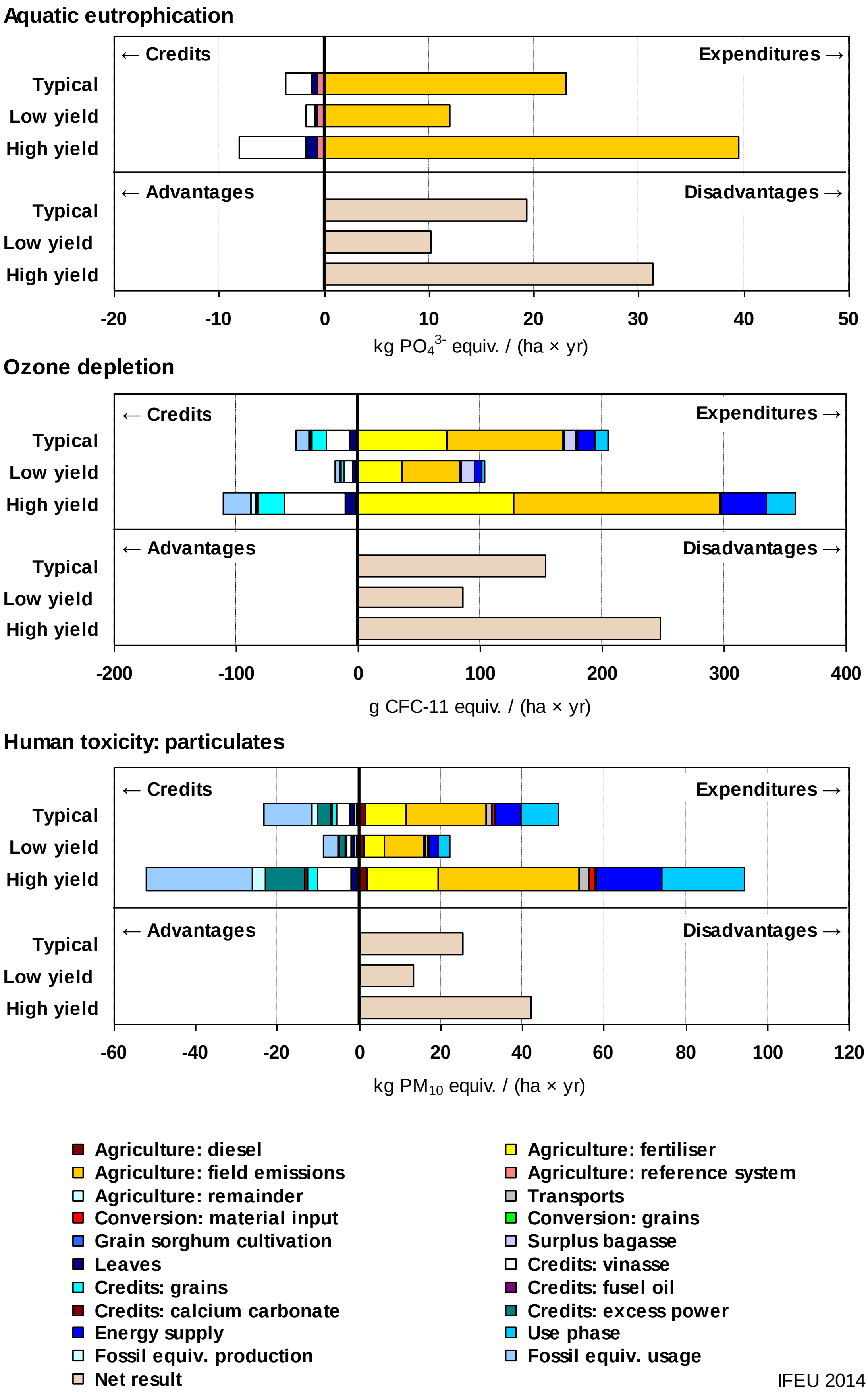



**Fig. 8-1** (continued).

### Different use options of by-products

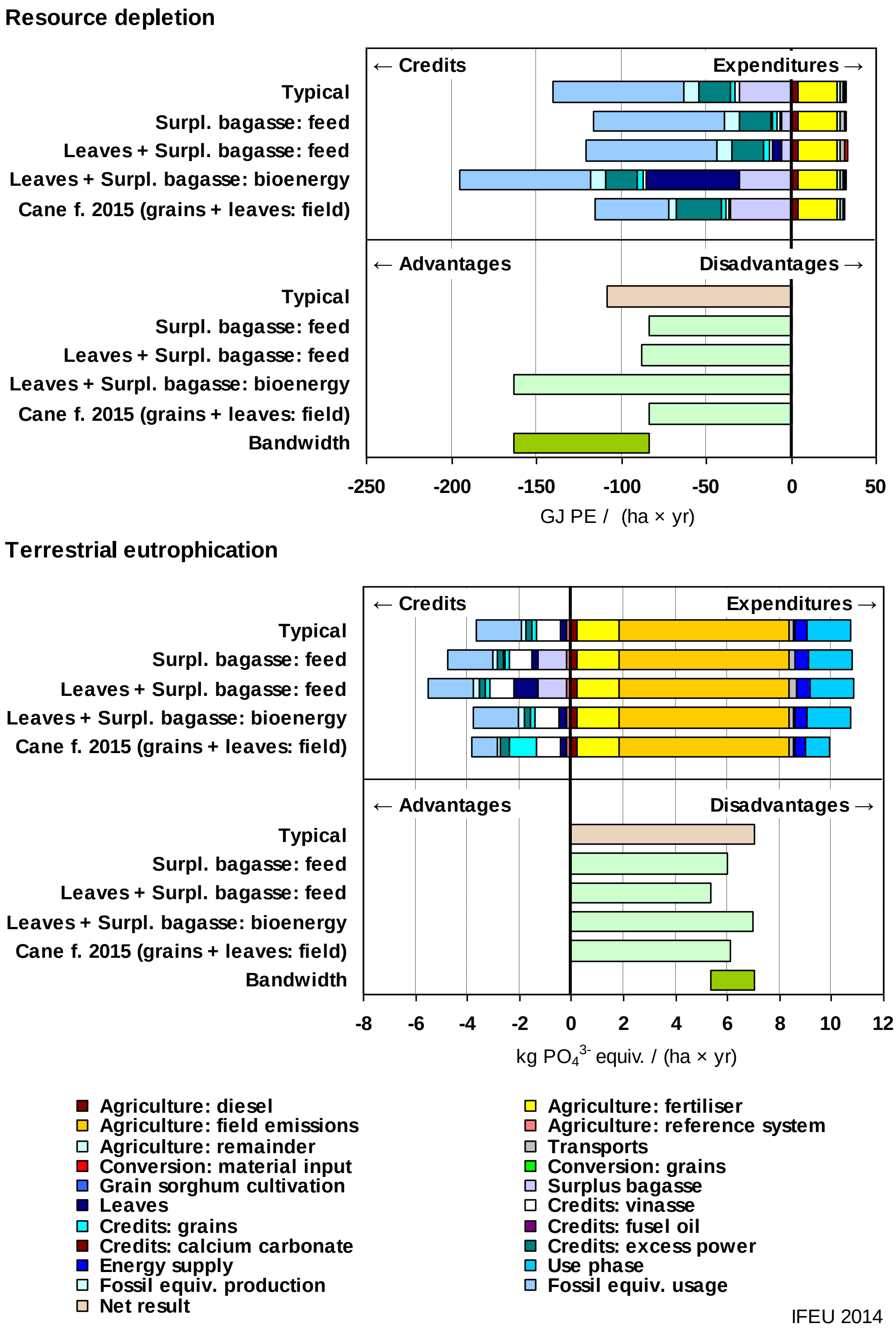



**Fig. 8-2** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) for sweet sorghum ethanol production of the cane fallow scenario and different use options of the by-products (leaves, surplus bagasse) in the impact categories resource depletion, terrestrial and aquatic eutrophication, ozone depletion and human toxicity. For further details see section ‘Comparison of by-product use options’ in subchapter 4.1.1.3.

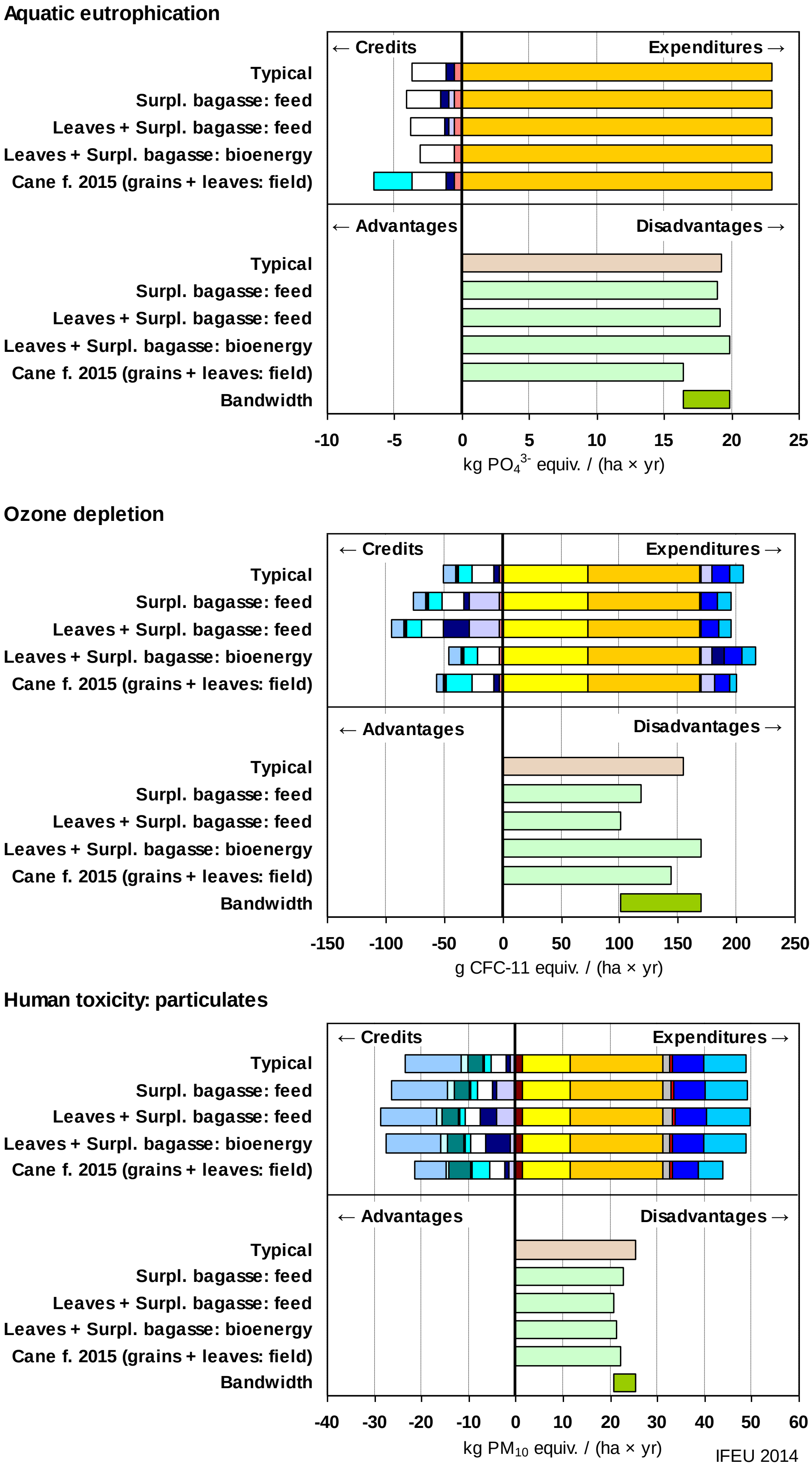



**Fig. 8-2** (continued)

### 8.3.2 Grain to food scenarios

#### Biomass production

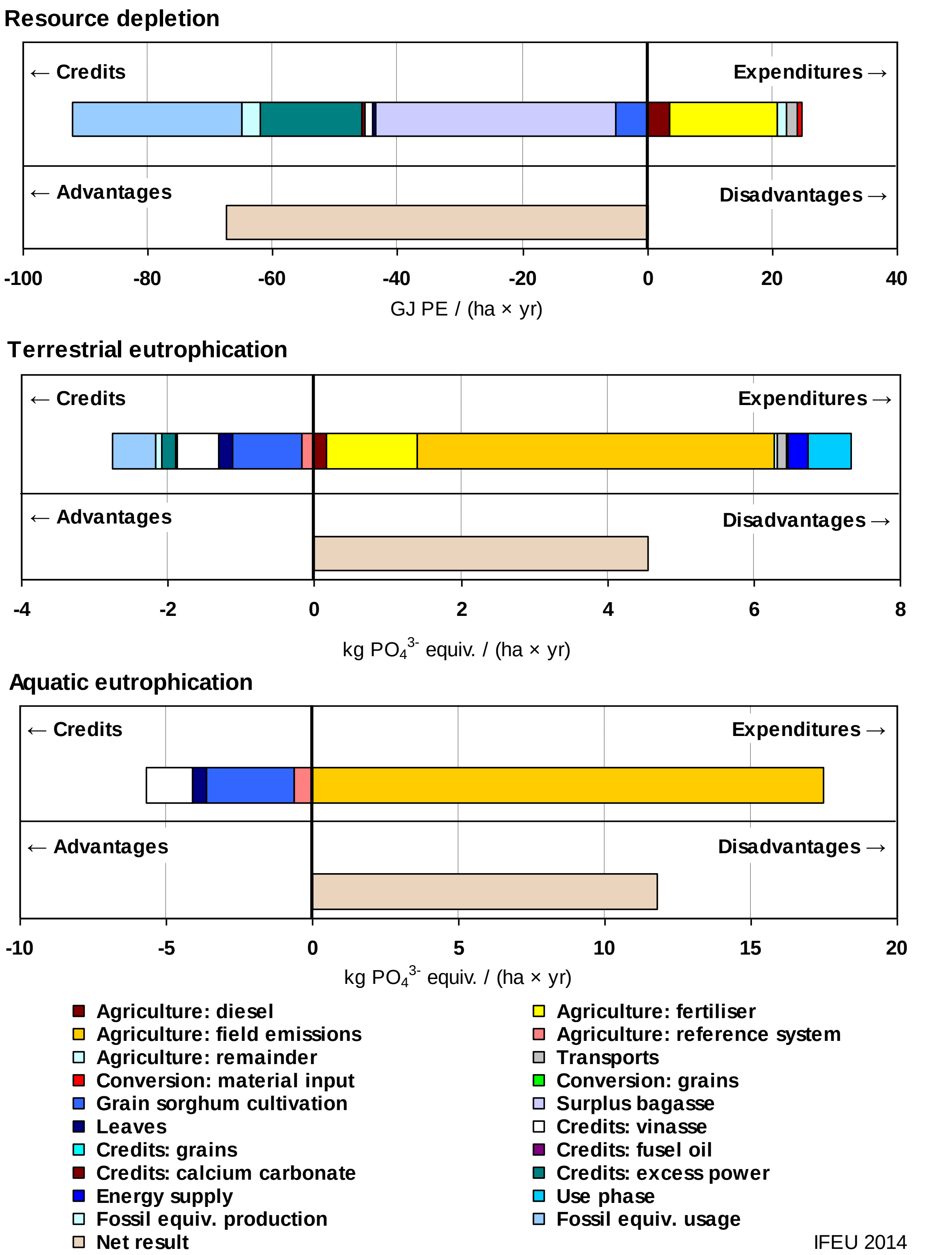



**Fig. 8-3** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) for sweet sorghum ethanol production of the grain to food scenario in the impact categories resource depletion, terrestrial and aquatic eutrophication, ozone depletion and human toxicity. For further details see subchapter 4.1.2.2.

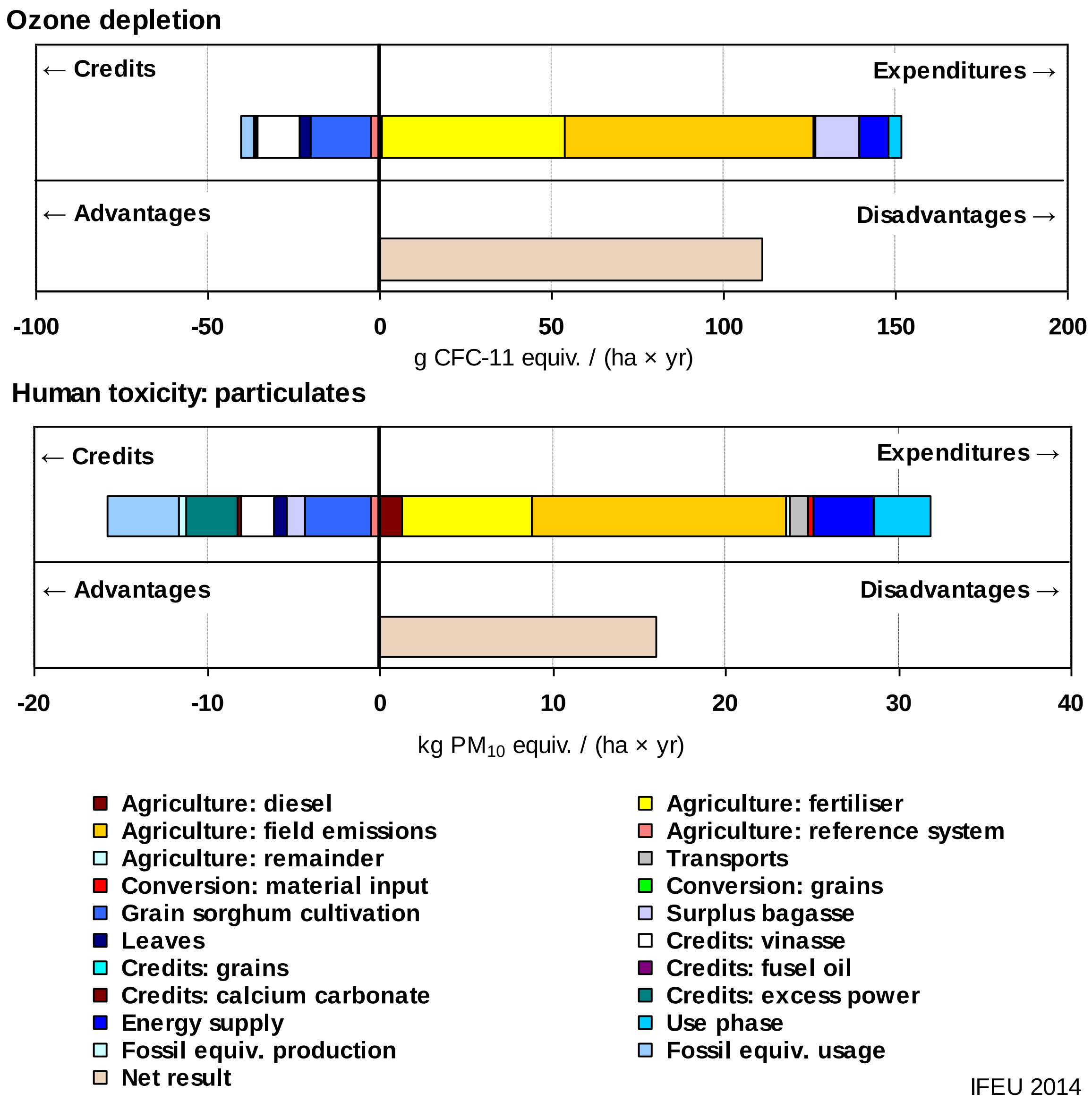



**Fig. 8-3** (continued)

## Extra high grain yields

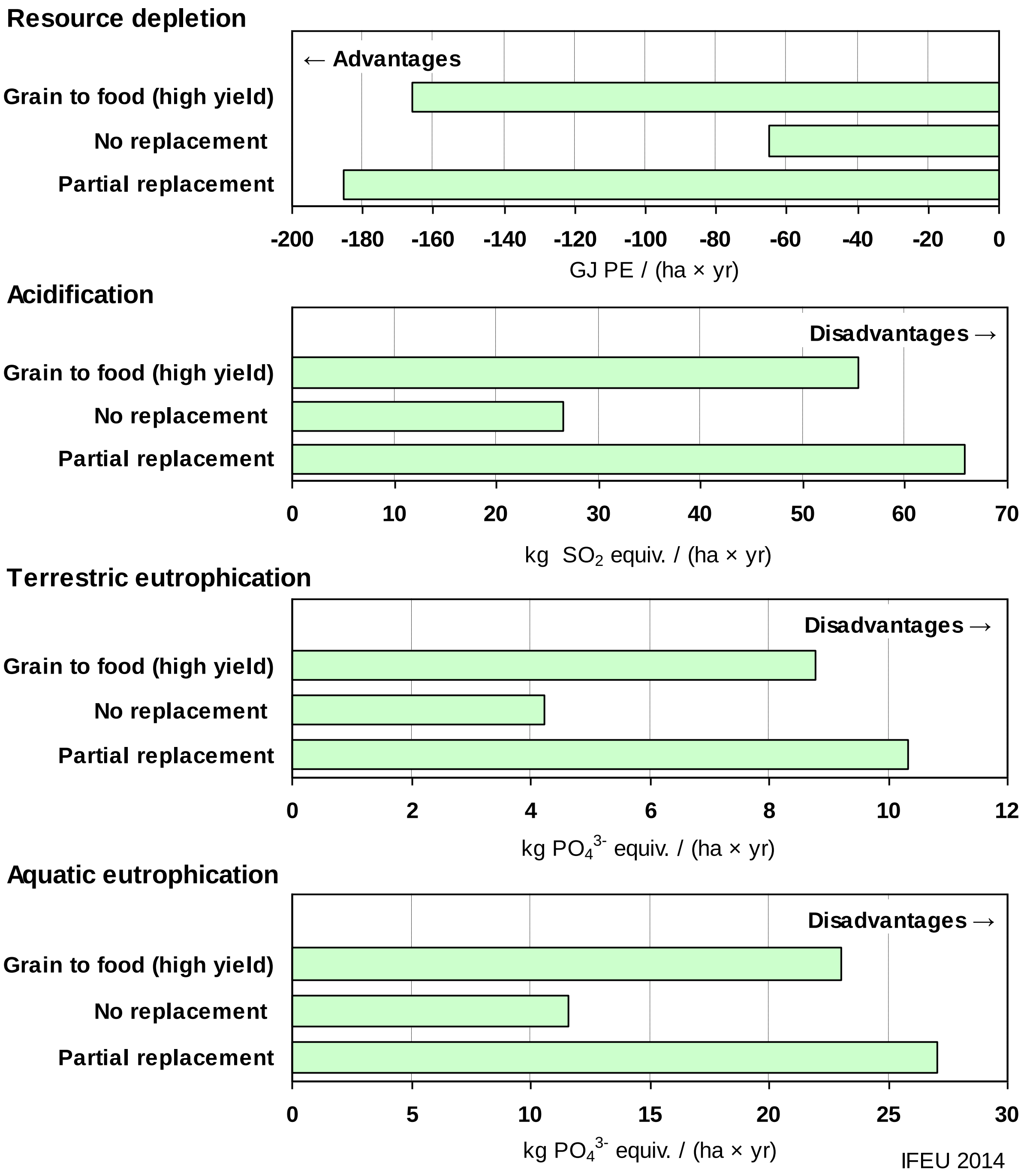
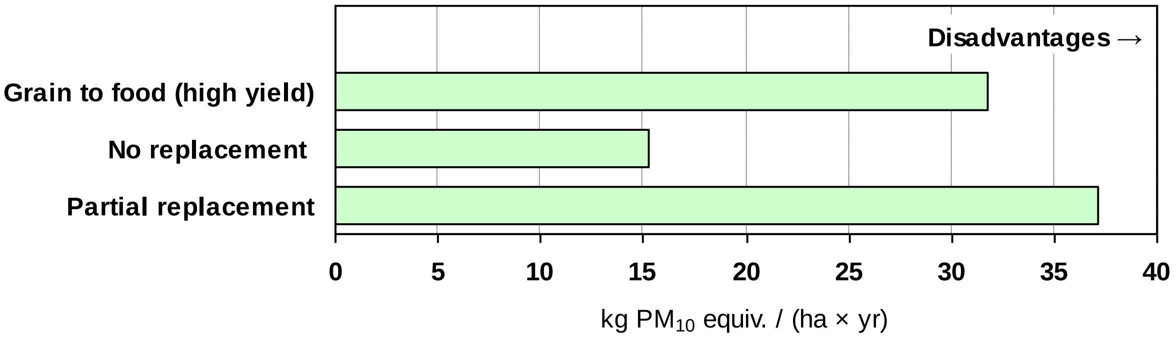
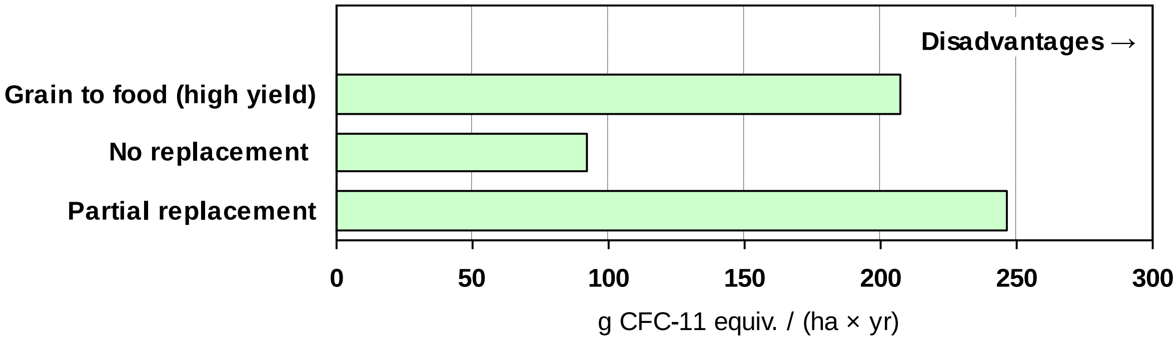



**Fig. 8-4** Comparison of the net results of the extra high yield options in the grain to food scenario for the environmental impact categories resource depletion, acidification, terrestrial and aquatic eutrophication, ozone depletion and human toxicity. For further details see section ‘Extra high yield’ scenarios in subchapter 4.1.2.3.

**Ozone depletion**




**Human toxicity: particulates**




IFEU 2014

**Fig. 8-4** (continued)

### 8.3.3 Syrup production scenario

#### Biomass production

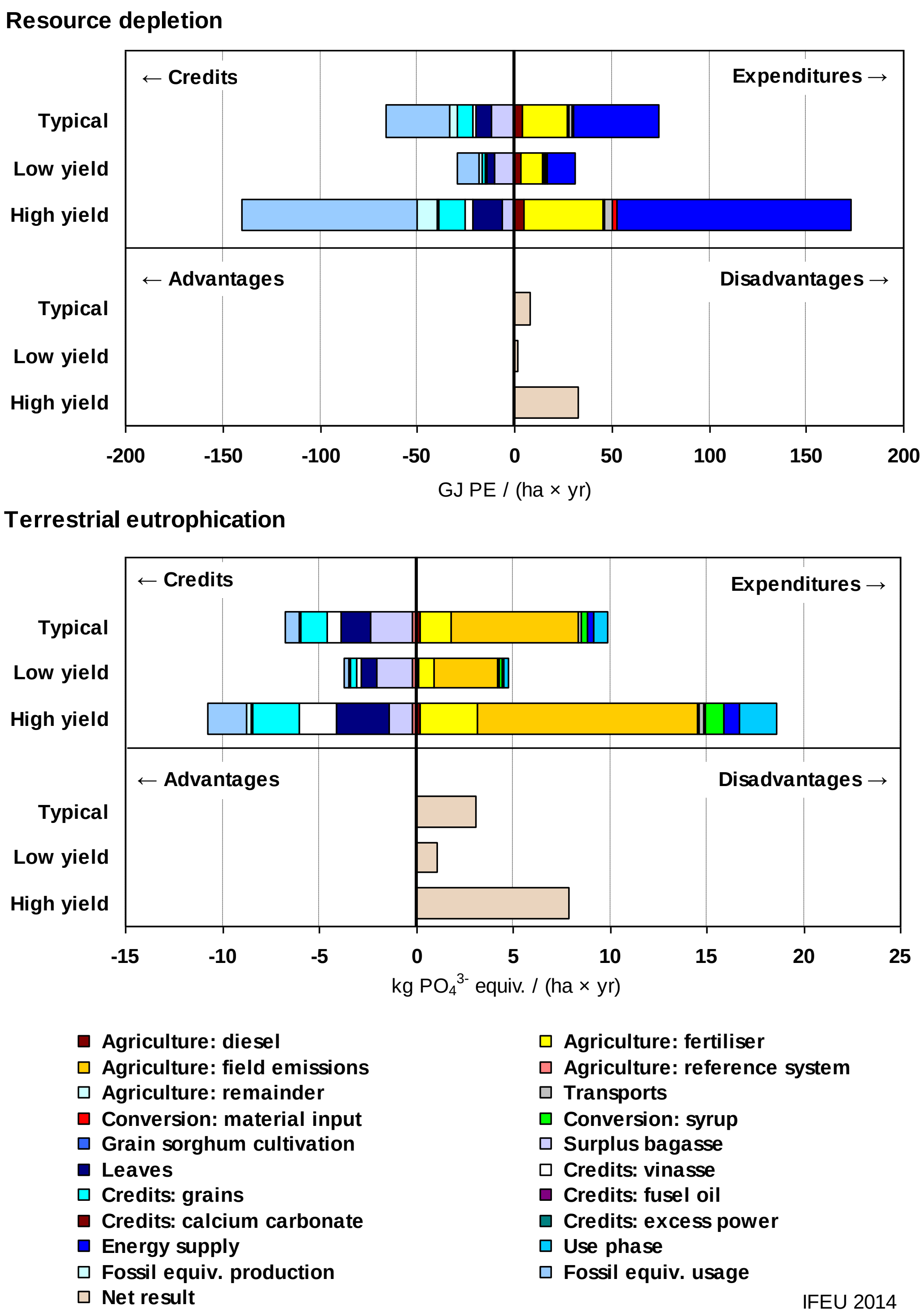



**Fig. 8-5** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) for biogas production from biomass sorghum of the syrup production scenario and different biomass yields (low, high) in the impact categories resource depletion, terrestrial and aquatic eutrophication, ozone depletion and human toxicity. For further details see section 'Biomass production' in subchapter 4.1.3.3.

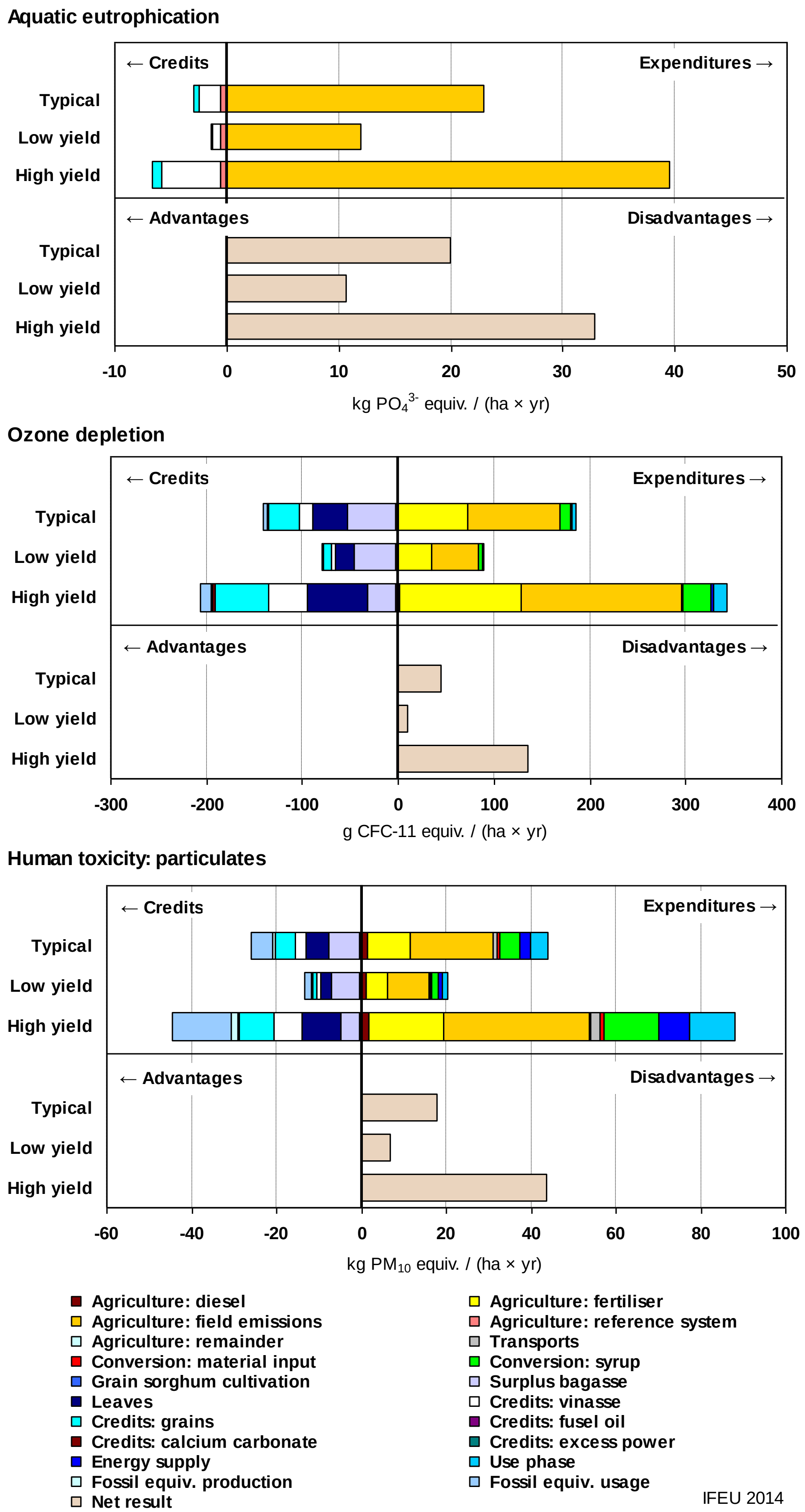



**Fig. 8-5** (continued)

### Different external energy carriers

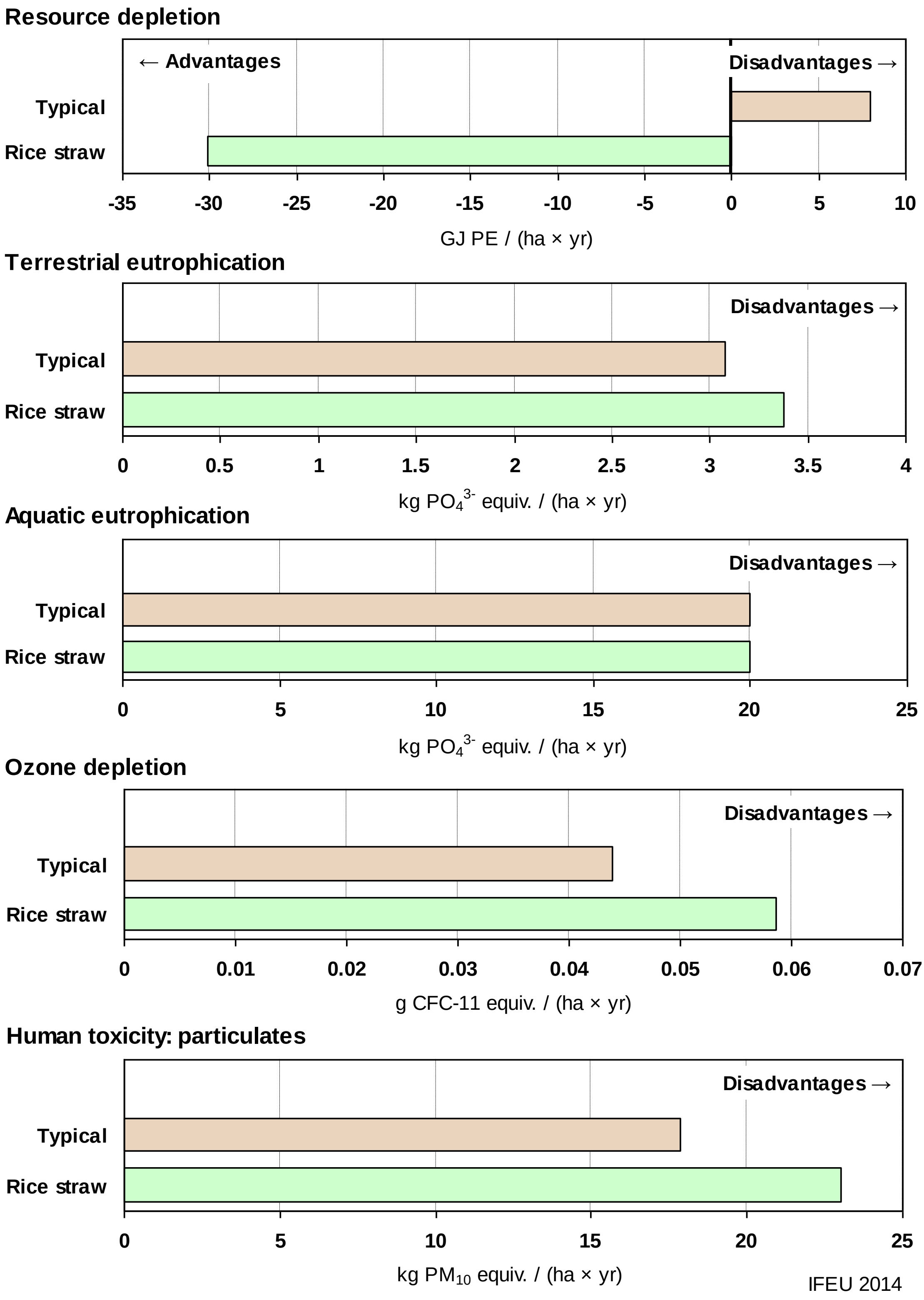



**Fig. 8-6** Comparison of the influence of different energy carriers on the net results for sweet sorghum ethanol production of the syrup scenario in the environmental impact categories resource depletion, terrestrial and aquatic eutrophication, ozone depletion and human toxicity. Results are based on typical cultivation and conversion conditions defined for the syrup production scenario.

## 8.4 Further LCA results of biomass sorghum

This subchapter contains further detailed LCA results of the biomass sorghum scenarios, which cannot be shown in subchapter 4.2 due to space constraints.

### Biomass production

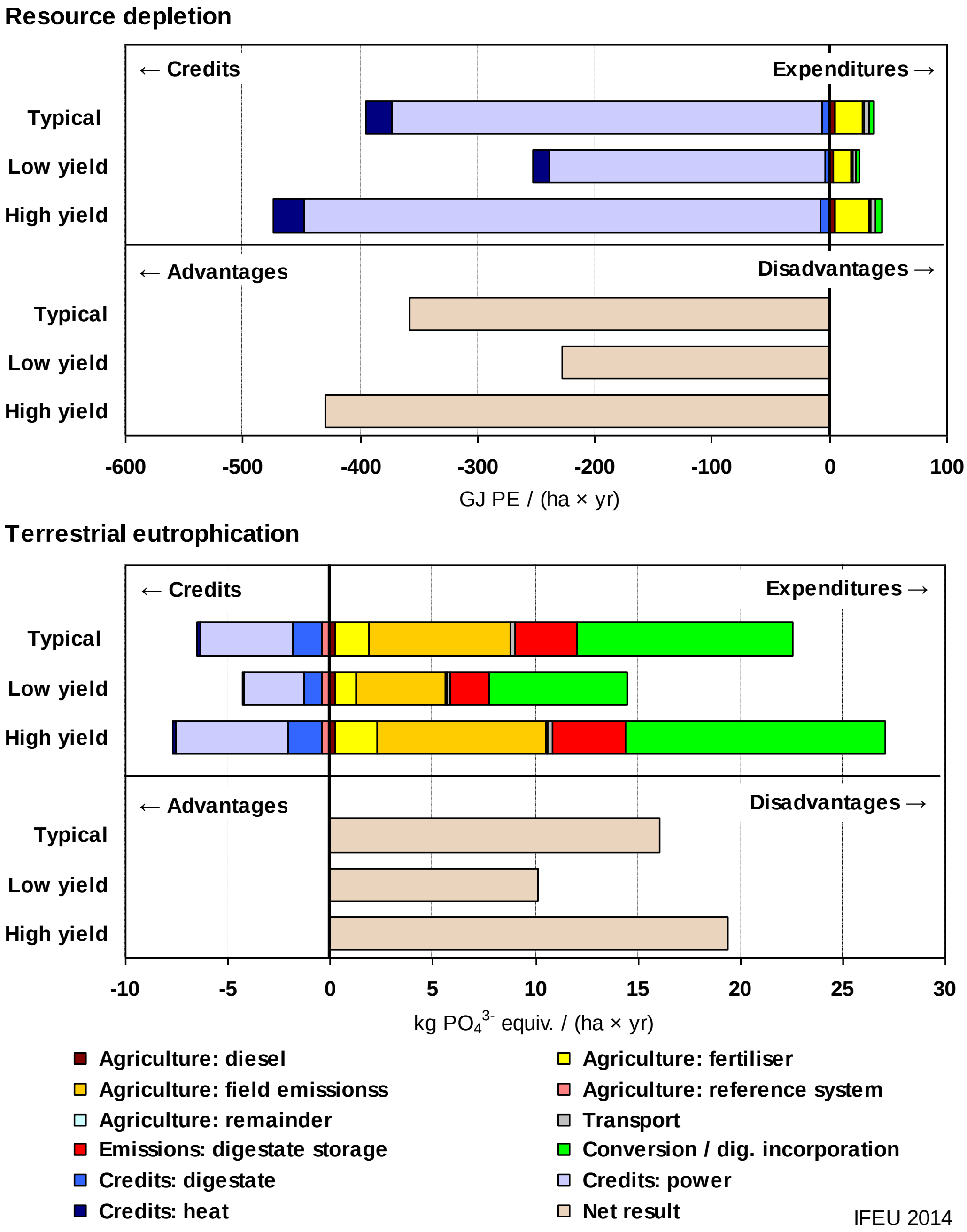



**Fig. 8-7** Contribution of single life cycle steps (coloured bars) to the net results (light brown bars) for the biogas scenario and different biomass yields (low, high) in the impact categories resource depletion, terrestrial and aquatic eutrophication and ozone depletion. For further details see section ‘Biomass production’ in subchapter 4.2.1.3.

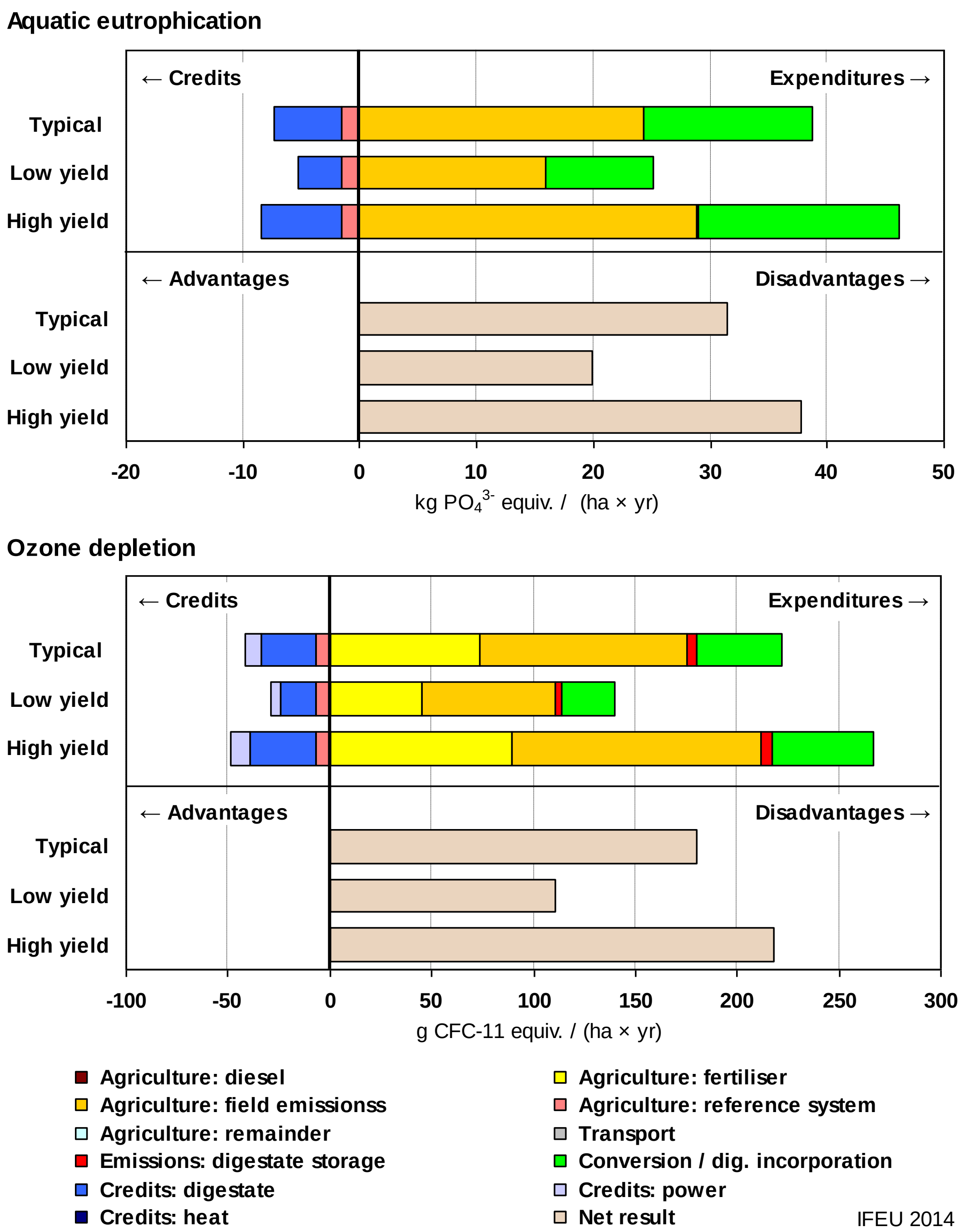



**Fig. 8-7** (continued)

## Plant specific variations

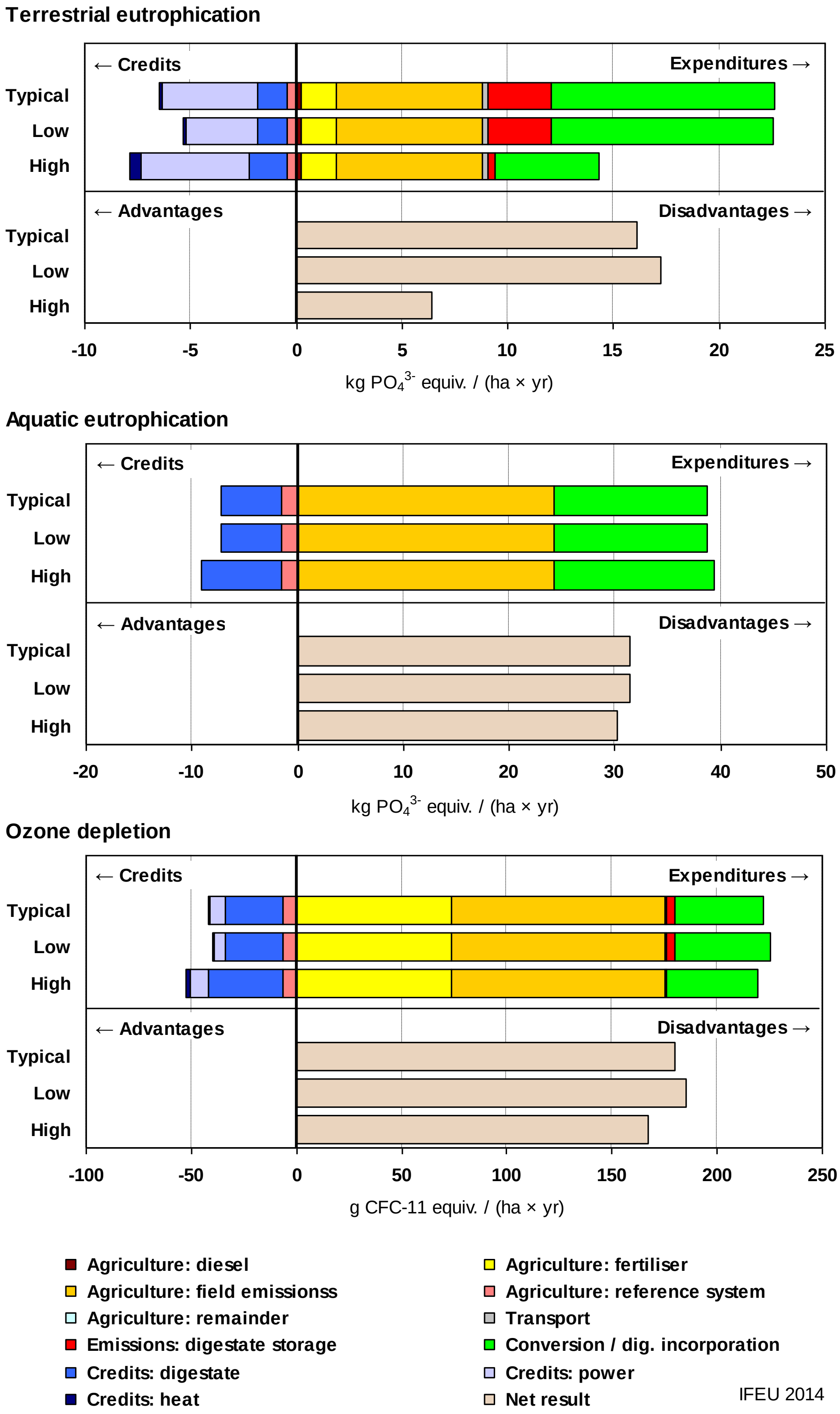



**Fig. 8-8** Comparison of conversion plant specific variations of biogas production from biomass sorghum for the impact categories terrestrial and aquatic eutrophication and ozone depletion. For further details see section 'Plant specific variations' in subchapter 4.2.1.3.

### 8.4.1 Biogas use options

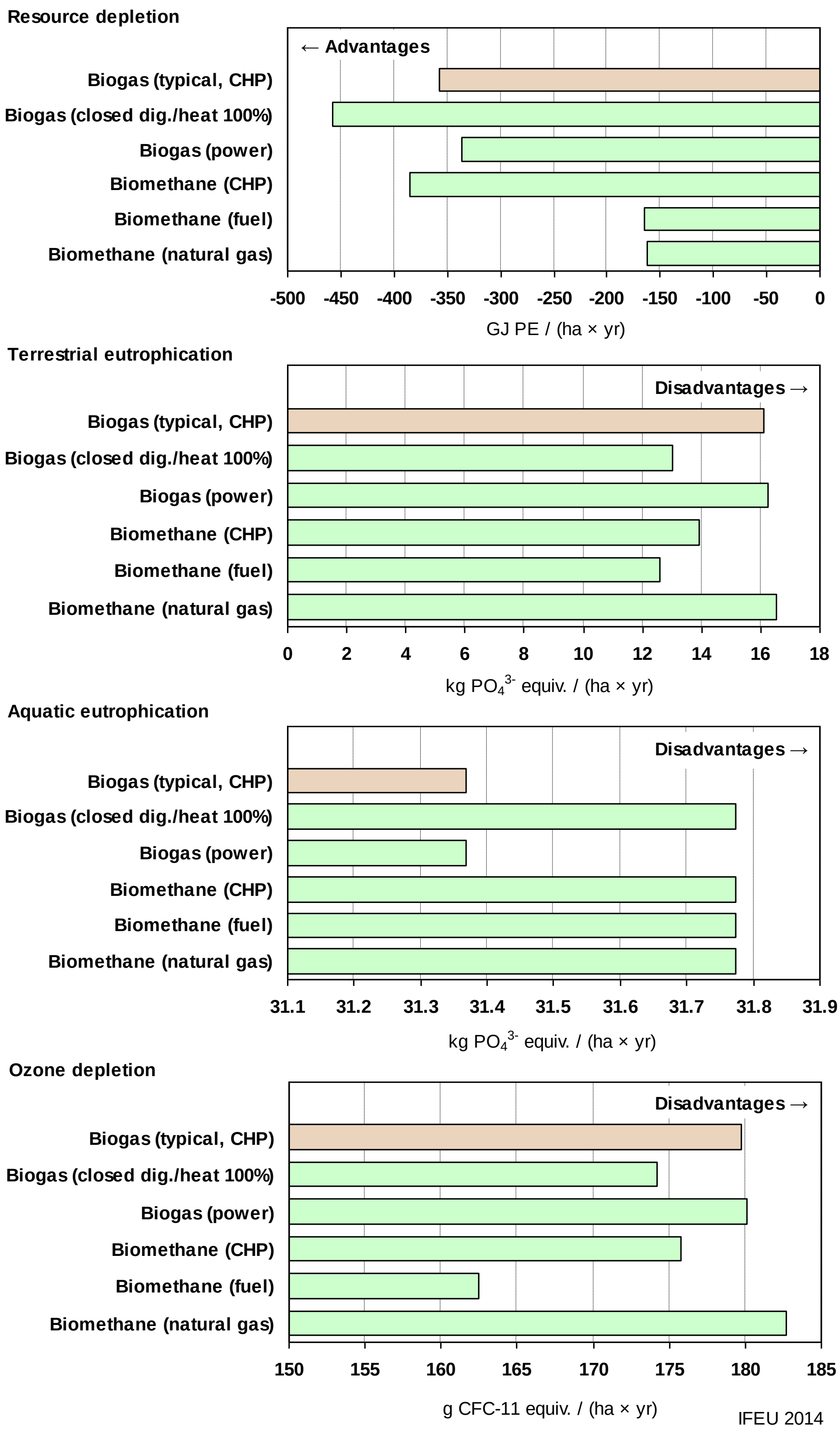



**Fig. 8-9** Overview of LCA results of different biogas use options for the categories depletion of non-renewable energy resources, terrestrial eutrophication, aquatic eutrophication and ozone depletion. Results are shown for typical cultivation conditions and per hectare per year. For further details see subchapter 4.2.1.4.

### 8.4.2 Alternative bioenergies from biomass sorghum

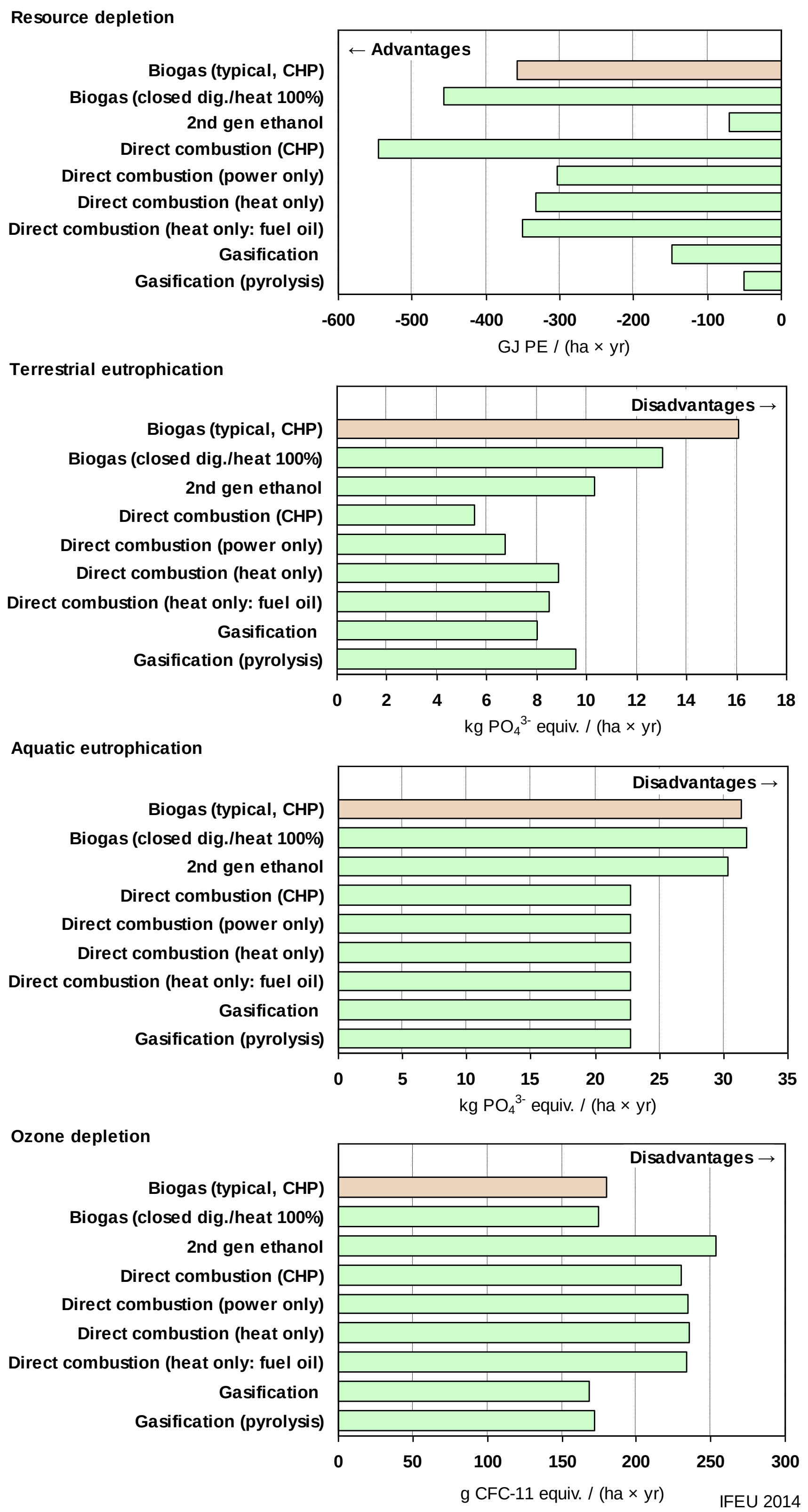



**Fig. 8-10** Overview of LCA results of alternative bioenergies for the categories depletion of non-renewable energy resources, terrestrial eutrophication, ozone depletion and aquatic eutrophication. Results are shown for typical cultivation conditions and per hectare per year. For further details see subchapter 4.2.3.

# 9 Glossary and abbreviations

| | |
|---|---|
| **1st generation biofuels** | Biofuels e.g. produced from sugar, starch, vegetable oil or animal fats using conventional technologies. |
| **2nd generation biofuels** | Biofuels e.g. produced from non-food biomass such as lingocellulose and waste biomass (e.g. wheat straw or corn stover) using innovative technologies. |
| **2G biofuels** | see 2nd generation biofuels |
| **ARC** | Agricultural Research Council, Potchefstroom, South Africa; http://www.arc.agric.za/ |
| **Bagasse** | Fibrous matter that remains after stalks are crushed to extract the juice. |
| **Biomass sorghum** | Sorghum cultivars with high lignocellulosic biomass yield, potentially used as energy crop. |
| **BtL** | Biomass-to-Liquid; synthetic biofuels produced via biomass gasification. |
| **C4 plant** | Plants using a 4-carbon molecule as a first product in the carbon fixation pathway (in contrary to a 3-carbon molecule of C3 plants) which leads amongst others to higher water use efficiencies. |
| **CFC-11** | Chlorofluorocarbon-11 |
| **$CH_4$** | Methane |
| **CHP** | Combined heat and power; co-generation of electricity and heat |
| **CIRAD** | Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Paris, France; http://www.cirad.fr |
| **$CO_2$** | Carbon dioxide |
| **Cultivar** | Plant or group of plants selected for some desirable characteristics. Cultivar is a general word that includes lines, varieties and hybrids |
| **DG ENVI** | Directorate-General for the Environment of the European Commission |
| **EIA** | Environmental impact assessment; a standardised methodology for analysing proposed projects regarding their potential to affect the local environment |
| **EMBRAPA** | Empresa Brasileira de Pesquisa Agropecuária, Brasília, Brazil; http://www.embrapa.br |
| **Energy sorghum** | Sweet and biomass sorghum cultivars used in this project |
| **Equiv.** | Equivalent |
| **Fibre sorghum** | Biomass sorghum cultivars with a high content of fibre; potentially used as fibre or energy crop |
| **FT fuel / diesel** | Fischer-Tropsch fuel / diesel; the FT process converts carbon monoxide and hydrogen into liquid hydrocarbons, which can be further processed e.g. into diesel |
| **GJ** | Gigajoule |
| **Grain sorghum** | Sorghum cultivars with high grain yield established as food or feed crop |
| **HCl** | Hydrochloric acid |
| **Hybrid** | Offsprings resulting from the cross between two genetically dissimilar parental lines. Usually, seeds from hybrids don't consistently provide the desired characteristics, so hybrid seed should be repurchased by growers for each planting season |
| **ICRISAT-IN** | International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India; http://www.icrisat.org |
| **Idle land** | Reference systems such as degraded soils or land that becomes free due to different reasons e.g. the intensification of existing land use |
| **IE** | Inhabitant equivalent |
| **IFEU** | Institute for Energy and Environmental Research Heidelberg, Germany; http://www.ifeu.de |

| | |
|---|---|
| **ILCD** | International reference life cycle data system |
| **ILCSA** | Integrated life cycle sustainability assessment |
| **JRC** | Joint Research Centre of the European Commission |
| **KWS** | KWS Saat AG, Einbeck, Germany; http://www.kws.de |
| **L.** | Linné |
| **Line** | Breeding material which tends to be genetically identical |
| **LCA** | Life cycle assessment |
| **LC-EIA** | Life cycle environmental impact assessment (assessment of local environmental impacts taking into account the stages during the entire life cycle of a product) |
| **LCIA** | Life cycle impact assessment |
| **LCI** | Life cycle inventory |
| **Molasses** | Viscous by-product of the refining of e.g. sugarcane into sugar |
| **N** | Nitrogen |
| **$NH_3$** | Ammonia |
| **NMHC** | Non-methane hydrocarbons |
| **$N_2O$** | Nitrous oxide, commonly known as laughing gas |
| **$NO_3^-$** | Nitrate |
| **$NO_X$** | Nitrogen oxide |
| **P** | Phosphorus |
| **Pesticide** | Pesticides (insecticides, fungicides, herbicides, etc.) are substances meant for preventing, destroying or mitigating any pest |
| **$PM_{10}$** | Particulate matter smaller than about 10 micrometres |
| **$PO_4^{3-}$** | Phosphate |
| **ODP** | Ozone depletion potential |
| **RED** | European Renewable Energy Directive; directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 |
| **$SO_2$** | Sulphur dioxide |
| **SWEETFUEL** | Project "Sweet Sorghum: an alternative energy crop"; supported by the European Commission in the 7$^{th}$ Framework Programme to exploit the advantages of sweet sorghum as potential energy crop for bio-ethanol production |
| **Sweet sorghum** | Sorghum cultivars with juicy stems and high juice sugar content in their stalks, potentially used as an energy and food crop |
| **UANL** | Universidad Autónoma de Nuevo León, México; http://www.uanl.mx |
| **UCSC** | Università Cattolica del Sacro Cuore, Piacenza, Italy; http://www.unicatt.it |
| **UCTE** | Union for the Co-ordination of Transmission of Electricity |
| **UNIBO** | Università di Bologna, Italy; http://www.unibo.it |
| **Variant** | Term used here to summarise sweet, grain, biomass, energy and fibre sorghum |
| **Variety** | Elite lines that are ready to be released as open pollinated |
| **Vinasse** | By-product of the fermentation of molasses to e.g. ethanol |
| **WIP** | WIP Renewable Energies, Germany; http: //www.wip-munich.de |
| **WP** | Work package |
| **Yr** | Year |