Assessment of energy and greenhouse gas inventories of Sweet Sorghum for first and second generation bioethanol

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Abstract

The assessment of energy and greenhouse gas balances is part of a larger effort by UN-Energy to provide decision making tools and aids to Governments and others involved in the planning and implementation of bioenergy development. The report's choice of tools is based on the international state of discussions at the time of writing and presents a building block to the Environmental Assessment Framework currently under development at FAO. Following a joint FAO and IFAD consultation in 2007 on Sweet Sorghum development for bioethanol production (FAO, 2007), this report is a revised study originally prepared for discussions in preparation of the High-level Conference on World Food Security: the Challenges of Climate Change and Bioenergy (Rome, 2008) as a case study to give more precise environmental parameters for this promising energy and food crop.

The study focuses on three main topics:

- The energy and greenhouse gas balances of different Sweet Sorghum pathways are examined by means of a quantitative analysis. For this purpose a so-called screening assessment is conducted which analyses the energy and greenhouse gas impacts along the entire life cycle of Sweet Sorghum for each examined production and use system. The results are compared to the environmental impacts of equivalent fossil fuels.
- Additional environmental impacts from the cultivation of Sweet Sorghum are examined qualitatively.
- Sweet Sorghum is compared to other crops available for biofuel production regarding selected technical aspects.

The (advantageous or disadvantageous) outcome of the energy and greenhouse gas balances and other environmental impacts are clearly determined by the following parameters: the choice of land, of agricultural inputs, of production method, of yield, and the use of by-products. A number of recommendations are made in view of data gaps for detailed local analysis and for framework conditions to assure sustainability of Sweet Sorghum production and conversion. Detailed data are given for each scenario calculation.

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Commissioned by the Food and Agriculture Organization of the United Nations (FAO), Rome

Executive Summary

In light of increased discussions regarding the competition between bioenergy and food, Sweet Sorghum has emerged as a promising energy crop that also offers potential solutions to this conflict. Due to the fact that it can be used for the production of food, first and second generation biofuels as well as for fertilizer, its cultivation is to be encouraged. However, to date neither a consistent picture nor sufficiently reliable scientific documentation exists regarding the crop's sustainability. Consequently, the Food and Agriculture Organization of the United Nations (FAO), Rome, commissioned the ifeu-Institute for Energy and Environmental Research GmbH Heidelberg (IFEU) to investigate the environmental impact of different Sweet Sorghum production systems. These production systems include the production of first and second generation bioethanol from different crop parts as well as a combined use for both biofuels and food.

The study focuses on three main topics:

- The energy and greenhouse gas balances of different Sweet Sorghum pathways are examined by means of a quantitative analysis. For this purpose a so-called screening assessment is conducted which analyses the energy and greenhouse gas impacts along the entire life cycle of Sweet Sorghum for each examined production and use system. The results are compared to the environmental impacts of equivalent fossil fuels.
- Additional environmental impacts from the cultivation of Sweet Sorghum are examined qualitatively.
- Sweet Sorghum is compared to other crops available for biofuel production regarding selected technical aspects.

Results: Energy and greenhouse gas balances – First and second generation bioethanol from Sweet Sorghum can contribute significantly to the conservation of fossil resources and to the mitigation of greenhouse gases. If the crop is used for the production of ethanol (from grains and sugar) and green electricity (from surplus bagasse), 3 500 litres crude oil equivalents can be saved per hectare cultivation area. If both food from grains and ethanol from the juice are produced, 2 300 litres crude oil equivalents can be saved per hectare cultivated area. Regarding greenhouse gases, between 1.4 and 22 kg CO_2 equivalents can be saved depending on yields, production methods and the land cover prior to Sweet Sorghum cultivation. For both categories, the exact values vary greatly with specific scenarios and local conditions. In general, the following parameters determine the results: type and efficiency of conversion technology, the use of by-products (e.g. bagasse), the crop yield per cultivation area, land use changes, as well as the type of fossil energy carriers that are replaced. Even if the seeds were used as food, bioethanol from the stem's sugar juice still shows clear advantages to fossil fuels. If both sugar and seeds were used as food, the respective conversion related energy and greenhouse gas expenditures could be compensated by producing second generation ethanol from the bagasse.

Energetically self-sufficient combined production of first and second generation bioethanol could be achieved by using part of the bagasse to generate process energy. However, the energy and greenhouse gas balances would produce a more favourable result if green electricity is produced from bagasse.

Results: Other environmental impacts – The fact that Sweet Sorghum has a low water demand is especially advantageous if it were grown in arid regions or areas with water shortages. Its low fertilizer demand reduces the risk of nutrient leaching and thus soil and water pollution, as well as making it well suited for small-scale subsistence farming. Its relatively short vegetation cycle allows Sweet Sorghum to be grown in double cropping systems, which in turn can lead under certain circumstances to greater agrobiodiversity and a reduced demand for fertilizers and pesticides. Under intensive practices Sweet Sorghum production risks similar disadvantages as other intensive monocultures, like soil degradation and loss or soil and water pollution due to more fertilizer and pesticide use. Establishing new Sweet Sorghum cultivation sites instead of integrating the crop into existing agricultural systems may lead to a loss of biodiversity, which is more detrimental for species-rich ecosystems. Like many other biofuels, Sweet Sorghum-based bioethanol has disadvantages with regards to certain emissions compared to its fossil equivalents, especially regarding acidification, eutrophication, photochemical smog and ozone depletion.

Results: Comparison with other biofuel crops – Due to a lack of cultivation and breeding experience, the yield stability of Sweet Sorghum is not as favourable as for many firmly established crops such as sugar cane. In principle, the cultivation and harvesting steps can be mechanized to a great extent, yet in practice affordable machines such as for harvesting, especially at small scale, are not yet available. A special advantage of Sweet Sorghum is that with currently existing cost-efficient conversion technologies both food and biofuels can be produced from this crop at the same time. This could reduce competition between food and bioenergy production. Additionally, Sweet Sorghum still delivers appreciable yields in soil of restricted suitability for food crops, a characteristic that many fully established energy crops, such as corn, do not share.

Need for further research and development – In order to be able to calculate specific energy and greenhouse gas balances, which are required for certification and emission's trade, some basic data and specific interactions still have to be elaborated, such as: conversion technologies, carbon sequestration in the crop parts and in the soil under different production systems, the exact demand of and yield response to mineral fertilizer as well as the yields from different production systems under different climate and soil conditions. Since the crop's yield has a considerable influence on the energy and greenhouse gas balances, it should be the starting point of future breeding endeavours which also need to include efforts towards stable yields and an optimized composition of single crop parts. Furthermore, the capacities to integrate the crop into low input cultivation systems and to produce it on carbon poor soils should be actively developed. In order to tap the full potential of this energy crop, environmental research should be accompanied by investigations with economic and social focus.

Conclusions and recommendations – Sweet Sorghum has a great potential to help save fossil resources and reduce greenhouse gas emissions. It is also a promising crop as regards competition between bioenergy and food production and the creation of new income sources for subsistence farmers. If its production and use is increased, it should generally be strived to comply with sustainable, low environmental impact agriculture practices and to support the pro-poor development. In order to better determine and develop the best potentials, FAO should encourage further research and development described above. In addition, a series of case studies in different regions and under varying framework conditions could shed significantly more light on many environmental, economic and social aspects. As a starting point, a virtual and real expert workshop should gather species specific data to fill gaps highlighted in the study and be the beginning of a time-limited network effort to bring sufficient practical and technical knowledge together to enable well informed decision making at different levels. Adequate dissemination efforts may have to follow.

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1 Background, goal and scope

Background

The production of bioenergy increasingly competes with the production of food and feed. In this context, Sweet Sorghum as a multi-purpose crop is expected to play an important role in safeguarding both fuel and food security. Considerable efforts are therefore under way to introduce and popularize new Sweet Sorghum varieties to several regions of the world. However, a large scale introduction of Sweet Sorghum as a bioenergy crop might have substantial environmental impacts.

At the FAO “Global consultation on pro-poor Sweet Sorghum development for bioethanol production and introduction to tropical sugar beet” in Rome in November 2007, it became clear that no consistent picture and little science-based documentation on the sustainability of Sweet Sorghum exist. Therefore, the Food and Agriculture Organization of the United Nations (FAO) commissioned the ifeu-Institute for Energy and Environmental Research Heidelberg, Germany, to provide an assessment of possible environmental impacts of Sweet Sorghum food and fuel production systems leading to first and second generation bioethanol. The results will serve to point out the benefits and risks of such systems and will show potentials and areas for most efficient improvements.

This study, as input to the High Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy and subsequently updated, is part of a larger effort to develop data, methods and tools for the assessment of socio-economic and environmental impacts from the development of bioenergy crops and their product chains *vis-à-vis* food security. To guarantee coherence among different tools and studies, the methodology and results of this study will be compatible with ongoing assessment tool developments under the Bioenergy and Food Security (BEFS 2008) and the Bioenergy Environmental Impact Assessment (BIAS 2008) projects.

Goal and Scope

The goal of this study is to evaluate the environmental implications of Sweet Sorghum product chains for first and second generation bioethanol compared to conventional fossil fuel.

The subgoals are as follows:

- Analysis of different production and use systems of Sweet Sorghum for first and second generation bioethanol including different cultivation systems, different use options of the by-products and different combined food and bioethanol production systems.
- Quantitative assessment of energy and greenhouse gas balances of all Sweet Sorghum systems investigated.
- Identification of the most significant influences on the results along the whole production and use systems and identification of optimization potentials.

- A qualitative outlook on environmental implications other than “resource depletion of fossil energy” and “greenhouse gas emissions” including categories such as acidification, ozone depletion, impact on ground and surface water bodies, soil erosion and agrobiodiversity.
- A qualitative outlook of Sweet Sorghum compared to some alternative fuel crops regarding relevant technical aspects such as experiences in cropping methods, mechanization or competition on land for food production.
- A summary of main conclusions and recommendations including need for further research, programmes, initiatives and incentives.

Details regarding the approach of the study can be found in chapter 2, including sections on the life cycle assessment (LCA) methodology, system boundaries and the analysed environmental impacts. Chapter 3 describes all Sweet Sorghum systems investigated within the framework of this study. The most important results are presented and discussed in depth in chapter 4. The final chapter (chapter 5) derives conclusions and recommendations regarding optimization potentials and the need for further research, programmes and initiatives. The annexes provide further details on the data and systems used for the analyses.

2 Methodology and data

2.1 Methodology

The quantitative evaluation of environmental impacts of Sweet Sorghum production systems, namely energy and greenhouse gas balances, is based on the methodology of life cycle assessment (LCA). The principles of life cycle assessments of products are regulated by international standards (the ISO 14040&14044; ISO 2006). The following aspects are covered in this study:

- The product's entire life cycle from raw material acquisition through production to the utilization of the product, i.e. a "well to wheels" approach (see Fig. 2-1).
- All inputs and outputs relevant for the environmental implications under consideration (biomass resources and other materials, waste water, energy, emissions and other products, etc.).

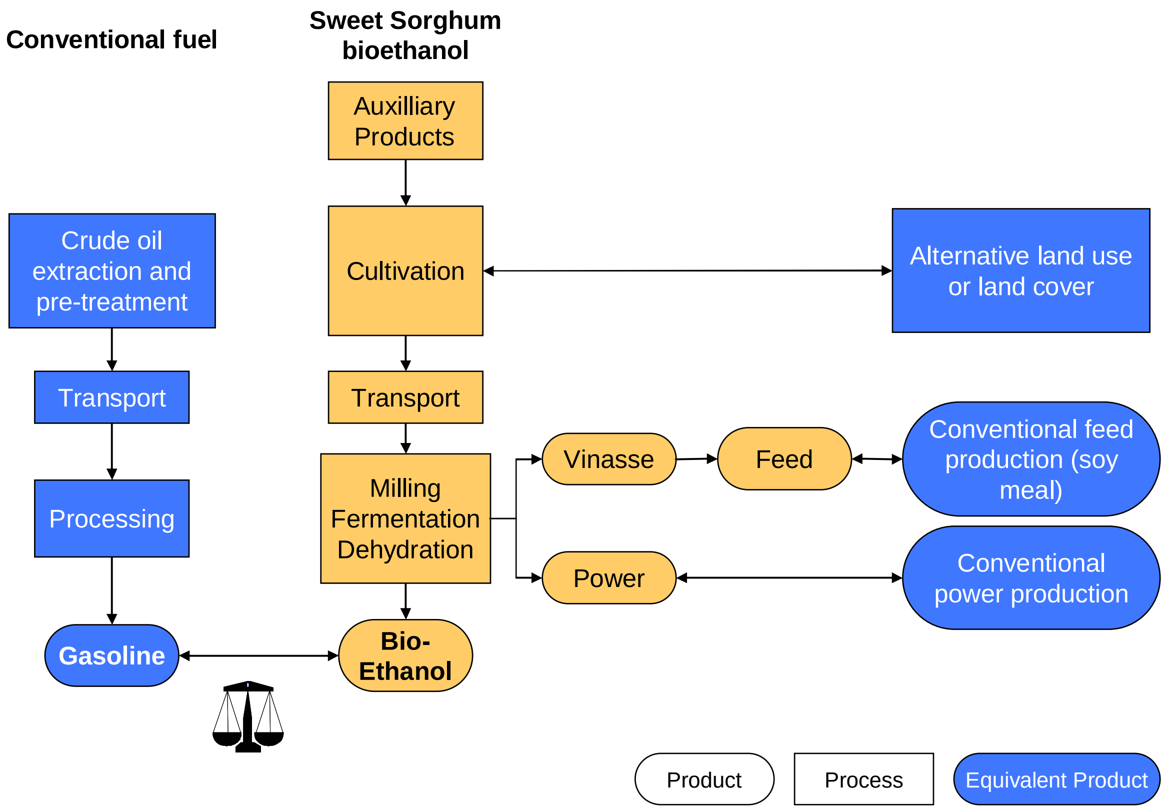

Fig. 2-1 Basic principle of the life cycle comparison between Sweet Sorghum and fossil fuel featuring the production steps from "well to wheel"

It is not the goal of this study to deliver a comprehensive and detailed life cycle assessment for a specific local case but rather to give indications for principle benefits, risks and opportunities. Therefore the evaluation is done as a screening assessment and describes basic interrelationships regarding fossil fuel "resource depletion" and "greenhouse gas emissions" and serves the purpose to give a conclusive overview on possible consequences of an introduction and / or expansion of Sweet Sorghum as a bioenergy crop and provide a base for specific local studies. Such case-specific studies which take into consideration local circumstances and requirements cannot be replaced by a screening assessment.

In order to quantify the influence of single life cycle stages, a number of sensitivity analyses are calculated. They provide a basis for identifying those parameters which have the greatest influence on the overall outcome and of analysing their specific impacts on the results. Through these investigations it is possible to understand the fundamental interrelations and to identify optimization potentials.

The quantitative analysis of further environmental impacts such as ”acidification”, ”eutrophication”, ”biodiversity” or ”water consumption” is outside the scope of this study. They will be dealt with qualitatively together with further environmental impact categories which are difficult to quantify (e.g. ”agrobiodiversity”, ”impact on ground and surface water”).

System boundaries

The assessment of energy and greenhouse gas balances is carried out following the methodology of the LCA standard (ISO 2006) and the scope definition required by these guidelines includes the following main items:

- **Functional unit:** the questions to be answered result in different functional units. Since land use efficiency is the most relevant parameter in the discussion on the competition of food and bioenergy crops, in this study the potential outcome from 1 ha of Sweet Sorghum is assessed and all results refer to this unit.
- **Geographic and time-related coverage:** the production and use of Sweet Sorghum biofuels is related to current conditions taking into account a perspective for 2010 if conditions are not mature today. No differentiation between countries or regions can be made within the scope of this study. Instead and in order to reflect the climatic and soil conditions of different geographical regions, the production system has been divided into three yield classes.
- **System boundaries:** in order to be compatible with the BIAS assessment tool currently under development (BIAS 2008), both the allocation and the credit method are applied in this study. In accordance with the LCA methodology, alternative land use issues are included as described in JUNGK & REINHARDT 2000. Concerning land use and / or land cover changes, direct changes are considered but not indirect ones since this study concentrates on the implications associated directly with the Sweet Sorghum systems (for distinction of direct and indirect land use change see DRAFT BIOMASS SUSTAINABILITY REGULATION 2007 and RENEWABLE ENERGY SOURCES DIRECTIVE (RES) 2008).
- **Depth of analysis:** all system inputs and outputs are taken into account, except for the manufacturing of production and processing equipment, vehicles and infrastructure. As described in detail in CALZONI *et al.* 2000, there is no need to include them in a screening assessment when the type of the bioenergy systems such as this one are investigated since their influence on the results is far below the respective bandwidths.

2.2 Data origin and quality

Concerning the origin of the basic data used in this study, two main categories are distinguished:

- Data on the upstream processes of ancillary products such as mineral fertilizers and conventional fuels as well as on the provision of electric power.
- Data on the cultivation of Sweet Sorghum and the conversion of its products to food or bioethanol as well as the biofuels' utilization in a car engine.

The former data originate from IFEU's internal database (IFEU 2008a). These data have been compiled and validated by IFEU throughout numerous studies. Where necessary, it was adjusted to development countries' state-of-the-art conditions.

All Sweet Sorghum specific data including inputs to and outputs from each life cycle stage from cultivation through conversion to utilization originate from an extensive literature research. Since cultivation and conversion of Sweet Sorghum ethanol is very similar to the production of ethanol from sugar cane, these data have been drawn on whenever specific data on Sweet Sorghum have been missing. Tables with all relevant data have been included in the specific paragraphs in chapter 3.

The following addresses some important aspects of the basic data divided into the main life cycle stages:

- **Cultivation:** data on yields, biomass distribution between different parts of the Sweet Sorghum crop and their respective nutrient, energy and water content as well as data on different inputs such as seeds, fertilizer or diesel fuel are derived from own estimations und calculations based on CARTER *et al.* 2000, GRASSI *et al.* 2002, PARI 2007, RAJVANSHI & NIMBKAR 2001, REDDY *et al.* 2005, REDDY *et al.* 2007, WOODS 2000 and WOODS 2007. Inputs of mineral fertilizer are calculated on the basis of nutrient removal and might differ from the actual application.
  Carbon stock changes are important impacts. Thus data on carbon stocks in soil and forests and in the Sweet Sorghum crop are calculated on the basis of FAIR 2000, FERNANDEZ *et al.* 2003, GRASSI n. y., IPCC 2006 and LASCO *et al.* 1999. For the case examined here, only few figures are known which are not necessarily representative either; they must thus be explored in more depth within a specific system-analytic approach.
- **Conversion:** generic data on the conversion of Sweet Sorghum grains and / or sugar to ethanol such as auxiliary materials and efficiencies have been derived from our own calculations and estimations based on ALEXOPOULOU 1999, CHIARAMONTI *et al.* 2002, FERNANDEZ 1998, GRASSI *et al.* 2002, LAU *et al.* 2006, PRASAD 2007, RAINS *et al.* 1993, REDDY *et al.* 2005, REDDY *et al.* 2007, WOODS 2000 and WORLEY *et al.* 1992.
  Where necessary, data have been completed from existing ethanol production plants for which data had already been collected in IFEU's internal database (IFEU 2008a). Relevant data can be found in chapter 3.2.2.
- **Utilization:** data on the utilization of Sweet Sorghum bioethanol and its by-products are derived and calculated on the basis of the internal IFEU database (IFEU 2008a).

Not all data are scientifically robust and some show high uncertainties and / or bandwidths. Available data on the amount of nitrogen fertilizer delivers an inconsistent picture. There are only few reliable sources on the conversion of Sweet Sorghum to bioethanol and the production of by-products. Furthermore, especially biomass and sugar yields vary strongly. In all relevant cases, the influence of the respective parameters is investigated with sensitivity analyses. Nonetheless, the data quality is definitely sufficiently sound to evaluate the Sweet Sorghum system and to meet the goal of the study. In very few cases data are highly uncertain so that no exact conclusions can be drawn e.g. in the case of Dried Distillers Grains with Solubles (DDGS) production for feed. These cases are addressed in the needs for further research in the conclusion chapter (chapter 5).

2.3 Environmental impacts

In this study, a wide range of environmental impacts have been analysed quantitatively and qualitatively. The quantitative evaluation covers categories “resource depletion” (depletable primary energy carriers, i. e. mineral oil, natural gas, different types of coal as well as uranium ore) and “greenhouse effect”. In the discussion of the results, a simpler, informal formulation is given priority over a scientific correct formulation: Results are named as **fossil energy savings**, whereas in the case of greenhouse gases results are called **greenhouse gas savings**.

The qualitative evaluation covers acidification, eutrophication, photo smog, ozone depletion, soil erosion / compaction, water consumption, soil organic matter and agrobiodiversity. The different environmental impact categories are described in Tab. 2-1.

Environmental category	Description
Quantitative evaluation	
Resource depletion* (energy)	Consumption of non-renewable primary energy carriers, i.e. fossil fuels such as mineral oil, natural gas and different types of coal as well as uranium ore. The procedures and general data for the calculation are documented in detail in BORKEN *et al.* 1999.
Greenhouse effect	Anthropogenic greenhouse gas emissions are considered to contribute to global warming and climate change. Besides carbon dioxide (CO_2), a number of other trace gases – among them methane (CH_4) and nitrous oxide (N_2O) – are included. The latter are converted into carbon dioxide equivalents (CO_2 equiv.) by a weighting of 23 for CH_4 and 296 for N_2O and are discounted over a period of 100 years (IPCC 2001). The procedures for the calculation are documented in detail in BORKEN *et al.* 1999.
Qualitative evaluation	
Acidification	Shift of the acid/base equilibrium in soils and water bodies by acid forming gases (keyword “acid rain”).
Eutrophication	Diffuse aerial input of nutrients into soils and water bodies caused by eutrophicating substances such as nitrous oxides or ammonia.
Photo smog	Formation of specific reactive substances, e.g. ozone, in presence of solar radiation in the lower atmosphere (keyword ”ozone alert”).
Ozone depletion	Loss of the protective ozone layer in the stratosphere through certain gases such as chlorofluorocarbons (CFCs) or nitrous oxide (keyword ”ozone hole”).
Soil erosion / soil compaction	Soil erosion describes the soil transport caused by water, wind and temperature influence and causes the reduction of soil fertility. Soil compaction increases erosion and is caused by the use of heavy agricultural machinery. It furthermore leads to a decline of soil micro-organisms and oxygen content and eventually decreasing yields.
Resource depletion (water)	The total water consumption of a crop during its cultivation influences above and below ground water reserves which is important in arid areas and areas with water shortages.
Impact on ground and surface water	Pollution of ground and surface water bodies by the input of nutrients (key word “algal bloom”) and pesticides.
Impact on soil organic matter	A positive soil organic matter balance is crucial for the long term preservation of soil fertility.
Agrobiodiversity	Describes the above and below ground biodiversity in agricultural systems. It depends on various physical and biological factors as well as different production methods and cropping cycles, on crop diversity, crop varieties and soil and pest management. Diversity in agricultural systems is crucial for the stability of the system and for the resilience of the system to pests, diseases and climate variability.
*for details see text	**IFEU 2008a**

Tab. 2-1 Environmental impact categories evaluated in this study

3 System descriptions

3.1 Sweet Sorghum – a short characterization

The following list gives a short characterization of Sweet Sorghum (after FAO 2007, FAO 2008, FAIR 2000, GNANSOUNOU *et al.* 2005, GRASSI n.y., IFEU 2008b, REDDY 2005, REDDY 2007, WOODS 2003):

- Scientific name: *Sorghum bicolor* (L.) Moench; common names include Sorghum (English), Zuckerhirse (German), durra (Africa), Jowar (India), bachanta (Ethiopia).
- Family: Graminaceae.
- Varieties: most countries where Sweet Sorghum is cultivated have their own breeding programmes aiming at the development of Sweet Sorghum varieties adapted to different cultivation conditions or for producing higher yields. However, there is no overview on the number and description of common varieties.
- Geographical distribution: originated in Ethiopia, today it has spread to other parts of Africa, India, Southeast Asia, the United States of America and Europe, in semi-arid to humid climates.
- Physical characteristics: annual; grows from seeds; stalk is 0,8-5 m high and contains a sugar-rich juice (sucrose, fructose, glucose); panicles can produce up to 4 000 starch containing grains; leaves are smaller than those of corn.
- C4 crop which is very drought resistant; shows a good adaptability to poor soil types and to saline soils; has a very short vegetation period and thus is ideal for double cropping (two times Sweet Sorghum or with alternative crops).

The Sweet Sorghum crop can be separated into three main parts which each can be used in various ways. Tab. 3-1 shows the different crop parts and their use options.

Crop part	Possible use options	Use options regarded in this study
Grains	Feed, food, first generation bioethanol	First generation bioethanol, food
Juice	Sugar, first generation bioethanol	First generation bioethanol, sugar
Bagasse	Feed, pulp, bioenergy, second generation bioethanol, compost, fertilizer	Bioenergy*, second generation bioethanol
Leaves	Feed, fertilizer, bioenergy, second generation bioethanol	Fertilizer, feed

* depending on the scenario either green electricity and / or combined heat and power production (used as process energy)

Tab. 3-1 Use options of Sweet Sorghum crop parts

3.2 Sweet Sorghum production and use scenarios

3.2.1 Cultivation and land cover changes

This chapter addresses two important aspects of Sweet Sorghum cultivation, namely inputs and outputs, and the reference system, namely land cover. The latter defines what the cultivated land area would be used for or which land cover would exist if the investigated product was not to be produced. The reference system is an essential part of an LCA.

In the production of Sweet Sorghum, many cultivation systems are possible: high input, low input, no-tillage farming or organic farming. Regardless of the cropping system, in this study, only external means of production are regarded (e.g. fertilizer, fuel for tractors etc.). Changes in soil characteristics such as the amount of soil organic matter due to certain cultivation methods such as organic or no-till farming are not taken into account in the calculations but are addressed later as further need for research.

From our knowledge and experience, the difference of energy and greenhouse gas balances between no-tillage and tillage systems is insignificant as far as the fuel input for tillage operations is concerned. As can be seen in chapter 4.2, the amount of diesel fuel has almost no impact on the overall greenhouse gas and energy balances. This is especially true for this study as some data are uncertain and / or show high bandwidths which influence the outcome of the balances to a higher extent than different cultivation methods.

On the other hand, the choice between conventional and organic farming based on the differences in fertilizer use might have an impact on the outcome of the energy and greenhouse gas balances. However, an advantageous impact might be compensated by a yield decrease leading to lower ethanol production. Compared to continuous monocultures, average annual energy yields per hectare over several years in organic systems will be less since in some years, due to crop rotation, non-energy crops have to be grown. However crop rotations are good agricultural practices in general and allow also for intermittent food crops and improving soil fertility. A potential yield reduction converted into one single year will be within the range covered by the different yield classes used in this study.

Further variations have been assumed for practices common in small-scale farming systems such as different use options for leaves or harvesting methods. Where appropriate, differences between small and large scale farming systems are described in the result chapter (chapter 4).

However, it is out of the scope of this study to deal with the different farming systems in depth. Usually, in screening LCAs, when assessing a system for the first time, emphasis is put on standard methods in order to show basic interrelations. For this study, two more aspects are important: 1) agronomic data for Sweet Sorghum are still quite variable so that a detailed differentiation of production systems would be counterproductive; 2) high yielding production systems are difficult to achieve without mineral fertilizer.

Cultivation

Sweet Sorghum is cultivated in very different geographical regions – ranging from the dry tropics to more humid and cooler climates. The cultivation under different climatic and soil conditions results in high differences of yields. In addition, despite considerable breeding efforts and achievements, yields are still variable. In order to capture all inter- and intraregional yield variations as well as possible variations between different production systems, the yields have been classified in three categories: “Low”, “Medium” and “High”.

Besides the total yield, also the juice extractability and therefore bagasse and sugar yields vary significantly due to different crop varieties and milling technologies. Therefore, in every yield class two juice / sugar yields have been assumed: “Sugar Low” and ”Sugar High”.

Average yields of the different crop parts (grains, juice, bagasse, leaves) as well as the different sugar yields are presented in Tab. 3-2. In the six selected scenarios (see chapter 3.2.3), medium biomass yields and a low sugar yield have been assumed (data marked yellow and with an asterisk). The influence of the different yields on the quantitative environmental impact categories (fossil energy savings and greenhouse gas savings) is described in the sensitivity analyses in chapter 4.3.

Biomass yield	**Low**		**Medium**		**High**	
Sugar yield	**Sugar Low**	**Sugar High**	**Sugar** Low**	**Sugar High**	**Sugar Low**	**Sugar High**
Yield Biomass total [t dm / (ha x yr)]	10		**20**		35	
Yield grains [t / (ha x yr)]	2		**4**		7	
Yield sugar* [t / (ha x yr)]	1.3	2.5	**2.5**	5.0	4.4	8.8
Yield Bagasse* [t / (ha x yr)]	4.8	3.5	**9.5**	7.0	16.6	12.3
Yield Leaves	2		**4**		7	
*calculated	**numbers in bold indicate the “Standard” scenario (scenario 1)				**IFEU 2008b**	

Tab. 3-2 Average yields of Sweet Sorghum crop parts

Cultivating Sweet Sorghum requires a number of inputs such as seeds, pesticides and diesel fuel (for tractors). The input of seeds and pesticides are unspecific and do not differ between the yield classes. Different amounts for diesel fuel, instead, are assumed due to differences during harvest. Data assumed for the six main scenarios are again marked yellow and with an asterisk. When the yield is varied in the sensitivity analysis, the respective data are adjusted accordingly. An overview of the most relevant input data is presented in Tab. 3-3.

Yield scenario	Seeds [kg / (ha x yr)]	Pesticides [kg / (ha x yr)]	Diesel fuel [kg / (ha x yr)] Establishment	Harvest
Low	7	5	60	30
Medium*	**7**	**5**	**60**	**60**
High	7	5	60	105
*numbers in bold indicate the "Standard" scenario (scenario 1)				**IFEU 2008b**

Tab. 3-3 Average inputs of seeds, pesticides and diesel fuel; basic data regarding primary energy use and greenhouse gas expenditures can be found in annex 8.2

The cultivation of Sweet Sorghum also requires the input of fertilizer. The amount of fertilizer has been calculated on the basis of nutrient removal and therefore changes subject to the yield. The amount of fertilizer assumed in this study might differ from the amount of fertilizer actually applied. In the calculation of fertilizer amount, the leaves remaining on the fields have been considered. Tab. 3-4 shows the different inputs of mineral fertilizer depending on the yield scenario.

Yield scenario	N [kg / (ha x yr)]	P_2O_5 [kg / (ha x yr)]	K_2O [kg / (ha x yr)]
Low	50	20	10
Medium*	**100**	**40**	**20**
High	175	70	35
*numbers in bold indicate the "Standard" scenario (scenario 1)			**IFEU 2008b**

Tab. 3-4 Fertilizer requirements based on nutrient removal; basic data regarding primary energy use and greenhouse gas expenditures can be found in annex 8.2

Land cover changes

When a comparison is being made between a bioenergy and a fossil energy carrier, it is always necessary to define an alternative way in which the required land might be used, if not for the production of bioenergy, or – in case natural vegetation is converted – what kind of alternative land cover would exist. Any environmental assessment of a bioenergy production system must take into account such alternative land uses or land covers, which are also referred to as the reference systems. In this study, fallow land is assumed as the agricultural reference system. Further background information can be found in JUNGK & REINHARDT 2000.

Every land cover change, even from degraded land to Sweet Sorghum cultivation, influences the area's carbon stock, i.e. carbon content of both soil and vegetation. Three possible developments can take place: a net carbon loss in case an area with dense vegetation (e.g. tropical dry forest) is converted, no change in the carbon stock in case an area with similar vegetation (e.g. savannah) is converted or a carbon gain in case an area with scarce vegetation is converted. Irrespective of loss or gain, any difference in carbon stock before and after Sweet Sorghum cultivation is reflected in the greenhouse gas balances and must be annualized ("written off") over a certain period of time. In this study, a depreciation period of 20 years was selected to be compliant with the BIAS framework currently under development (BIAS 2008). This time period is also used in the European sustainability strategy ('Proposal for a Directive of European Parliament and of the Council on the promotion of the use of energy from renewable sources' COUNCIL OF THE EUROPEAN UNION 2008). As described in chapter 2, only direct land use change is regarded in this study. A more comprehensive and case-specific study, however, also has to include indirect land use changes. Since the yield depends on soil and climatic conditions, which on their part influence the natural vegetation of a region, yields and different vegetation types are connected and different carbon stock changes are possible under different yield scenarios.

The different yields and the possible carbon stock changes are depicted in Tab. 3-5.

Yield scenario	Carbon loss [t C / (ha x yr)]	Carbon neutral [t C / (ha x yr)]	Carbon gain [t C / (ha x yr)]
Low		0	+ 10
Medium	- 35	0	+ 5
High	- 35	0	
			IFEU 2008b

Tab. 3-5 Carbon stock changes for different yield scenarios

The scenario "carbon neutral" was chosen as a base for all life cycle scenarios regarded in this study. Thus carbon changes do not influence the greenhouse gas balances and changes due to other parameters become visible. The influence of the carbon stock changes on the greenhouse gas balance is assessed with the help of a sensitivity analysis in chapter 4.3.2.

3.2.2 Conversion systems, products and by-products

Along the Sweet Sorghum life cycle, a range of products and by-products are generated. Fig. 3-1 gives an overview of these products and their respective use considered in this study. In the annex, more detailed overviews can be found explaining which by-products are derived from which scenario.

The main product examined in this study is first and second generation bioethanol which is used as biofuel substituting conventional fuel (gasoline) on the basis of the energy content. First generation ethanol is ethanol derived from the fermentation of the sugar contained in Sweet Sorghum juice or starch contained in the grains. Second generation ethanol in this study is cellulosic ethanol, which is made by converting cellulose, as from bagasse, into sugars using chemical or thermal pre-treatment and enzymes. The sugars can then be fermented to produce ethanol in the same way as first generation bioethanol production.

The **leaves** are removed and either are left on the field or used as feed. In the latter case, wheat is substituted on the base of its energy content.

The **grains** are either used as food or fermented into first generation bioethanol. In the production of ethanol from grains, stillage is generated as by-product. It can either be concentrated and directly used as feed or can be further dried and pelletized and used as feed in form of DDGS (Dried Distillers Grains with Solubles). Both stillage and DDGS substitute soy meal on the base of their protein content.

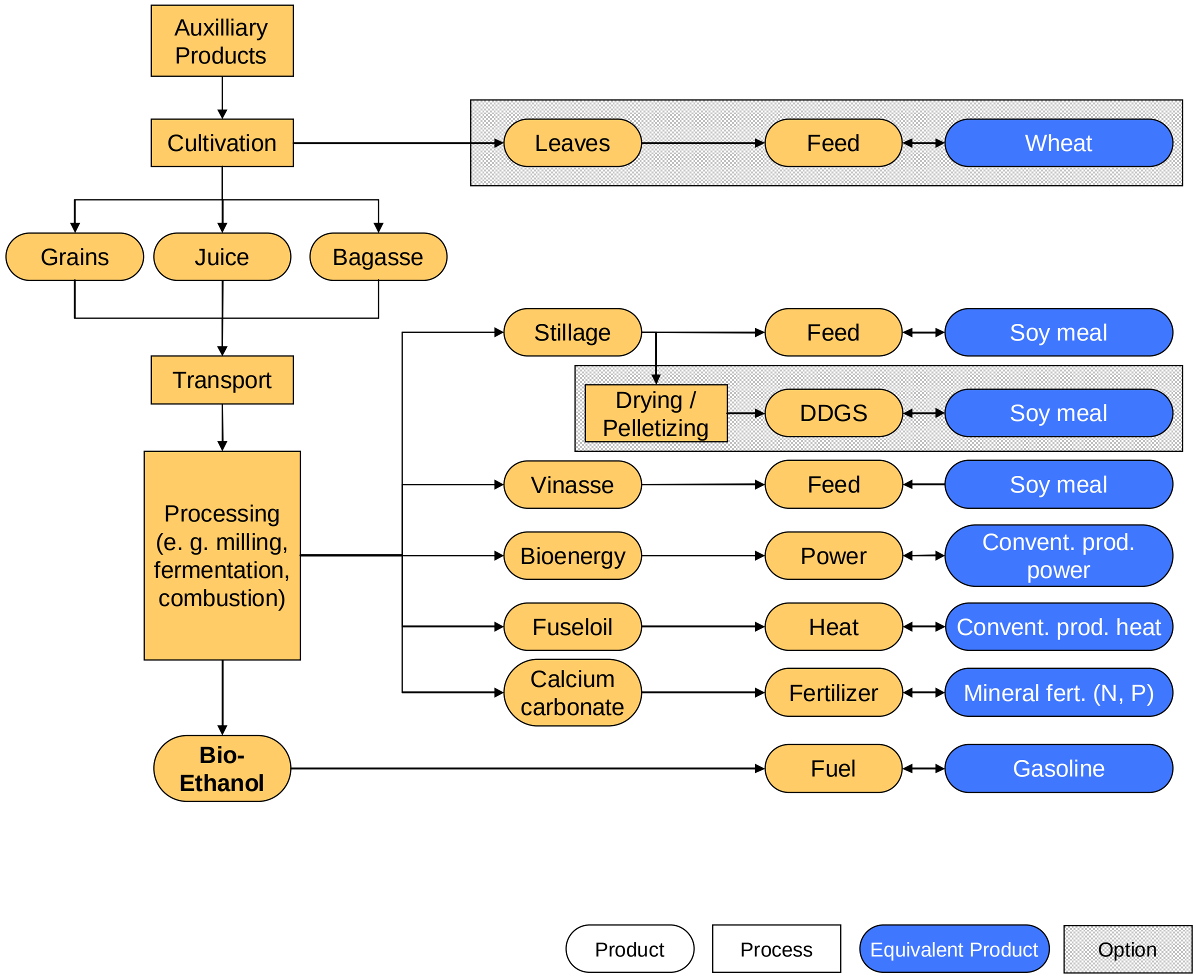

Fig. 3-1 Products and by-products from Sweet Sorghum cultivation and processing examined in this study and their equivalents in terms of conventional products (on the right)

The stem is separated into juice and bagasse. Depending on the Sweet Sorghum crop variety and on the milling technology different juice and bagasse yields are possible (see Tab. 3-2). Once separated from the bagasse, the **sugar** will be either converted into crystalline sugar or into first generation bioethanol. During the fermentation process, vinasse is generated as a by-product. It is concentrated and used as feed substituting soy meal on the base of protein content.

The **bagasse** can be used in two ways: First, it can be combusted to produce high pressure steam which is used to generate electricity and heat for the ethanol conversion process. Surplus bagasse is used to produce electricity which substitutes conventionally produced electricity. Different fossil energy carriers can be substituted. In order to evaluate the whole range of results, two extreme cases are examined in the sensitivity analysis: power from hard coal and power from natural gas (see chapter 4.3.5). In the six scenarios, coal is assumed as standard. Second, bagasse can be converted into second generation bioethanol.

All processes can be realized self-sufficiently with bagasse providing the process energy or they can be fuelled by an external fossil energy carrier. The production of second generation ethanol is self-sufficient in any case since the process energy can be provided from by-products.

Tab. 3-6 shows an overview of relevant data for energy expenditures and rates of biomass conversion used in this study.

	Data	Unit	
Energy input ethanol from sugar	13.1	GJ / t	EtOH
Ethanol from sugar	0.5	t / t	sugar
Energy input ethanol from grain	3.5	GJ / t	EtOH
Ethanol from sugar	0.3	t / t	grains
Ethanol from bagasse	0.13	t / t	bagasse
Energy input sugar from juice	5.0	GJ / t	juice
			IFEU 2008a; IFEU 2008b

Tab. 3-6 Energy expenditures and conversion rates

3.2.3 Synthesis of all scenarios

In this study, six different life cycle scenarios are examined leading to first and second generation bioethanol. In all scenarios, vinasse is produced as by-product from the grain fermentation and leaves are used as fertilizer.

Tab. 3-7 gives an overview of the different life cycle scenarios examined in this study. The "Standard" scenario (scenario 1) is used as the base for different sensitivity analyses.

Detailed flow-charts of the different life cycles can be found in annex 8.1.

Number	Scenario	Juice	Grains	Bagasse	Leaves
1	**Standard**	First generation bioethanol	First generation bioethanol & stillage	Process energy & bioelectricity	Fertilizer
2	**Grains food**	First generation bioethanol	Food	Process energy & bioelectricity	Fertilizer
3	**Food & EtOH 2**	First generation bioethanol	Food	Second generation bioethanol (autarkic)	Fertilizer
4	**Grains & Juice food**	Food (fossil fuel input)	Food	Second generation bioethanol (autarkic)	Fertilizer
5	**EtOH 2 extended autarkic**	First generation bioethanol	First generation bioethanol & stillage	Second generation bioethanol (autarkic)	Fertilizer
6	**EtOH 2 maximum fossil**	First generation bioethanol	First generation bioethanol & stillage	Second generation bioethanol (fossil fuel input)	Fertilizer

Tab. 3-7 Overview of all life cycles considered in this study

Standard scenario (scenario 1)

Grains and juice are converted into first generation bioethanol. The process energy is provided by the combustion of bagasse. Since only part of the bagasse is needed to generate the process energy for grain and sugar conversion, the remaining part of the bagasse is calculated as producing surplus bioelectricity and thus substituting conventional fossil energy used for generating the equivalent amount of electricity.

Grains food (scenario 2)

In order to address the issue of competition between food and fuel, in this scenario the grains are used as food. Juice, bagasse and leaves are used as in the standard scenario: for first generation bioethanol, process energy / bioelectricity and fertilizer. Since less bagasse is needed for providing the process energy, more surplus bioelectricity can be generated.

Food & EtOH 2 (scenario 3)

The juice again is converted into first generation bioethanol and the grains are used as food. The bagasse is partly used to generate the process energy; the surplus bagasse is then converted into second generation bioethanol. Since the whole bagasse is used no surplus bioelectricity can be produced.

Grains and juice food (scenario 4)

Here, both grains and juice are used as food. The sugar processing is fuelled by coal, therefore the whole bagasse can be converted into second generation bioethanol.

EtOH 2 extended autarkic (scenario 5)

This scenario is a variation of the “Standard” scenario. Grains and juice are converted into first generation bioethanol, being fuelled by part of the bagasse. The surplus bagasse is converted into second generation bioethanol. The whole process is realized autarkic with no external fossil fuel input necessary.

EtOH 2 maximum fossil (scenario 6)

This scenario aims at a maximum output of second generation bioethanol. Grains and juice are converted into first generation bioethanol and the whole bagasse is converted into second generation bioethanol. All processes are fuelled with coal as external energy carrier.

Synthesis of relevant data

Tab. 3-8 shows all relevant yields of products and by-products for the six scenarios.

Sweet Sorghum biomass	**20 t dm / (ha x yr)**				
Scenario	**EtOH Grains** [t / (ha x yr)]	**EtOH Juice** [t / (ha x yr)]	**EtOH Bagasse** [t / (ha x yr)]	**Stillage & Vinasse** [t / (ha x yr)]	**Bioelectricity** [MWh / (ha x yr)]
Standard	1.24	1.25		2.61	5.13
Grains food		1.25		1.09	5.37
Food & EtOH 2		1.25	1.03	1.09	
Grains & Juice food			1.20		
EtOH 2 extended autarkic	1.24	1.25	0.98	2.61	
EtOH 2 maximum fossil	1.24	1.25	1.20	2.61	
					IFEU 2008b

Tab. 3-8 Synthesis of yields of products and by-products for all scenarios

3.3 Sensitivity analyses for the different scenarios

Besides the variations in the scenarios, there are other factors which may influence the environmental performance of Sweet Sorghum. Some of the relevant parameters already have been described in the previous chapters such as yield and sugar variations or changes in carbon stocks (see chapter 3.2.1). In this chapter, additional sensitivity analyses are presented. The respective results are presented in chapter 4.3.

Where not stated otherwise, variations are based on the “Standard” scenario described in the previous chapter.

DDGS instead of stillage as end-product

During the fermentation process of the grain, stillage is generated as a by-product. It can either be dried and directly used as feed (“Standard”) or it can be concentrated and pelletized and thus converted into DDGS which also is used as feed. In the case of DDGS production, higher energy inputs are necessary for drying and pelletizing the stillage. Both products replace soy meal on the base of their protein content.

Tab. 3-9 shows the respective protein contents and the energy consumption for the ethanol production from grains with stillage or DDGS as by-product.

Energy input Standard (stillage)	**Energy input DDGS**	**Protein content**		
		Stillage	**DDGS**	**Soy meal**
[GJ / t EtOH]	[GJ / t EtOH]	[% (fm)]	[% (fm)]	[% (fm)]
3.5	16.0	5.6	35.8	42
				IFEU 2008a; IFEU 2008b

Tab. 3-9 Energy inputs for stillage and DDGS production and protein contents

Use of leaves as fertilizer or feed

In the main scenarios, Sweet Sorghum leaves are left on the field as fertilizer. However, in small-scale farming systems also the use of the leaves as cattle feed is common practice. In this case, wheat, as feed, is assumed to be substituted by the leaves. The amount of substituted wheat has been calculated based on the energy content of both leaves and wheat. The use of leaves as feed also influences emissions due to transportation as a higher weight has to be transported. Furthermore, more mineral fertilizer has to be applied on the field to compensate the higher nutrient removal.

Tab. 3-10 quantifies all major differences as a result of removing leaves from the field and using them for feed.

Scenario	Fuel for transport [to x km / (ha x yr)]	Amount of mineral fertilizer needed to substitute removal [kg / (ha x yr)]			Energy content (LCV) [MJ / kg dm]	
		N	P_2O_5	K_2O	Leaves	Wheat
“Standard”	1330	100	40	20		
‘Leaves as feed’	1530	110	48	24	17.5	17.1
						IFEU 2008b

Tab. 3-10 Differences due to the use of leaves as feed; basic data regarding primary energy use and greenhouse gas expenditures can be found in annex 8.2

Variation of substituted conventional energy carriers

Surplus bioelectricity generated from Sweet Sorghum bagasse substitutes electricity generated with different fossil energy carriers. In order to evaluate the corresponding range of results, two extreme cases are examined: power from hard coal and from natural gas. These energy carriers differ considerably with respect to their emissions of carbon dioxide thus leading to different credits for avoided emissions.

Variation of external fossil energy carrier

In the “EtOH 2 maximum fossil” scenario the whole bagasse is converted into second generation ethanol. The process energy for the first generation ethanol conversion processes is generated with external fossil energy. The choice of the fossil energy carrier can have a significant influence on the greenhouse gas balances since they differ considerably with respect to their emissions of carbon dioxide. Therefore, both coal and natural gas have been examined as external fossil fuel.

Mechanical versus manual harvest

Whereas in large scale production systems Sweet Sorghum is harvested mechanically, in small-scale systems often no adequate and / or affordable machinery is available to separate the different crop parts. In this case, the harvest is realized manually and only the diesel fuel for establishment (60 kg / (ha x yr)) is calculated. The fuel used for harvesting is set to zero.

Credit versus allocation method

In LCAs, different methods exist to deal with the by-products such as bagasse or stillage. In the credit method, credits are given for all by-products of the bioethanol production on the basis of the conventionally produced goods substituted by the by-products (see Fig. 3-1 and all figures in annex 8.1). This is because through the use of the by-products the environmental impacts caused by the production of the conventional products are avoided. All avoided environmental impacts due to the by-products are credited to the bioethanol.

In contrast, the allocation method is based on the approach that all environmental impacts caused by a process are caused by both, the main product and the by-products. As a consequence, all environmental impacts (e.g. greenhouse gas emissions) are allocated proportionately to the product and the different by-products. Different references are possible such as mass, energy content (e.g. lower heating values) or costs. To be in line with the European sustainability strategy ('Proposal for a Directive of European Parliament and of the Council on the promotion of the use of energy from renewable sources' COUNCIL OF THE EUROPEAN UNION 2008), in this study the lower heating values of products and by-products serve as a base for allocation. Furthermore, a second allocation calculation is done based on the product's and by-products' masses.

There is no common agreement on which of the two methods to use in life cycle assessments. With the credit method reality can be reflected much more detailed and realistically. However, the inclusion of the by-products' uses makes the calculations very complex. Moreover, the fact that the by-products can be used in different ways and that very different goods can be substituted can lead to great bandwidths in the results.

This is why often in common guidelines the use of the allocation methodology is propagated. At first sight, it delivers clearer results in terms of a rather narrow bandwidth and calculations are much simpler compared to the credit method. This makes the allocation method an interesting tool when it comes to the need for quick results and decisions.

However, in both methodologies results are greatly influenced by the underlying questions and resulting system boundaries and therefore are difficult if not impossible to compare. Therefore, there is a need for standardization and harmonization which is currently strived for in different international guidelines and agreements such as in the international life cycle standards (ISO 14040&14044; ISO 2006), the BIAS framework (BIAS 2008) or within the Global Bioenergy Partnership (GBEP 2009).

Both methodologies are shown in Fig. 3-2 and Fig. 3-3. Fig. 3-2 shows the credit methodology as used in this study and explained in chapter 2.1, and Fig. 3-3 shows the substitution methodology. For both methodologies, the "Standard" scenario is taken as a basis, i.e. juice and grains are used for ethanol production and part of the bagasse is used for process energy production. The remaining part of the bagasse can be used for allocation.

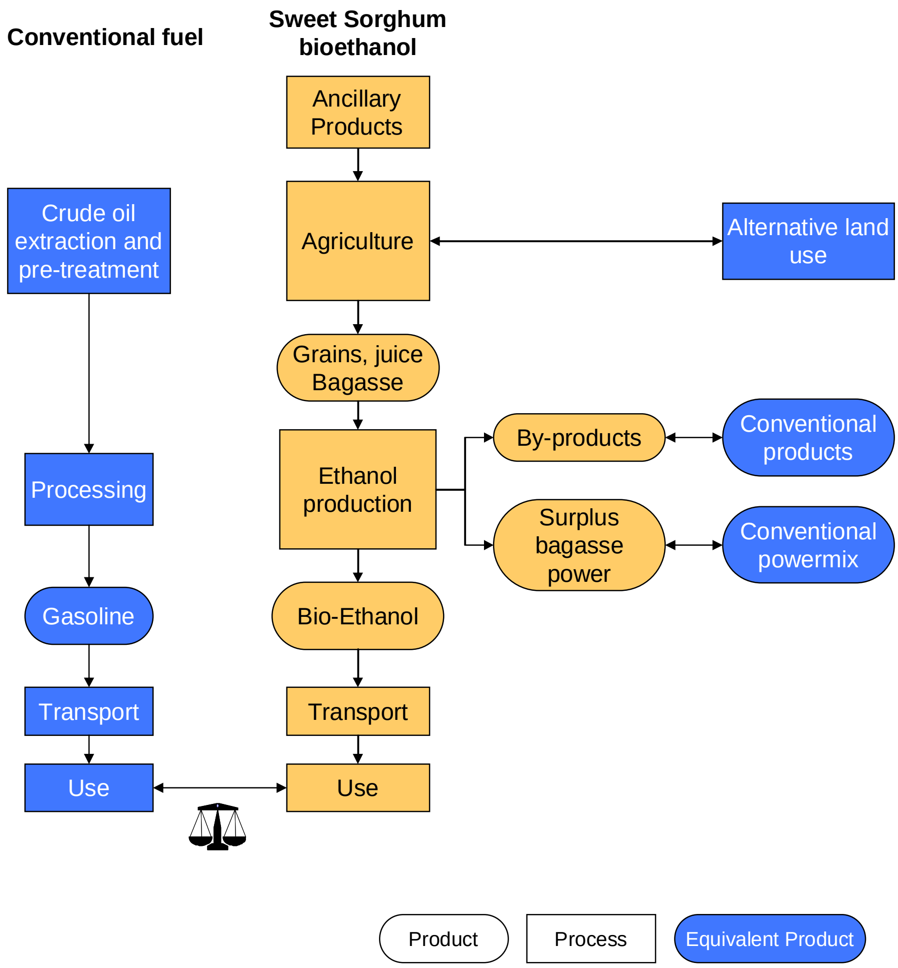

Fig. 3-2 The Sweet Sorghum production and use system based on the **credit method**

Fig. 3-3 displays the proportions of the respective products and by-products based on the lower heating values and based on masses (in parentheses). The allocation based on energy content will serve as an example to explain the calculation of the proportions. In the "Standard" scenario, 33 GJ bioethanol are produced per hectare from juice and from grains. For juice ethanol, the by-products sum up to 6 GJ, for grain ethanol they sum up to 15 GJ. As a result, 84 percent and 68 percent, respectively, of the greenhouse gas emissions occurring during cultivation and conversion are allocated to both bioethanol types. In total, 66 GJ ethanol and 92 GJ (surplus) bagasse are produced. Therefore, 42 percent of all greenhouse gas emissions accumulated during cultivation and conversion plus all emissions occurring during transport and ethanol use are allocated to the bioethanol. If the single allocation steps are summed up, 32 percent of all greenhouse gases are assigned to the bioethanol.

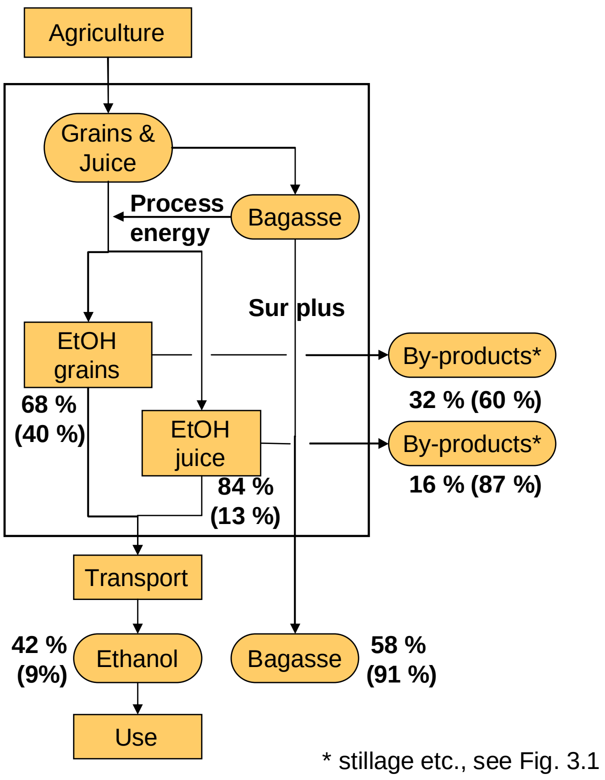

Fig. 3-3 Proportions of products and by-products used for **allocation** based on the energy content and their masses (in parentheses)

In contrast, if allocation is based on the products' masses, finally only 9 percent of all emissions are allocated to ethanol. This is because a high amount (by weight) of bagasse is produced compared to ethanol. Per hectare, 2.5 t ethanol are produced compared to 26 t bagasse.

4 Results

This chapter displays the results of the evaluation of the Sweet Sorghum production and use systems. First, the quantitative results of the six main scenarios regarding “greenhouse house gas savings” and “fossil energy savings” are presented. Then, a number of sensitivity analyses will demonstrate the influence of selected parameters on the results. In a third and fourth part, additional environmental impacts of Sweet Sorghum bioethanol production systems will be described qualitatively and Sweet Sorghum will be compared with alternative fuel crops regarding selected technical aspects.

Reading the diagrams

Fig. 4-1 shall serve as an example to explain how the graphs in this chapter can be read. In the Credits / Expenditures section each scenario is described by two bars. The first bars show on the right side all expenditures necessary for the production of bioethanol (e.g. cultivation and transport of biomass, the production of ethanol, its transport and use). To the left all credits are depicted derived from the use of by-products such as stillage. The second bars show the expenditures connected to the production and use of the conventional fuel replaced by the biofuel. These bars are divided into the amount of the fossil equivalent that is substituted by bioethanol derived from grains, juice and bagasse. The balances shown in the Balances section are calculated as follows: credits for the bioethanol production and the expenditures for the fossil equivalent are summed up and subtracted from the expenditures for the bioethanol production. The balance thus quantifies the amount of primary energy or greenhouse gases which can be saved by the use of bioethanol instead of fossil fuel.

4.1 Results of the main scenarios

As has been described in chapter 3.2, the six main scenarios have different system boundaries and therefore cannot be compared unrestrictedly. Comparisons are only possible between scenario 1, 5, 6 and scenario 2 and 3.

Fig. 4-1 shows the amount of primary energy which can be saved per hectare cultivated land area if conventional fuel is substituted by first and second generation bioethanol. Fig. 4-2 presents the respective results for the amount of greenhouse gases.

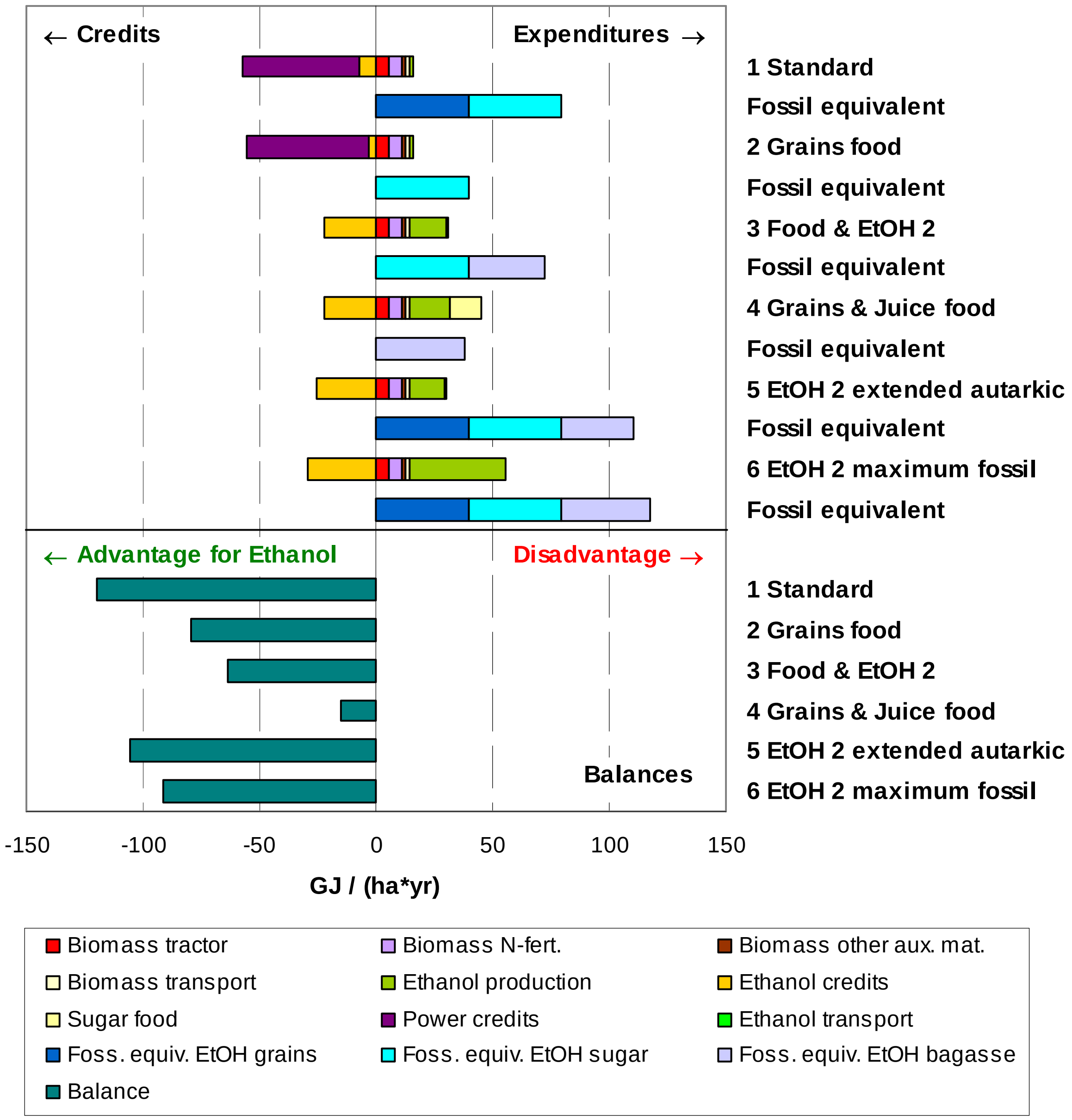

Fig. 4-1 Results of the life cycle comparison between Sweet Sorghum first and second generation bioethanol and conventional fuel regarding **fossil energy** savings. Upper part: detailed expenditures and credits. Lower part: resulting advantages and disadvantages for Sweet Sorghum bioethanol

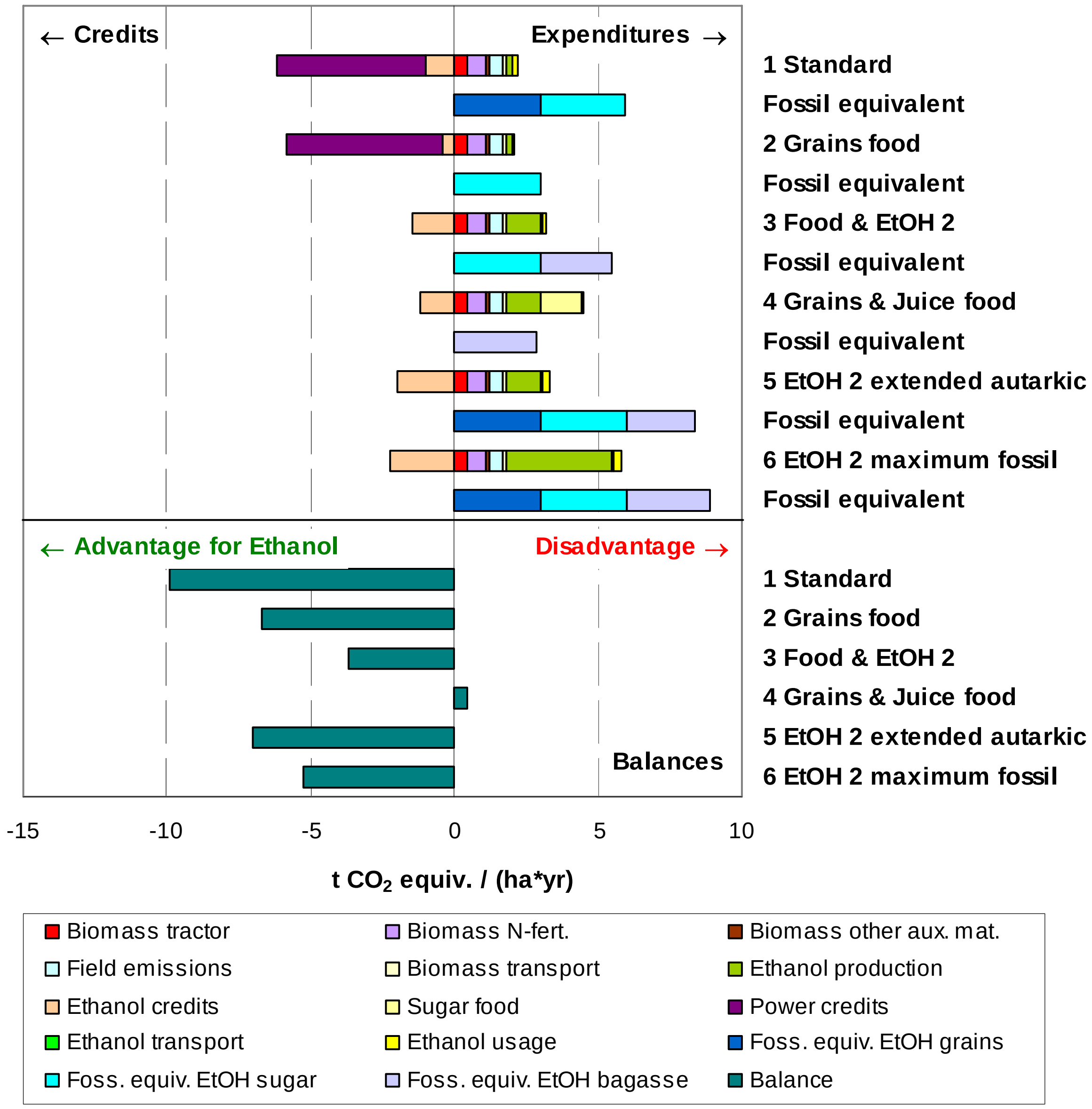

Fig. 4-2 Results of the life cycle comparison between Sweet Sorghum first and second generation bioethanol and conventional fuel regarding **greenhouse gas** savings. Upper part: detailed expenditures and credits. Lower part: resulting advantages and disadvantages for Sweet Sorghum bioethanol

Reading the diagram (Example: "Standard" scenario), Fig. 4-2:

If Sweet Sorghum bioethanol is used instead of fossil fuel, credits and expenditures add up to a saving of about 10 t CO_2 equivalents / (ha x yr) (see balances section). In the production of first generation bioethanol from 1 ha of land, on the one hand about 2 t of greenhouse gases (CO_2 equivalents) are emitted, on the other hand about 6 t of greenhouse gases (CO_2 equivalents) are credited for the use of by-products. The expenditures for the production and use of the equivalent fossil fuel are 6 t of greenhouse gases (see credit / expenditure section).

Results

- Compared to fossil fuels, first and second generation bioethanols from Sweet Sorghum hold considerable potentials to help saving fossil energy carriers and greenhouse gases. An exemption is scenario 4 which is disadvantageous regarding saving of greenhouse gases.
- The overall positive results are due to credits for bioethanol and the respective by-products (especially surplus bioelectricity in the case of first generation bioethanol production which substitutes for conventional electricity) which more than compensate expenditures for bioethanol production.
- Energy and greenhouse gas balances follow similar patterns.
- Even if the grains are used as food instead of being processed into ethanol, there is still a considerable potential to save fossil energy and greenhouse gases with the production of first generation bioethanol from the juice. If the process is realized self-sufficiently with the surplus bagasse used for green electricity production (scenario 2), the savings are higher than if the whole bagasse was used for the production of second generation bioethanol (scenario 3). In the latter case, the process is fuelled with coal.
- If both juice and grains are used as food (scenario 4), the expenditures more or less match the credits which are derived from the ethanol production of the bagasse – the balance is virtually equalized. This is the case for both, the energy and the greenhouse gas balance. The ethanol and the credits for the respective by-products derived from the production process can compensate the expenditures for the food production – mainly for cultivation and for external fossil energy which fuels the sugar production. Therefore, no negative environmental impacts result from the food production.
- The energy and greenhouse gas balances tend to be more advantageous if bagasse is used for the generation of process energy instead of being converted into second generation bioethanol (see scenarios 1 & 5). Though additional ethanol is produced from bagasse (see light violet bar) and higher credits exist due to the use of additional by-products (see light orange bar), the missing credit for bioelectricity cannot be compensated.
- The production of both first and second generation bioethanol at the same time can be realized self-sufficiently with bagasse used for process energy (see scenario 5). At the same time, the substitution of conventional fuel leads to significant fossil energy and greenhouse gas savings. These savings, however, are smaller than if only first generation ethanol would be produced, as described in the previous paragraph.
- Alternatively, the production of both first and second generation bioethanol can be fuelled with coal as external energy carrier (see scenario 6). In this case, the whole bagasse is converted into ethanol instead of producing process energy. Although additional ethanol is produced (light violet bar), this cannot compensate the increased expenditures due to the use of fossil energy. Energy and greenhouse gas balances are more advantageous if all production processes are realized self-sufficiently.

Conclusions

Compared to fossil fuels, first and second generation ethanol from Sweet Sorghum hold considerable potentials to help saving fossil energy carriers and reduce greenhouse gas emissions since most expenditures are more than compensated by credits for bioethanol and the respective by-products.

Even with the use of the grains as food there is significant potential for saving fossil energy and greenhouse gas emissions with the help of first generation ethanol produced from juice. This makes Sweet Sorghum an ideal crop for reducing the competition between food and fuel.

If both grains and juice are used as food, energy and greenhouse gas balances are neutral. This means that under maximized food production in form of grains and sugar, all expenditures occurring during the food production can be compensated by the ethanol production from bagasse. Here, no negative environmental impacts occur regarding fossil energy savings and greenhouse effect.

With the combination of first and second generation ethanol, considerable savings of greenhouse gases and fossil energy can be achieved. However, the savings are higher if the bagasse is not converted into second generation bioethanol but used for the generation of process energy fuelling the production of first generation bioethanol and for the generation of surplus electricity which could replace conventional power.

If the production of first and second generation bioethanol is a priority, these processes should be realized self-sufficiently since the fuelling with external fossil energy leads to fewer advantages regarding fossil energy and greenhouse gas savings.

4.2 Influences of the single production steps

In most diagrams of the Results chapter several production steps have been included. In order to show the influence of the different production steps on the overall outcome, one detailed diagram is exemplified for the “Standard” scenario (Fig. 4-3). The qualitative results can be applied to all other scenarios, accordingly. Since in this case greenhouse gas and energy balances run parallel, only the greenhouse gas balance is shown.

On the right hand side (“Expenditures”), nitrogen fertilizer, diesel fuel for tractor and field emissions of N_2O due to nitrogen fertilizer application have the biggest influence. Though each of these factors is relatively small, the influence of biomass cultivation as a whole is significant.

On the “Credit” side, the credit for conventional power substitution through bioelectricity generated from surplus bagasse is the most important.

On the other hand, expenditures for the transport of biomass and ethanol and for the use of auxiliary material for the ethanol conversion process such as enzymes and different chemicals have only a minor impact on the results.

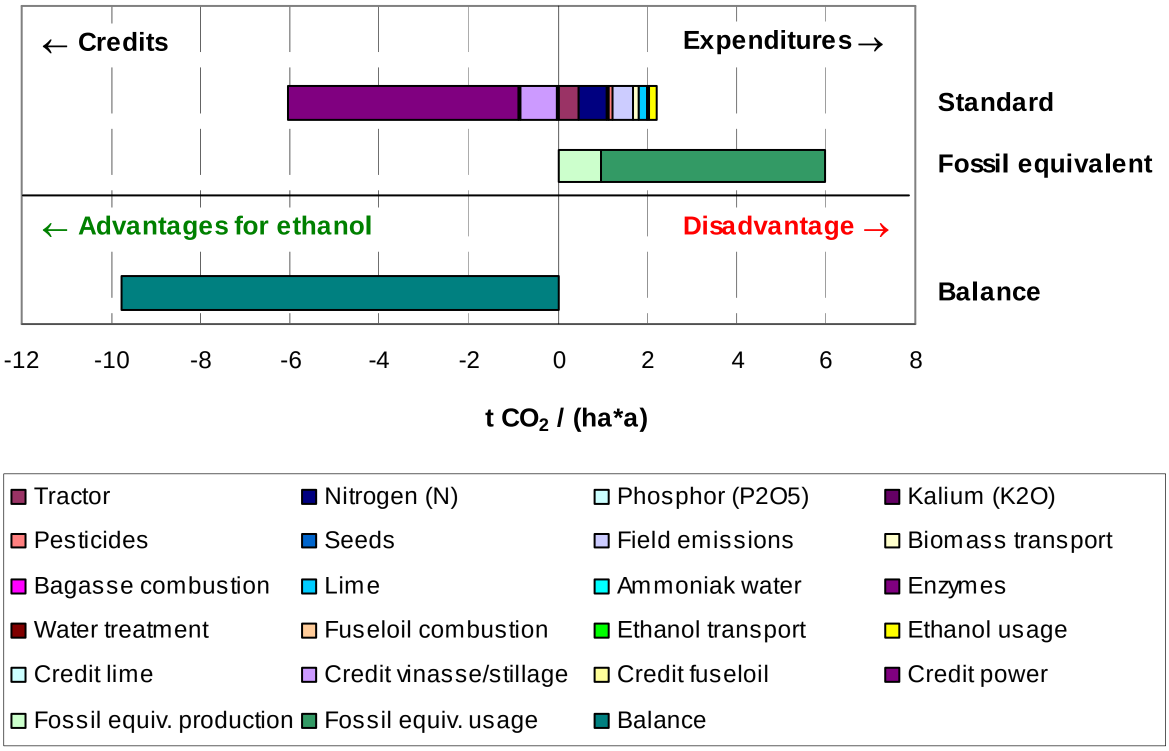

Fig. 4-3 Detailed **greenhouse gas** balance for the “Standard” scenario

Although highest benefits can be derived from an increased ethanol or bioelectricity output, there are some possibilities to influence the overall outcome of the greenhouse gas balance by changing the cultivation system. For example, the switch to a no-tillage production system will not show significant impact on the greenhouse gas balance based on a reduction of fuel input, whereas organic farming could show an advantageous impact regarding greenhouse gas savings from fertilizers and should be further investigated.

4.3 Sensitivity analyses for the different scenarios

Several parameters influence the life cycle of Sweet Sorghum first and second generation bioethanol. In this section, different sensitivity analyses are presented in order to quantify the influence of specific production steps and to help interpret their meaning for the environmental effects of the production and use of Sweet Sorghum.

In many cases, results for greenhouse gas emissions and energy depletion follow similar patterns. In these cases, either only the greenhouse gas balances like in Fig. 4-4 or only the energy balances are shown.

4.3.1 Different biomass and sugar yields

As described in chapter 3.2, different yield scenarios are studied: “Low”, “Medium” and “High”. Furthermore, different juice and therefore sugar yields have been considered: “Low” and “High”.

Fig. 4-4 shows the resulting greenhouse gas balances for the different yield scenarios. In the upper part, different biomass yield scenarios with a constant sugar yield are displayed, in the lower part, for the “Medium” yield scenario two different sugar yields are compared. The fossil equivalent bars are disaggregated by fossil equivalents substituting ethanol produced from the grains and ethanol produced from the sugar. Since greenhouse gas balance and energy balance behave the same, only the results for the greenhouse gas balance are presented.

Results

- Both, the increase of biomass yields and the increase of sugar yields lead to higher savings in greenhouse gases per hectare of cultivated area.
- If biomass yields are increased to high yields, about 13 t of additional greenhouse gases can be saved compared to low yields. Higher total yields lead to an increase of all three relevant crop components: grains, sugar and bagasse. Thus, both the ethanol production (blue bars) and the surplus bioelectricity production (dark violet bar) are increased and in total add to an increase of greenhouse gas savings.
- In contrast, the potential of saving greenhouse gases through better juice extraction methods and / or higher juice or sugar contents are marginal. If sugar extraction is doubled, there is almost no change in the greenhouse gas balance. Higher sugar yields lead to an increased process energy consumption requiring more bagasse. Since the bagasse yield stays the same, there is less surplus bagasse and thus less surplus electricity to be taken as a credit (dark violet bar). Thus, the increased ethanol yield is partly outweighed by a decreased surplus electricity production.
- **Sub-item** – high input versus low input farming: usually, high yielding systems require higher input of fertilizer leading to higher expenditures. However, these higher inputs are far outweighed by higher credits for ethanol due to higher yields.

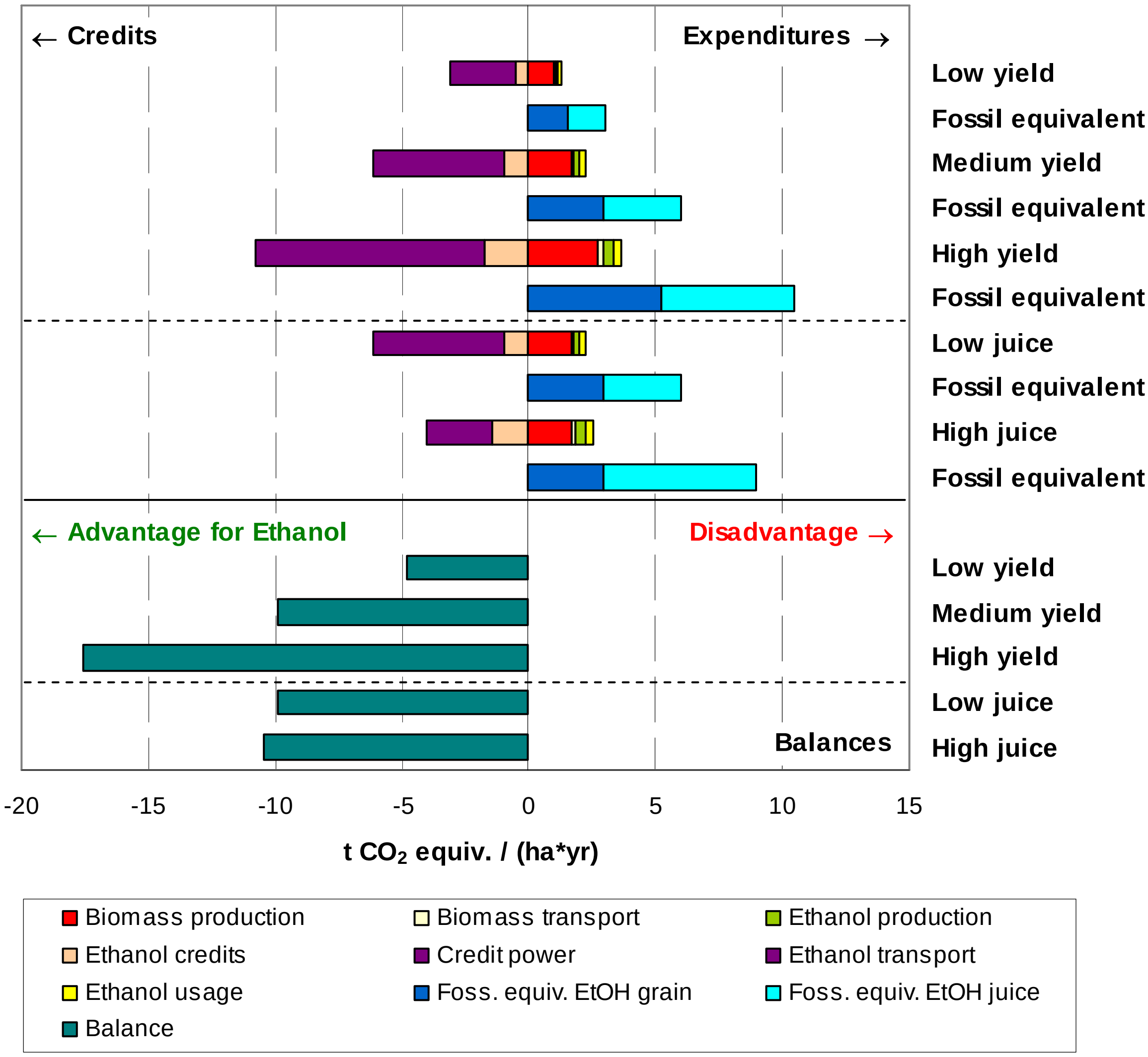

Fig. 4-4 **Greenhouse gas** balances for Sweet Sorghum ethanol from the "Standard" production scenario under consideration of three different biomass yields ("High", "Medium" and "Low") and two different sugar yields ("Low" and "High")

Reading the diagram (Example: 3rd bar in the balances section), Fig. 4-4:

Fuelling average passenger cars with Sweet Sorghum first generation bioethanol from the "Standard" high yield production scenario instead of with conventional fuel saves yearly and per hectare almost 18 t of greenhouse gases (CO_2 equivalents).

Conclusions

Yields of biomass show a significant influence on the results of the greenhouse gas balances. Higher biomass yields per hectare due to optimized crop varieties and cultivation methods lead to higher savings of greenhouse gases.

Higher juice and sugar yields show the tendency of improving the greenhouse gas balances. Nevertheless, the influence is only of minor importance compared to the influence of total yield increases.

Both, higher total and higher sugar yields have by far more impact on the balances than changes in the amount of fertilizer. Therefore, from a climate protection point of view, efforts should be put on optimized crop varieties and cultivation methods aiming at higher total yields. Higher sugar yields due to better varieties or improved technologies rank second. The results also offer a chance for small-scale producers who do not have access to optimized conversion technologies for high juice extractions.

4.3.2 Yield and land cover changes

As indicated in chapter 3.2, the carbon stock of the land used for Sweet Sorghum cultivation may change. Depending on the areas chosen as production area, the carbon stock can increase, decrease or stay the same. The so-called land cover change can significantly influence the outcome of the greenhouse gas balance.

Fig. 4-6 exemplifies the impact of the land cover changes examined in this study on greenhouse gas emissions. In order to show differences between greenhouse gas and energy balances, the impact on fossil energy savings is also presented in Fig. 4-5. As described in chapter 3.2, yields and carbon stocks are connected and different carbon stock changes are possible under different yields. The figure therefore is disaggregated into three different yield levels: “Low”, “Medium” and “High”.

Results:

- The choice of a specific area for the cultivation of Sweet Sorghum has a strong influence on the carbon balance of the soil, i.e. on the greenhouse gas balance of Sweet Sorghum ethanol. The higher the carbon stock of the natural vegetation, the higher are the carbon losses (grey bar) and therefore the lower are the greenhouse gas savings. However, despite land cover changes, the greenhouse gas balance always stays advantageous since the expenditures due to carbon losses are overcompensated by the ethanol production and credits for the use of by-products.
- On the contrary, carbon stock changes do not show impacts regarding fossil energy saving since the different production processes stay the same and therefore require the same input of primary energy.
- Higher yields usually mean better soil and climatic conditions and often are connected with dense natural vegetation and thus high carbon stocks. For example, in the “High yield” scenario, no carbon gains are assumed but high carbon losses. Therefore, the higher the yields, the higher are the risks for carbon losses. On the other hand, better production conditions can lead to higher carbon gains if for example Sweet Sorghum is cultivated on fertile, but abandoned soil. However, in the case of higher yields, carbon losses are overcompensated by higher ethanol and by-product yields resulting in increased greenhouse gas savings compared to lower yields.

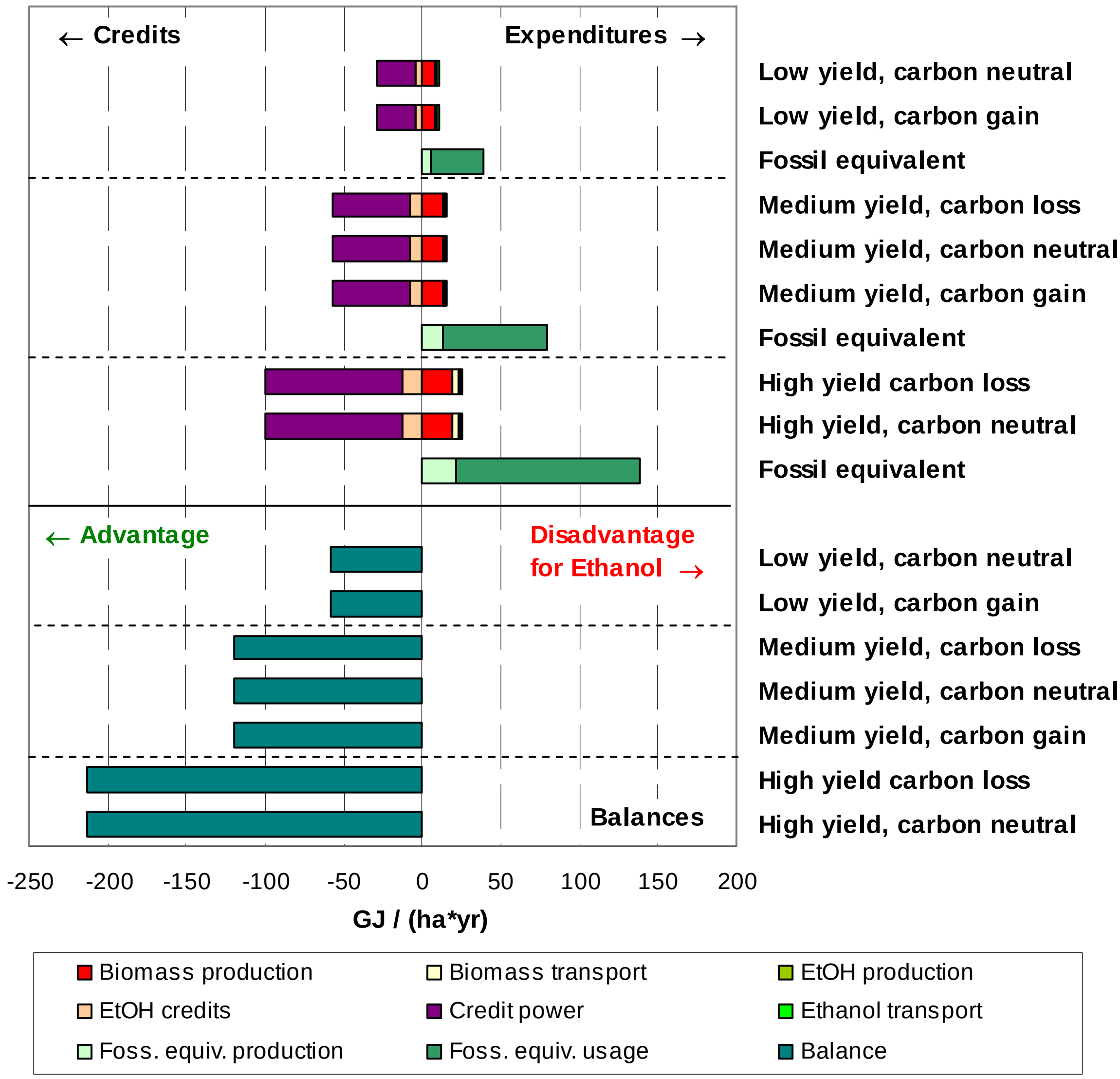

Fig. 4-5 Detailed **fossil energy** balances for Sweet Sorghum ethanol from the "Standard" production scenario under consideration of three different yields ("Low", "Medium" and "High") and three different carbon stock changes ("Carbon loss", "Carbon neutral" and "Carbon increase")

Reading the diagram (Example: 4th bar in the balances section), Fig. 4-5:

Replacing conventional fuel as a passenger car fuel by Sweet Sorghum first generation bioethanol from the "Standard" production scenario can lead to yearly savings of about 120 GJ of fossil energy per hectare of cultivated area when there is no carbon stock change and when a medium yield is assumed.

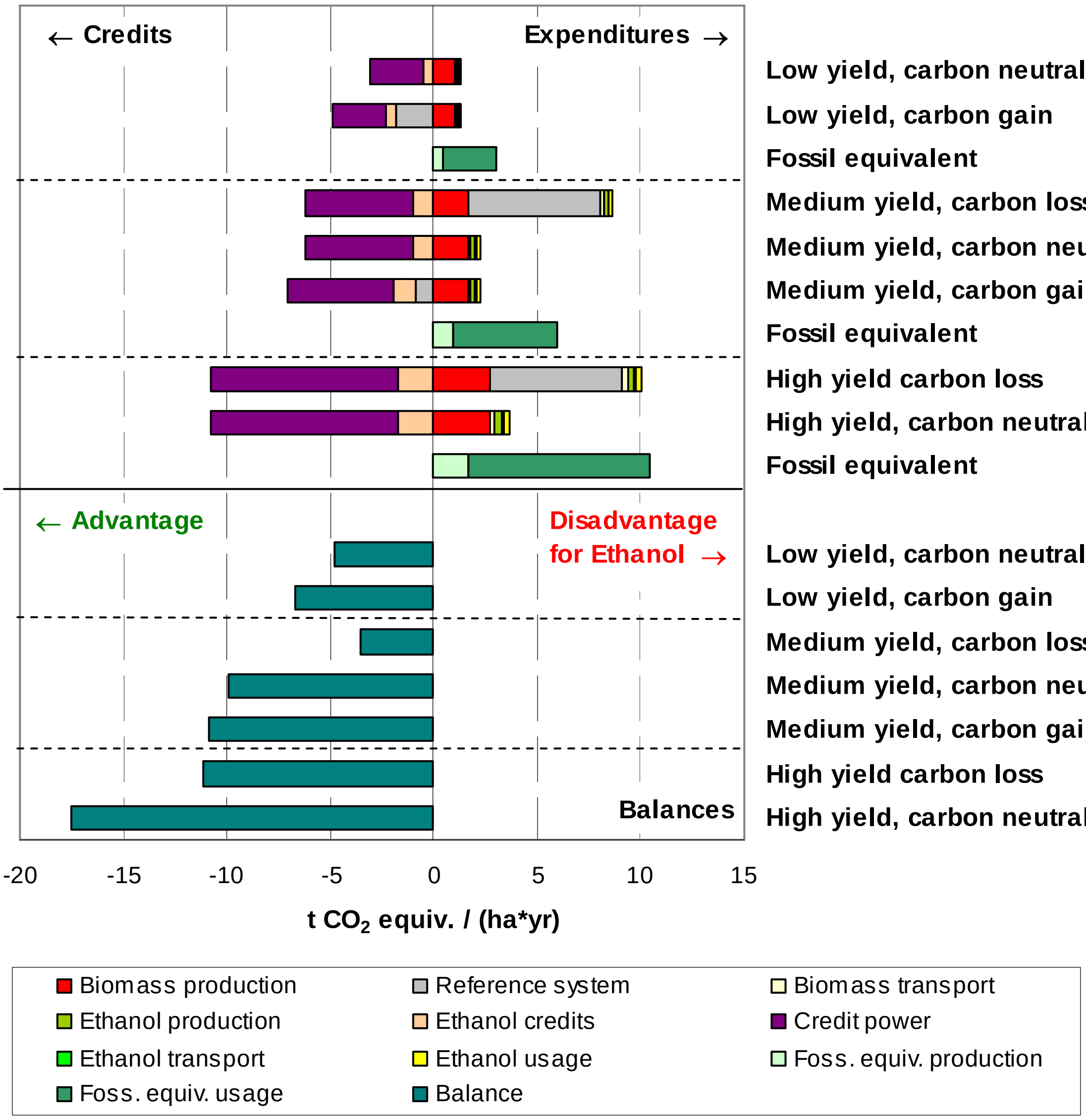

Fig. 4-6 Detailed **greenhouse gas** balances for Sweet Sorghum from the "Standard" production scenario under consideration of three different yields ("Low", "Medium" and "High") and three different carbon stock changes ("Carbon loss", "Carbon neutral" and "Carbon increase")

Conclusions

When land cover changes are involved, the quantitative outcome of the greenhouse gas balances depends largely on the carbon stocks of the above- and below-ground biomass as well as the carbon inventory in the soil. The establishment of new Sweet Sorghum cultivation areas influences the carbon inventory of the area under cultivation. Any accumulative or depleting change has an immediate and clear impact on the greenhouse gas balance; generally, this impact is the more disadvantageous the lower the yields of Sweet Sorghum are and the denser the natural vegetation is.

Therefore, when a piece of land is developed for Sweet Sorghum cultivation, a reduction of the carbon inventory of this area must be prevented. Further enormous potential for saving greenhouse gases are offered if Sweet Sorghum is cultivated on carbon poor (e.g. degraded) soils. Investigations on these possibilities should be strongly encouraged.

4.3.3 DDGS instead of stillage as by-product

In the production of ethanol from Sweet Sorghum grains, stillage is produced as a by-product. As described in chapter 3.2, it can either be concentrated and used directly as feed or it can be dried, pelletized and used as DDGS. Both stillage and DDGS as by-products have been compared in two different conversion systems: in a self-sufficient system which is fuelled by bagasse (“Standard” scenario) and in a system which is fuelled by coal as external energy carrier (scenario 5). The qualitative results apply also for all other scenarios. Fig. 4-7 summarizes the results. Since in this case greenhouse gas and energy balances behave the same, only the energy balance is shown.

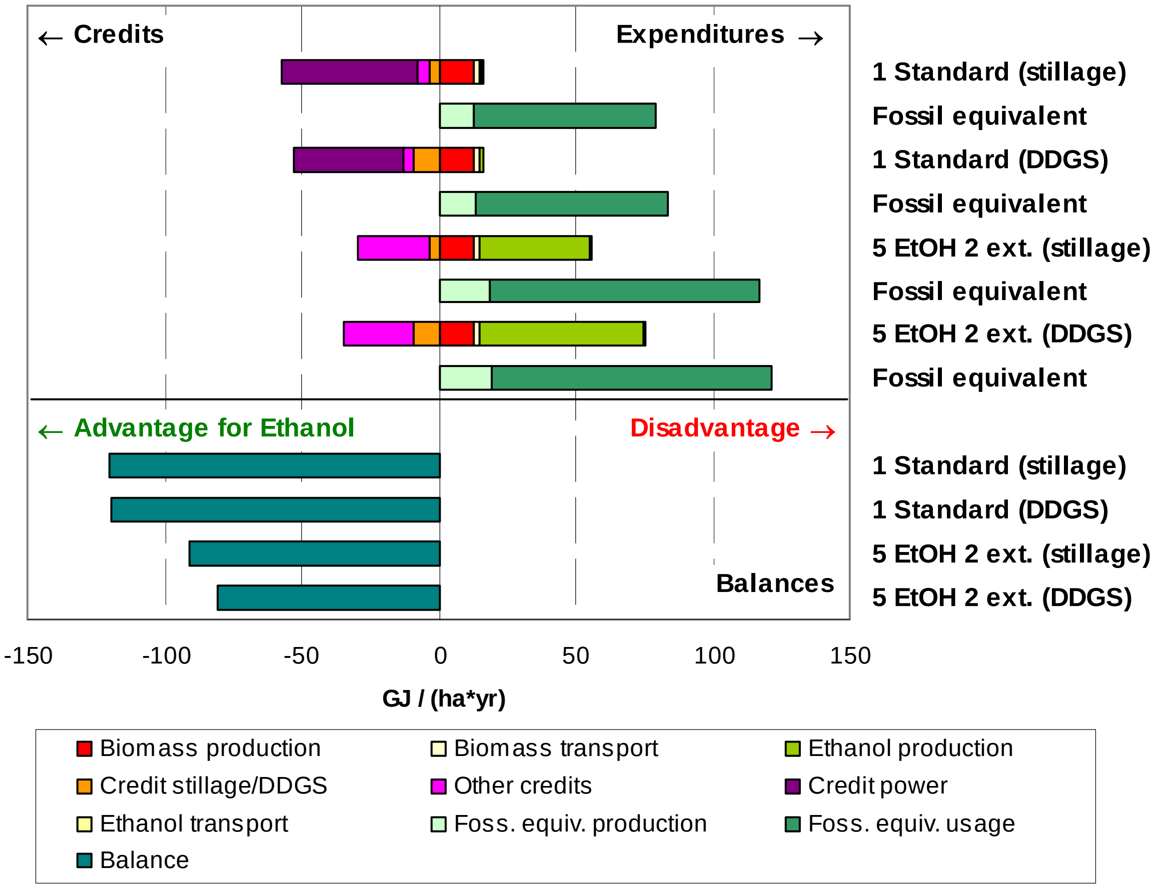

Fig. 4-7 Detailed **fossil energy** balances for the “Standard” scenario (scenario 1) and the “EtOH 2 extended” scenario (scenario 5) under consideration of two uses of the by-product of grain ethanol: direct use as stillage or conversion to DDGS

Reading the diagram (Example: 2nd bar in the balances section), Fig. 4-7:
If conventional liquid fuel is substituted by Sweet Sorghum first generation bioethanol produced in the “Standard” process, 120 GJ of fossil energy per hectare of cultivated area can be saved yearly if the stillage is processed to Dried Distillers Grains with Solubles (DDGS).

Results

- In both scenarios (1: “Standard” and 5: ”EtOH 2 extended”) the production of DDGS shows fewer advantages with regard to saving fossil energy due to the higher energy input for drying and pelletizing. This development is stronger where external fossil energy carriers are used to fuel the conversion process as is the case in the “EtOH 2 extended” scenario.
- In the “Standard” scenario the higher input of bagasse for the provision of process energy leads to less surplus electricity and thus to a reduced credit (dark violet bar). However, the reduced electricity credit is almost totally compensated by an increased credit for DDGS (orange bar). Both factors lead to almost no difference in the balances.
- When external fossil energy is used to generate process energy (scenario 5), higher expenditures occur on the right side (light green bar). Also credits for DDGS are higher than for stillage. However, they cannot compensate the increased energy expenditures leading in total to a more disadvantageous balance when DDGS is produced. If stillage is used as end-product, about 12 percent more greenhouse gases can be saved.
- In this case it can be observed that from a resource depletion point of view, there are only small differences between stillage and DDGS production. In most life cycle assessments on bioethanol the production of stillage is more advantageous than DDGS production due to an increased use of energy for the DDGS production. Under certain framework conditions and depending on future system designs, however, the balances can be equal as it is the case here. Therefore, from a current point of view and with the existing data base it is not possible to draw a final conclusion on whether stillage or DDGS should be produced.

Conclusions

Vinasse can be processed into Dried Distillers Grains with Solubles (DDGS) associated with a reduced production of surplus electricity from bagasse or higher expenditures for external fossil energy carriers. From a current non-specific point of view as in this study, stillage and DDGS do not differ much as concerns energy depletion. Product choice could be based on other environmental parameters or social and / or economic factors. Stillage cannot be stored nor transported over long distances. Thus, it is best to be used in a local market or in a joint cattle farm whereas DDGS could serve as a cash product even on the world market. However, data on this conversion process are very uncertain and more detailed research is needed to come to a clear final conclusion.

4.3.4 Use of leaves as fertilizer or feed

In chapter 3.2, different use options for Sweet Sorghum leaves have been described. In the main scenarios they are left on the field as fertilizer by default. However, their use as feed is also common practice. In the following, the outcomes regarding greenhouse gases are presented for both options. Since in every scenario leaves are used as fertilizer, for all scenarios quantitatively the same results can be expected. Fig. 4-8 compares the two variants.

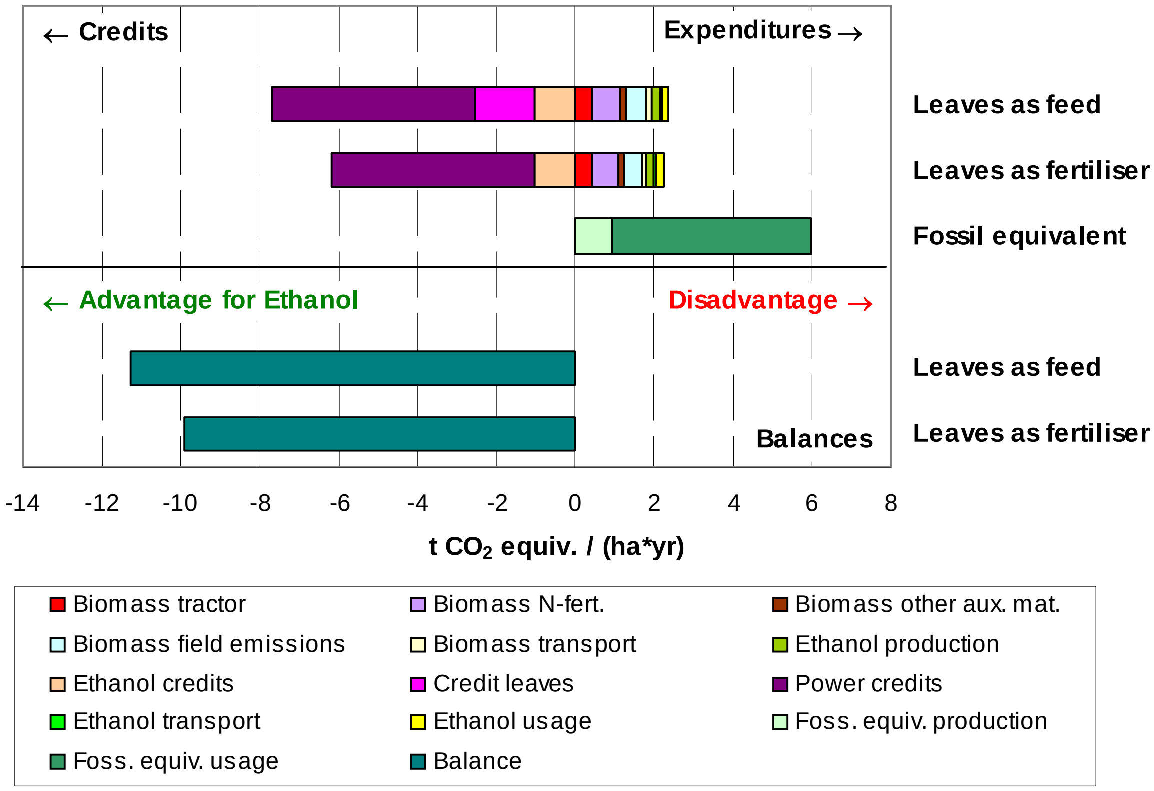

Fig. 4-8 Detailed **greenhouse gas** balances for the “Standard” scenario under consideration of two use options for leaves: as fertilizer or as feed

Reading the diagram (Example: 1st bar in the balances section), Fig. 4-8:

Compared to conventional liquid fuel, the utilization of Sweet Sorghum first generation bioethanol saves about 11 t greenhouse gases (CO_2 equivalents) yearly per hectare of cultivated area if the leaves are used as feed.

Results

- If leaves are used as feed instead of leaving them on the field as fertilizer about 17 percent more greenhouse gases can be saved.
- If leaves are used as feed, higher expenditures for mineral fertilizer (violet bar) and field emissions (light blue bar) due to an increased need for mineral fertilizing occur. However, these expenditures are overcompensated by credits for wheat which is substituted by the leaves. In total, this results in higher greenhouse gas savings if compared to the use of leaves as fertilizer.

Conclusions

If leaves are used as feed instead of being left on the field as fertilizer, the greenhouse gas balance can be improved significantly. Therefore, from a climate protection point of view, the leaves should be used as feed instead of being left on the field as fertilizer. However, in addition to the influence on the greenhouse gas emissions, also other aspects have to be taken into consideration such as the influence on the soil organic matter in the case that the leaves are removed from the fields. This aspect is dealt with qualitatively in chapter 4.4.

4.3.5 Variation of substituted conventional energy carriers

As described in chapter 3.2, in case surplus electricity is generated, which substitutes conventional electricity, the choice of substituted energy carrier can influence the results of energy and greenhouse gas balances. Fig. 4-9 and Fig. 4-10 illustrate the effect on energy and greenhouse gas balances if coal and natural gas are substituted.

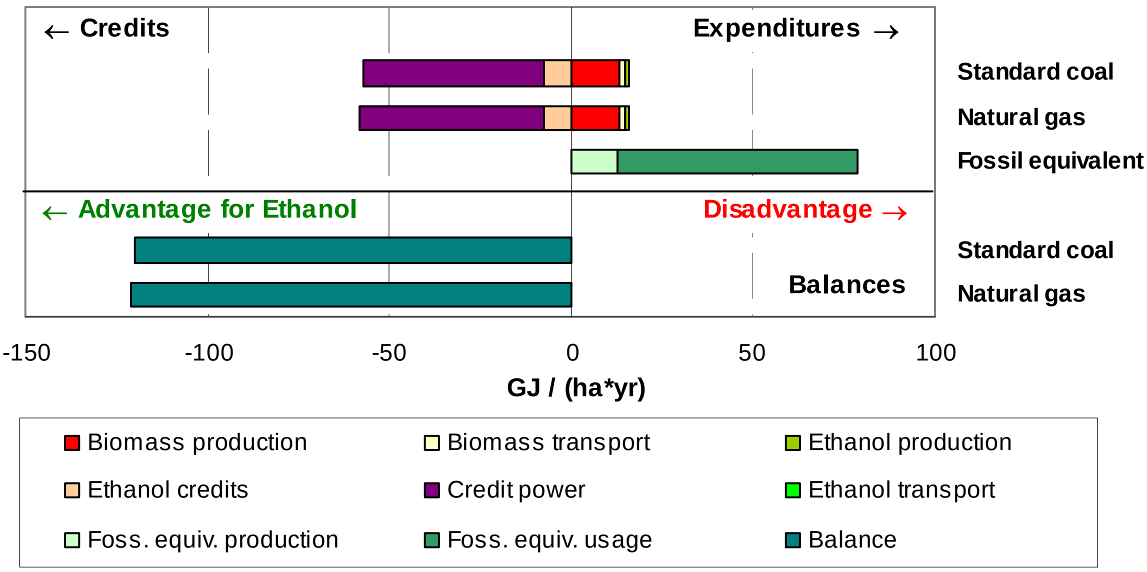

Fig. 4-9 **Fossil energy** savings for different substituted fossil energy carriers in the “Standard” scenario

Reading the diagram (Example: balances section), Fig. 4-9:

Substituting conventional liquid fuel with Sweet Sorghum ethanol from the “Standard” production scenario can lead to yearly savings of about 120 GJ of fossil energy per hectare of cultivated area when electricity produced with either coal or natural gas is substituted with the surplus bioelectricity.

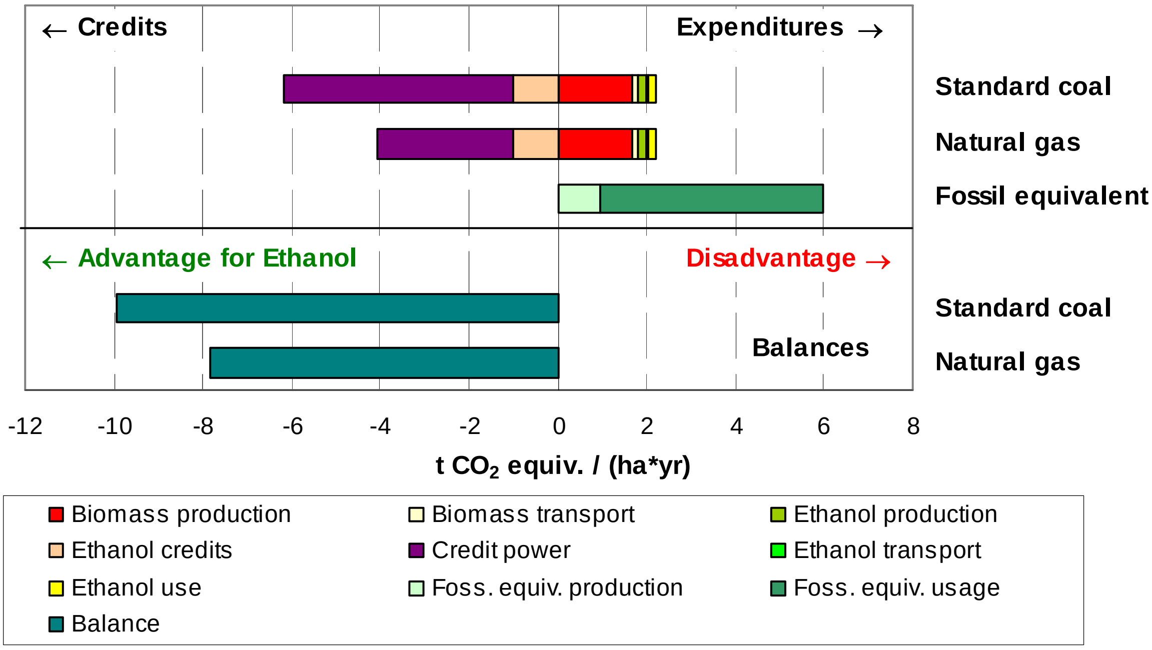

Fig. 4-10 **Greenhouse gas** savings for different substituted fossil energy carriers in the "Standard" scenario

Results

- The balances of greenhouse gas savings and energy depletion do not run parallel. There is basically no difference regarding fossil energy savings whereas the difference regarding greenhouse gas savings is clearly in favour of coal substitution. The reason is that in the production with coal and natural gas about the same amount of primary energy is used and that the efficiencies of power production for both coal and natural gas are similar. This results in similar balances regarding fossil energy depletion. On the contrary, in the combustion for power production coal substitution shows significantly higher amounts of greenhouse gases emitted per GJ power produced.
- Substituting power produced from hard coal by Sweet Sorghum bioelectricity clearly leads to more advantages regarding the greenhouse gas savings than replacing power from natural gas. In such a case about 27 percent of additional greenhouse gases can be saved per hectare of cultivated area.

Conclusions

When bagasse is used as an energy carrier for bioelectricity generation, the amount of saved greenhouse gas emissions depends on the energy carrier that was used to produce the replaced electricity. The more fossil carbon emitted during the combustion of the fossil energy carrier can be saved, the more advantageous is the outcome of the greenhouse gas balance. This means that wherever it is possible to replace coal as a fossil energy carrier, more advantageous greenhouse gas balances are obtained.

4.3.6 Variation of external fossil energy carrier

As described in chapter 3.2, the simultaneous production of both first and second generation bioethanol (“EtOH 2 Maximum” scenario) can be fuelled with external energy (coal or natural gas) instead of being realized with process energy derived from the bagasse.

The comparison of both coal and natural gas energy carriers as for their effect on either energy or greenhouse gas balances are shown in Fig. 4-11 and Fig. 4-12, respectively.

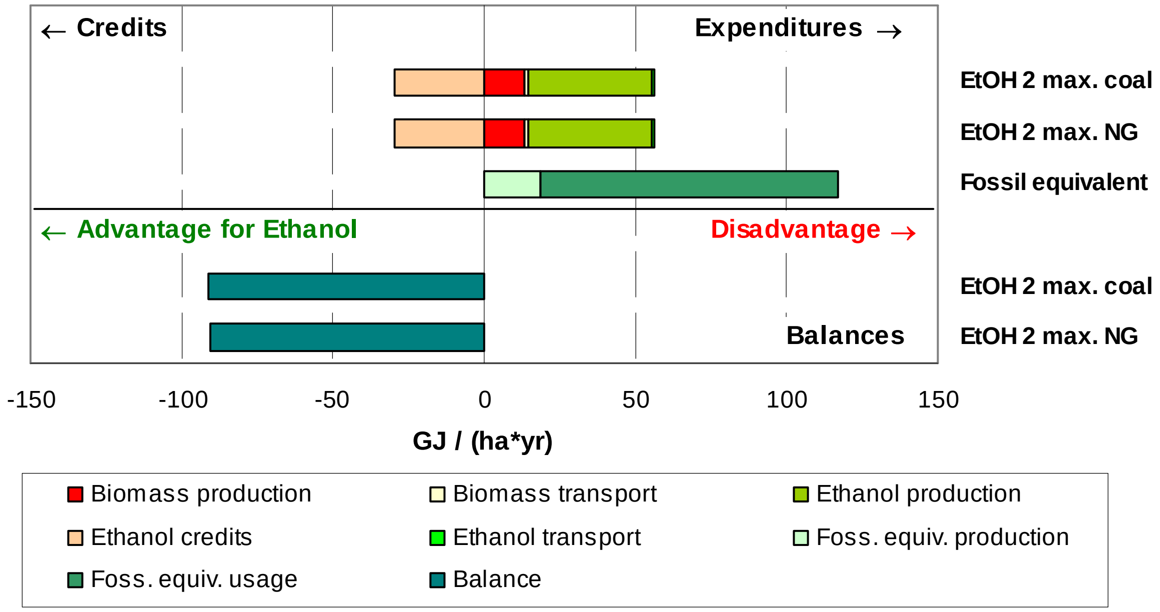

Fig. 4-11 **Fossil energy** savings for different external fossil energy carriers in the case of a maximized second generation ethanol production from bagasse

Reading the diagram (Example: balances section), Fig. 4-11:

Substituting conventional liquid fuel with Sweet Sorghum ethanol from the “EtOH 2 Maximum” production scenario can lead to yearly savings of about 90 GJ of fossil energy per hectare of cultivated area when coal or natural gas are used as external energy carriers for the conversion process.

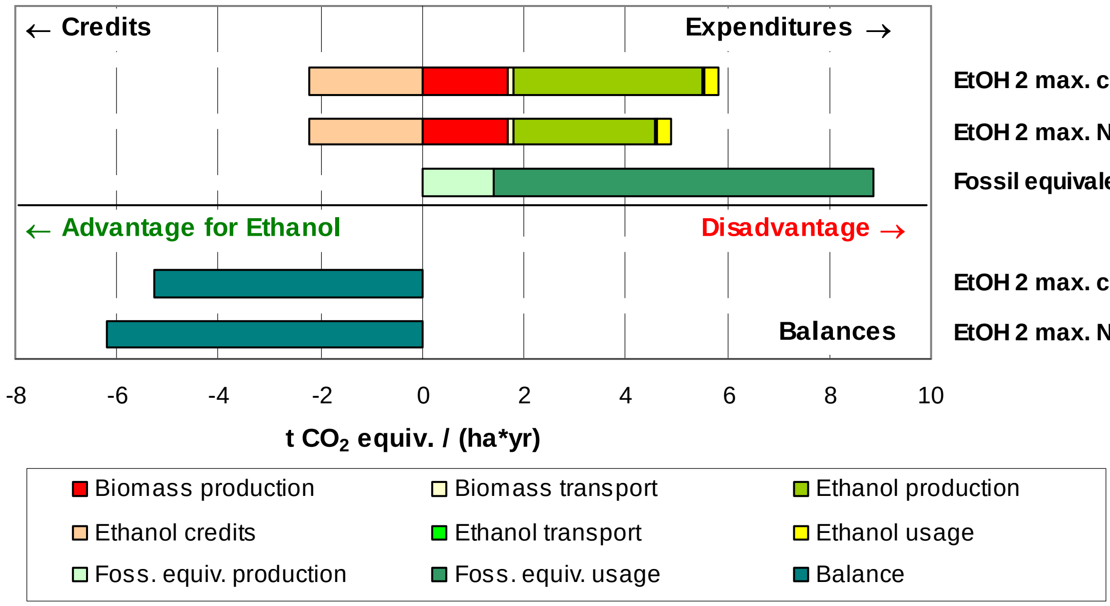

Fig. 4-12 **Greenhouse gas** savings for different external fossil energy carriers in the case of a maximized second generation ethanol production from bagasse ("EtOH 2 maximum")

Results

- The balances of greenhouse gas savings and energy depletion do not run parallel. There is only a minor difference in the energy depletion whereas greenhouse gases clearly differ. Using coal and natural gas as energy carrier for the conversion process about the same amount of primary energy is used and the efficiencies during the conversion process for both energy carriers are similar. This results in similar balances regarding energy depletion. However, during the combustion for power production both energy carriers show significant differences regarding the amount of greenhouse gases emitted per GJ power produced.
- The choice of the external energy carrier in the case of a maximized production of second generation bioethanol from bagasse has a significant influence on the outcome of the greenhouse gas balance. Since the combustion of natural gas causes less emissions, expenditures for ethanol production (light green bar) are much smaller than if coal was used.
- In total, the use of natural gas instead of coal leads to a more advantageous greenhouse gas balance. With natural gas, about 18 percent of additional greenhouse gases can be saved per hectare of cultivated area compared to the use of coal.

Conclusions

If the production of both first and second generation ethanol is fuelled by external fossil energy instead of being realized self-sufficiently, the choice of the external fossil energy carrier shows a significant influence on the outcome of the greenhouse gas balance. Regarding fossil energy savings, however, no difference between coal and natural gas as process energy carriers can be noted. Therefore, a main aim should always be to use an energy carrier which accounts for lower emissions of greenhouse gases such as natural gas – or, better still, renewable energies.

4.3.7 Mechanical versus manual harvest

The harvest of Sweet Sorghum can either be realized mechanically with harvesting machines or manually (see chapter 3.2.1). Fig. 4-13 shows the influence of the choice of the harvesting method on the outcome of the greenhouse gas balance for the “Standard” scenario. Since harvesting methods are the same in all scenarios, quantitative results of this analysis hold true for also all other scenarios. Since greenhouse gas and energy balances run parallel, only results regarding greenhouse gases are shown.

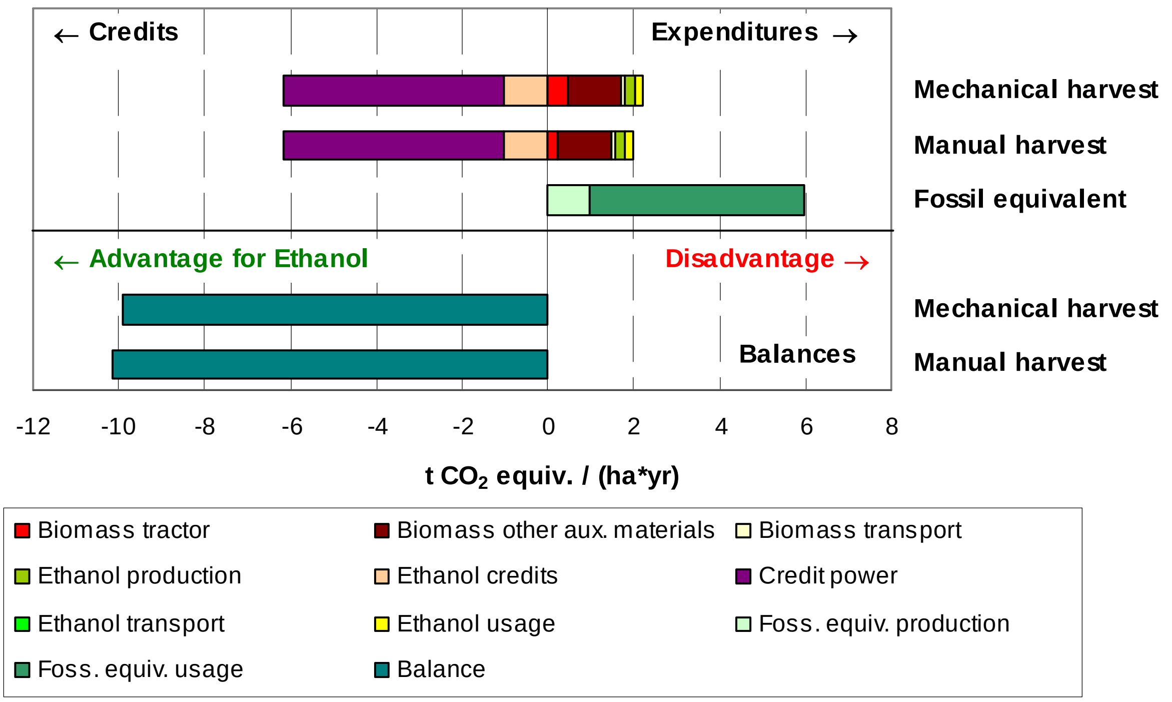

Fig. 4-13 **Greenhouse gas** balances of the “Standard” scenario under consideration of two different harvesting methods: mechanical and manual

Reading the diagram (Example: 1st bar in the balances section), Fig. 4-13:

Compared to conventional liquid fuel, the utilization of Sweet Sorghum first generation ethanol saves almost 10 t of greenhouse gases (CO_2 equivalents) per hectare of cultivated area if the crop is harvested mechanically.

Results

- The manual harvest of Sweet Sorghum shows a slight advantage over a mechanical harvest regarding the saving of greenhouse gases.
- This difference, however, is only of minor importance. Only 2 percent more greenhouse gases can be saved if Sweet Sorghum is harvested manually instead of mechanically. Although by harvesting manually, the emissions caused by the diesel fuel are halved (see red bar), the total savings are small since tractor emissions represent a relatively small percentage of total emissions from the whole lifecycle.

Conclusions

The choice of harvesting methods, i.e. mechanical or manual harvesting, only has a very minor influence on the outcome of the greenhouse gas balances. Therefore, from a climate protection point of view, there would be no difference between small-scale production of Sweet Sorghum and large scale production as far as the degree of mechanized harvesting is concerned. The decision on the harvesting methods can be primarily based on other environmental parameters and social or economic factors.

4.3.8 Credit versus allocation method

As described in chapter 3.2, there are different methodological approaches to deal with products and by-products being generated along the full life cycle. The influence of the credit and allocation method on the outcome of the greenhouse gas balances of the “Standard” scenario are exemplified in Fig. 4-14.

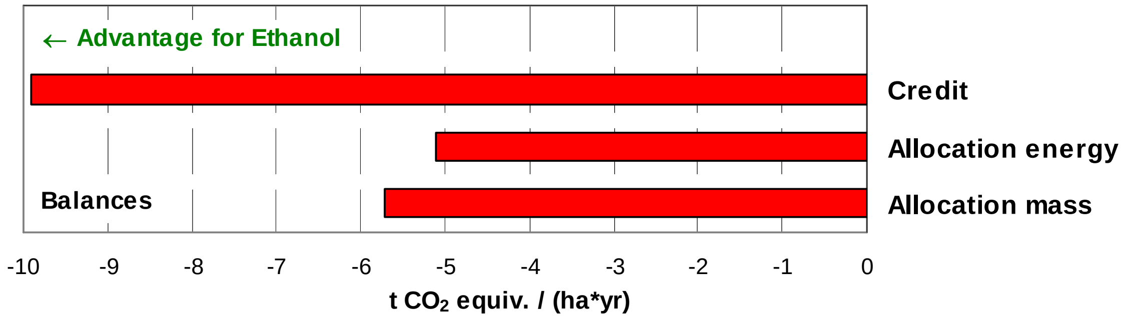

Fig. 4-14 Results of the greenhouse gas balances using either the credit or allocation method for considering the by-products of the “Standard” Sweet Sorghum production and use scenario

Reading the diagram (Example: 2nd bar), Fig. 4-14:

The application of the allocation method results in savings of about 5 t of CO_2 equivalents per hectare if conventional liquid fuel is substituted by Sweet Sorghum first generation ethanol (“Allocation energy”).

Results

- The methodology used for dealing with the by-products has a significant influence on the outcome of the greenhouse gas balance. In this case, the allocation method leads to far less advantageous results than the credit method. The allocation method only indicates savings of about 5 t CO_2 equivalents whereas the credit method indicates a saving of approximately 10 t CO_2 equivalents. This is due to the fact that the credits gained for the by-products lead to higher savings of greenhouse gases than allocating part of the greenhouse gases to these very by-products.
- Also within the allocation method, different results are obtained – depending on the reference. In this case, the use of product masses as reference leads to better results than using their energy contents. High amounts (by weight) of bagasse and other by-products are produced so that only a small share of emissions is allocated to ethanol. In contrast, if allocation is based on energy contents, a higher share of emissions is allocated to ethanol due to its higher heating value compared to all other by-products.

Conclusions

Different methodological approaches to calculate the energy and greenhouse gas balances such as the credit or the allocation method can lead to significantly different results when applied to the Sweet Sorghum production and use scenarios under investigation. Generally, existing life cycle assessments on bioenergy should be compared with great caution. Due to different system boundaries and methodologies, a comparison is usually not possible.

If future assessments are to be compared, it is absolutely necessary to harmonize and standardize the respective methodologies and system boundaries and to identify them in detail with each analysis. Such a standardization and harmonization has been strived to be achieved in various frameworks such as in the international life cycle standards (ISO 14040&14044; ISO 2006), the BIAS framework (BIAS 2008) or within the Global Bioenergy Partnership (GBEP 2009).

4.4 Additional environmental impacts

Besides the greenhouse gas emissions and depletion of non-renewable resources, a wide range of additional environmental impacts from Sweet Sorghum cultivation and use have been assessed. Most impacts can be divided into having benefits for the environment or being associated with negative risks.

Tab. 4-1 gives a summary of all environmental impacts considered in this chapter. The effects of the single impact categories are discussed in detail.

Acidification

If compared to the complete production and utilization chain of fossil fuel, the production and use of bioethanol from Sweet Sorghum shows disadvantages regarding acidification of ecosystems as a result of acid rain/fall out. This is the case with many biofuels produced from energy crops (see CALZONI *et al.* 2000). Major contributors are sulphur dioxide (SO_2) and nitrogen oxides (NO_x). Both substances emanate from the combustion of fossil energy carriers for the production of process energy used in the conversion process. Fossil energy carriers differ in their emission rates. Thus, with the choice of a low emission energy carrier such as natural gas or renewable energies these emissions can be reduced. A second source is the use of bioethanol in cars where considerable emissions of nitrogen oxides (NO_x) occur.

Eutrophication

As is the case with many biofuels (CALZONI *et al*. 2000), the production and use of Sweet Sorghum bioethanol also results in higher eutrophication impact than using equivalent amounts of fossil fuels. In this study, only eutrophication caused by nutrient input from the air is considered. Impacts on above and below ground water bodies are dealt with further below. Emission of nitrogen oxides (NO_x) and ammonia (NH_3) are the main contributors. As mentioned above, nitrogen oxides are emitted during the conversion process and during the use of ethanol in cars. Ammonia emissions are due to the use of mineral nitrogen fertilizer in the production of Sweet Sorghum. Main emissions occur after the application of the fertilizer since part of the nitrogen is emitted into the air in form of ammonia.

Compared to other biofuel crops, however, the emissions occurring during the cultivation of Sweet Sorghum can be reduced since it can be produced under low input conditions for example in small-scale farming systems. Emissions and thus the contribution to eutrophication increase with the intensification of Sweet Sorghum production since high yielding intensive production systems require high inputs of fertilizers.

Ozone Depletion

Compared to fossil fuels, the production and use of Sweet Sorghum bioethanol shows disadvantages regarding ozone depletion. This is also a common fact with biofuels (CALZONI *et al.* 2000). Ozone depletion is mainly caused by nitrogen oxides (NO_x) which are emitted during the conversion process and during the use of bioethanol in cars. Emissions occurring during the conversion process are caused by the combustion of fossil energy carriers for the production of process energy. These emissions can be reduced by using low emission energy carries such as natural gas instead of coal or, better still, by using renewable energies.

Photo Smog

The production and use of Sweet Sorghum bioethanol also shows higher risk of photo smog creation when compared to conventional fuels. This pattern can be found with many biofuels (CALZONI *et al.* 2000). Photo smog describes the creation of photo-oxidants such as ozone in air layers at ground levels. The photo-oxidants occur from unsaturated carbon hydrates and nitrogen oxides. Both substances are emitted during the conversion process and the use of ethanol as fuel. As described in the previous paragraphs, emissions occurring during the conversion process can be reduced by using low emission energy carries.

Impact on ground and surface water

In good agricultural practices, fertilizer inputs always should be adapted to nutrient removal, thus serious leaching of nutrients into the ground water body is unlikely to occur. With Sweet Sorghum the risk of leaching can be further reduced since it can be grown with low rates of fertilizers without a significant reduction in biomass (FAIR 2000). An intensification of production, however, increases the risk of nutrient leaching since high yielding intensive production systems require high inputs of fertilizers. Further risks can occur for surface water through soil erosion. Sweet Sorghum shows a slightly higher risk of erosion especially during early development stages as seedlings develop only slowly and thus leave the soil uncovered. Integrating Sweet Sorghum production into no-till practices may further reduce that risk.

In many developing countries it is common to intercrop Sweet Sorghum with other crops such as pigeon peas or chickpeas. These crops are grown simultaneously with Sweet Sorghum on the same plot which further reduces the risk of nutrient leaching. Since intraspecific competition on nutrients and water is higher than interspecific competition, with intercropping resources are used more efficiently and there is less risk for excessive nitrogen which could leach. Furthermore, the short growth period of Sweet Sorghum allows for double cropping in which a second crop is planted after the first has been harvested. This decreases nutrient leaching through soil erosion since the crop cover period is prolonged compared to a single cropping system.

Beside nutrient leaching in ground and surface water there is a risk of pesticide contamination if they are applied improperly. Since in large-scale production systems increased pesticide use may be regarded necessary there is an increased risk of pesticides leaching into adjacent water systems. However, small-scale farmers are often less careful in their application and thus may carry a potentially larger risk. In both cases, double cropping and intercropping might reduce the risk since a carefully chosen increased agrobiodiversity requires fewer pesticides due to increasing the diversity or abundance of natural enemies. Pesticide-free, preventive cultivation practices such as those for good integrated pest management (IPM) and organic farming minimize environmental health risks of pesticides.

Soil erosion / soil compaction

Under certain circumstances, the production of Sweet Sorghum can increase soil erosion and soil compaction. Since it is an annual crop it requires frequent field work. In intensive, large scale production systems, this work is done with heavy machinery which contributes to soil compaction and thus soil erosion. Here, the introduction of no-till practice minimize the risk to some extents. In contrary, the cultivation of Sweet Sorghum in small-scale farming systems is done manually and thus bears little risks of soil erosion and compaction.

The short vegetation period of Sweet Sorghum (90-120 days, GNANSOUNOU *et al*. 2005) shows risks and opportunities. On the one hand, in tropical countries Sweet Sorghum can be harvested twice a year with only ratoons used (SCHAFFERT 2007); here, the need for field work is minimized. On the other hand, if crops other than Sweet Sorghum are cultivated, machinery use is doubled. Both variations, however, increase the period of soil coverage which reduces soil erosion compared to an uncovered soil.

Besides the use of machinery also the growth rate of seedlings is important. Sweet Sorghum seedlings only develop very slowly, thus the soil is covered rather late in the year which increases the risk of erosion in the first months of cultivation.

Water consumption

Due to the high efficiency of C4 photosynthesis, water use efficiency (WUE, i.e. the production of dry matter divided by water loss) of Sweet Sorghum is very high. Furthermore, Sweet Sorghum shows a higher drought resistance than maize or sugar cane (low evapotranspiration and the ability to stop transpiration if water is limited) and thus requires less water per unit ethanol produced (FAIR 2000). Compared to sugar cane, Sweet Sorghum uses only 1/3 of the amount of water (LI 2007). It can thus be cultivated in large areas under rainfed conditions. The low water use conserves both above and below ground water resources.

However, since sufficient water supply increases yields, large-scale high yielding production systems could use irrigation. In certain areas, also irrigation during the establishment period can be advantageous to yields. Since the use of irrigation water can have negative impacts on ground water resources, particularly if applied in arid areas or areas with severe water shortages, proper timing is important to reduce this impact.

Impact on soil organic matter

Sweet Sorghum is an annual crop of which every part (stem, grains and leaves) can be used. Therefore, large amounts of organic matter are removed from the field each year which decreases the soil organic matter and thus eventually soil fertility. In order to minimize this risk, leaves should be left on the field instead of being used as feed or for the generation of second generation bioethanol. This would also decrease the amount of mineral fertilizers necessary. In part, also intercropping and rotation of Sweet Sorghum with other crops can preserve the soil organic matter.

Agrobiodiversity

The cultivation of Sweet Sorghum can have several positive impacts on agrobiodiversity. The introduction of an additional crop as such increases diversity in existing agricultural systems, which contributes to the stability of these systems and to an increased income security especially for small-scale farmers. Its suitability for small-scale farming is likely to lead to a large number of locally selected varieties, contributing to the crop's diversity and richer genetic choices in the future

Due to the short growth period of Sweet Sorghum, double cropping systems can be established in which a second crop is planted after the first has been harvested. If chosen properly, this has positive impacts on agrobiodiversity by providing a habitat for a variety of insects and soil organisms that would not be present in a single crop environment. Agrobiodiversity can be further increased by intercropping where two or more crops are grown simultaneously on the same plot. Additionally, IPM, no-till and organic methods and generally the reduction of chemical inputs can be adopted to further increase agrobiodiversity. Its lesser input requirements and thus an easier integration into such low input production systems make it more suitable than other ethanol energy crops for farming practices that conserve natural and agrobiodiversity.

Summary

As regards non-greenhouse gas emissions and pollution, Sweet Sorghum has effects similar to other energy crops since these emissions largely depend on the actual agricultural practices. Regarding eutrophication, acidification, ozone depletion and photo smog, it adds more air pollutants than the fossil fuels it may replace. Due to its lower soil fertility tolerance, nitrogen related emissions may be more favourable than for other energy crops. For biodiversity impacts Sweet Sorghum may be a more favourable crop choice.

In Tab. 4-1, a summary of all additional environmental impacts related to the production and use of Sweet Sorghum is listed. The cultivation system has been divided into small and large scale production systems since the impacts can vary. Impacts occurring during conversion and use of bioethanol are the same in both systems. All impacts have been ranked into three categories: + positive; 0 no impact; – negative.

Impact parameter	**Sweet Sorghum production systems**	
	Large scale production	**Small-scale / low input production**
Acidification	–	–
Eutrophication	–	0 to –
Ozone depletion	–	–
Photo smog	–	–
Soil erosion / soil compaction	– / –	– / 0
Water consumption	+	+
Impact on ground and surface water	0 to –	0
Impact on soil organic matter	+ to –	+ to –
Agrobiodiversity	0 to +	0 to +
+ positive; 0 no impact; – negative		

Tab. 4-1 Additional environmental impacts of different Sweet Sorghum production systems

4.5 Comparison with other biofuel crops

In order to facilitate crop choices, Sweet Sorghum has been compared to soy bean, sugar cane, Jatropha, maize, wheat and cassava as alternative fuel crops regarding technical aspects. Besides environmental impacts these technical aspects are important factors when it comes to the creation of future energy development programmes or in the case of investment choices. However, the comparison of the crops does not give clear hints in favour or against certain crops but leads to mixed and differentiated results. Instead it facilitates choices, especially local choices, which in any case will have to be made based on the multitude and variety of local conditions. The main differences between the crops depend on the levels of knowledge and experience concerning production systems and technology used, climatic conditions, crop specific characteristics and others.

Tab. 4-2 shows a summary of the comparison of Sweet Sorghum with other fuel crops. The different technical aspects are described in detail in the following paragraphs.

Experiences in cropping method

Soy bean, sugar cane, maize and wheat are long-term established crops which have also been used for energy production for many years. Therefore, experiences exist for specific cropping methods under different climatic, soil and management conditions. Jatropha, on the contrary, is a relatively new energy crop where only very little cultivation and almost no breeding experiences exist. A little more is known about cassava and Sweet Sorghum. They have been cultivated for a long period of time in many countries, however there is still lack of systematic experience when it comes to optimized cropping methods in the use as energy crop. Among the needed experiences are optimum stand density, the application of fertilizer and pesticides or the timing of harvesting.

Breeding experiences

Similar to experiences with cultivation methods, there are many breeding experiences for large-scale soy bean, sugar cane, maize and wheat production. Different varieties are available and yields are quite stable. The same holds true for cassava which has been cultivated in many countries for many years as an export cash crops. For Jatropha, on the contrary, there are almost no breeding experiences, resulting in low and very unpredictable yields. Also for Sweet Sorghum, the potential of production improvements and yield stability through breeding efforts is still very high. Despite considerable breeding efforts e.g. in China, genetic variability is still significant. Further breeding efforts are necessary to develop new varieties which are suitable for biofuel and / or food production and meet different priorities such as adaptation to different climatic, soil and management conditions, rates of sugar or grain yields, starch and sugar contents or flexibility of planting dates.

Mechanization

With regard to mechanization, establishment, harvest and conversion technologies have to be dealt with separately. Sweet Sorghum, in contrast to sugar cane, Jatropha and cassava can be established from seeds which allows for an easy mechanization (LI 2007). The same holds true for soy bean, maize and wheat. Harvest technologies for soy bean, sugar cane, maize and wheat are already well established, which is a great advantage over Sweet Sorghum and Jatropha.

For the latter two, such technologies still have to be developed or optimized. While Jatropha still has to be harvested manually, there are already special harvesters available for Sweet Sorghum. However, they are not yet produced on a large scale and not yet affordable for smaller production units in developing countries. Although harvesters used for sugar cane could be used, they do not allow for a complete mechanization and usually lead to a decreased quality of the juice.

When it comes to conversion, technologies for soy bean, sugar cane, maize and wheat are well established. Jatropha oil and Sweet Sorghum juice and cassava show characteristics quite similar to soy bean, sugar cane or potatoes, and thus they can easily be converted with existing and well established technologies.

Potential for ethanol production

Similar to sugar cane, maize and wheat, Sweet Sorghum can be used for the production of first and second generation biofuel at the same time. This may be an advantage in the future when second generation biofuel will become cost effective. At the moment, however, only the production of first generation biofuel is well established and widely used. In contrast to this, cassava, Jatropha and soy bean can only be used for first generation biofuel production.

Competition between food and fuel use

The direct competition of the use of the crops for fuel or food varies between the crops. Jatropha can only be used for fuel and non-food products and thus there is no competition at all. Cassava, soy bean and sugar cane are either used for food or fuel and thus fuel use fully and directly competes for the use as food. Sweet Sorghum, maize and wheat, instead, can combine use for both food and fuel from the same harvest. Bioethanol and food production from maize and wheat, however, is only possible if second generation ethanol is produced from the non-food parts of the crops. In contrast, Sweet Sorghum can combine both food from the grains and first generation ethanol from the juice. Therefore, Sweet Sorghum is currently the only crop which can produce food and fuel at the same time by using currently available and economically feasible technologies.

Competition on land use with natural ecosystems

All assessed fuel crops compete with natural ecosystems through direct land use change for the establishment of new production areas. Often, the conversion of natural ecosystems is connected with biodiversity decrease and the loss of natural habitats. The dimension of this loss, however, depends on the vegetation zone where the crops are cultivated and the biodiversity that can be found there. It also depends on the degree to which it is possible to integrate the crops in existing agricultural systems by adapting rotation systems or by cultivating them on fallow land. However, similar possibilities may exist for the integration of other energy crops. The specific advantages of Sweet Sorghum still have to be proven.

The improvement of existing low input farming practices through ecological methods like organic agriculture can increase food production sufficiently while freeing land for energy production. In such systems Sweet Sorghum has an advantage due to its low input requirements and short cropping cycle.

Competition on land use for food production

The competition on land use for food production, apart from economic, policy and social pressures, usually depends on the soil quality. Soy bean, sugar cane, maize and wheat usually require good soil qualities and thus always will compete for land suitable for food production. In contrary, cassava, Jatropha and Sweet Sorghum also grow on marginal soils where the risk and severity of a conflict with food production is much less. However, since all crops show higher yields when cultivated on fertile soils, there is a high risk of competition for food production if cultivation shifts to high quality soils due to intensification. The use of less productive soils most likely will require some additional incentives.

Year round production

As is the case with cassava tubers and sugar cane juice, the juice of Sweet Sorghum cannot be stored for a long period of time without risking high sugar losses. The result is a very limited production window (harvest to conversion) within a year. This is a drawback compared to soy bean, Jatropha, maize and wheat. Their fruits can easily be stored and thus a year round ethanol production is possible. However, the use of the storable Sweet Sorghum grains allows also for extended ethanol production periods. Due to the short vegetation period, Sweet Sorghum can be double cropped with other ethanol fuel crops which could then provide the input for a year round ethanol production. Also a combination with sugar cane is possible, where Sweet Sorghum is grown on fallow land. Very careful planning and coordination is necessary to optimize the economic use of conversion facilities.

Summary

Sweet Sorghum has a few advantageous characteristics such as easy mechanization, a reduced competition for food and fuel as well as on land use for food production. These facts can make it already now, and even more so once the weak points have been improved, a food and energy crop of first choice for production scales and systems that emphasize environmental and food security and for many climatic areas unsuitable for sugar cane.

In Tab. 4-2 the alternative fuel crops are ranked in three categories which are relative to Sweet Sorghum: + more/better than Sweet Sorghum; – less/worse than Sweet Sorghum; O the same as Sweet Sorghum.

Tab. 4-2 Comparison of other energy crops with Sweet Sorghum

Parameter	Soy Bean	Sugar cane	Jatropha	Maize	Wheat	Cassava
Experiences in cropping methods	+	+	–	+	+	+
Breeding experiences	+	+	–	+	+	+
Mechanization:						
Establishment	O	–	–	O	O	–
Harvest	+	+	O	+	+	+
Conversion	O	O	O	O	O	O
Potential for ethanol production*	1st	1st & 2nd	1st	1st & 2nd	1st & 2nd	1st
Competition for food or fuel use	+	+	–	+	+	–
Competition with natural ecosystems	O	O	O	O	O	O
Competition on land use for food production	+	+	O	+	+	O
Year round production	+	–	+	+	+	–

* Potential for the production of first (1st) and second (2nd) generation ethanol, explanation see chapter 3.2.2

+ more/better than Sweet Sorghum; – less/worse than Sweet Sorghum; O the same as Sweet Sorghum

5 Conclusions and recommendations

The assessment of the environmental impacts associated with Sweet Sorghum production systems combining food and fuel and delivering first and second generation bioethanol lead to numerous single results. These are divided into outcomes of the energy and greenhouse gas balances and the qualitative assessment of other environmental impacts. Besides assessing environmental impacts, Sweet Sorghum has also been compared with alternative fuel crops concerning some technical aspects. From these results and comparisons, several conclusions and recommendations have been drawn.

In this study, basic interrelations have been assessed. For more exact quantitative calculations it is absolutely necessary to conduct case-specific energy and greenhouse gas balance assessments. In such cases, the detailed design for investigation is determined by the main questions, e.g. it could be a country-specific or production site-specific analysis.

5.1 Main conclusions

- Sweet Sorghum shows great potential as a future multi-purpose crop which combines flexibility between feed, food and fuel production. Especially first generation bioethanol can already be produced from the grains and from the sugary juice. Since Sweet Sorghum still shows good yields under low-input conditions it can be very attractive for small-scale farmers in developing countries who wish to produce food for subsistence and at the same time gain a cash product. Furthermore, Sweet Sorghum can have advantages regarding many environmental aspects besides saving fossil energy carriers and greenhouse gas emissions. It can preserve water resources and as a low input crop bears little risk to have polluting impacts on ground and surface water bodies. In addition, its introduction into existing farming systems can help enrich agrobiodiversity and minimize erosion processes. Its adaptation into no-till and organic production systems can bring further environmental benefits. Additional positive environmental impacts can be obtained from the integration of double cropping and / or intercropping in optimized production systems since this contributes to a more efficient use of solar, nutrient and land resources.
- Sweet Sorghum also shows a great potential for saving fossil energy and greenhouse gases. Even if grains are used as food instead of using the whole crop for bioethanol production, these potentials are still high. How much fossil energy and greenhouse gases can be saved depends on different factors such as the design of the life cycle (e.g. the use of bagasse as feed or fuel) or the country specific boundary conditions (e.g. the fossil energy carriers used for power production). Certain life cycle stages prove to be especially relevant for the outcome of the energy and greenhouse gas balances:
    - **Cultivation:** the establishment of Sweet Sorghum on areas with natural vegetation influences the carbon inventory of the area in question. Any accumulative or depleting change has a clear impact on the outcomes of the greenhouse gas balance. Therefore, in the cultivation of Sweet Sorghum any negative change in the carbon stock should be prevented, e.g. by not converting rich natural vegetation and / or by cultivation on carbon poor soil.

- **By-products:** the production of bioelectricity from surplus bagasse leads to high credits for the ethanol production which are a crucial factor in the greenhouse gas and energy balances. Especially in the case of greenhouse gas savings, the amount of the credits depends on the conventional energy carrier which is replaced. High advantages occur in regions where electricity produced from coal can be substituted.
  For improved greenhouse gas and energy balances, the leaves should be used as feed instead of being left on the field as fertilizer. This may however affect soil fertility and yields in the long run.
- **Conversion:** the combustion of surplus bagasse, instead of its conversion to second generation bioethanol, leads to higher benefits as regards greenhouse gas and fossil energy balances. If first and second generation bioethanol is to be combined, the choice of energy carrier has an influence on the outcome of the greenhouse gas balance. To achieve best results, the whole process should be realized self-sufficiently instead of being fuelled with an external fossil energy carrier.
  If grains are used as food, the production of ethanol from the rest of the crop is still advantageous regarding greenhouse gas and fossil energy savings. If both grains and juice are used as food, all energy and greenhouse gas expenditures for the food production can be compensated by the ethanol production (second generation) from the bagasse.
- **Methods:** the selection of the methodology of how to deal with products and by-products has a significant impact on the outcomes of the results. Therefore, respective guidelines or frameworks need to be very specific and should exactly define how to proceed.
- **Transport, mechanization levels** of production and harvesting, the provision of **pesticides** as well as of **auxiliary products** used in the conversion processes are of minor importance for the overall greenhouse gas and energy balances. Here, the choice can be based on alternative aspects like other environmental parameters, social or economic factors.

– Despite considerable environmental advantages, the conversion and use of Sweet Sorghum as a biofuel shows some disadvantages regarding acidification, eutrophication, ozone depletion and photo smog. Furthermore, an expansion of Sweet Sorghum cultivation bears certain risks for humans and the environment, as does expansion of agricultural areas in general, for example when the crop competes with fresh water resources or natural ecosystems. However, expansion of production area and / or replacement of food crops will always have a variety of negative impacts which need to be carefully examined for each specific case. If Sweet Sorghum is grown within a high input production system, this may cause the same negative environmental impacts as any crop production in such a system, through e.g. nutrient leaching or soil compaction. Yet impacts may be less than from other crops under those conditions due to lower input needs and double cropping options. Another example is the competition for land under food production, if Sweet Sorghum is grown on very fertile soils. It is therefore important to select and maintain a sustainable cultivation context and optimized use of Sweet Sorghum in an overall environmentally sound way considering also fundamental aspects of food security.

- In comparison with different bioenergy crops, there is no consistent, clear advantage or disadvantage over one crop or another since each crop shows advantages under different boundary conditions. With well known, specific boundary conditions, however, clear advantages or disadvantages may emerge.

5.2 Recommendations for programmes, initiatives and incentives

- The fact that **Sweet Sorghum can produce feed, food and fuel at the same time under low input conditions** makes it ideal for the combination of subsistence production and the production of cash crops in small-scale farming systems of developing countries. The introduction of corresponding (decentralized) production and market structures should support the pro-poor development of this crop. Especially in regions with decentralized farming structures, programmes for encouraging **ethanol production should aim at integrating subsistence farming or small-scale producers** in their overall concept, emphasize low input or organic farming and consider also other renewable and bioenergy sources.
- Further benefits for subsistence and small-scale farmers result from the possibility to **intercrop Sweet Sorghum with other food crops** such as edible mushrooms which can be sold or consumed by the producers themselves. Its short growth cycle allows quick adaptation to weather conditions by rotating with other crops. This increases income diversification and thus **minimizes climate vulnerability or food insecurity.** Respective programmes should encourage an increased use of these cultivation possibilities.
- The cultivation of Sweet Sorghum as biofuel crop allows for **many choices**, for example **regarding harvesting methods or the use of by-products**. It can therefore easily be integrated into various farming systems taking into consideration local social or economic factors. The introduction of Sweet Sorghum into existing production systems can increase agrobiodiversity and **creates additional opportunities** for income generation and small business development.
- The development of natural land for Sweet Sorghum production systems, as is the case for any land use change of this kind, has negative impacts on the biodiversity and carbon stock of the area. Respective programmes should therefore **aim primarily at the integration of Sweet Sorghum into existing agricultural production systems or its cultivation on carbon poor soils.**
- The production of **second generation bioethanol** is not yet economically profitable, nor does it lead to any further substantial savings of fossil energy carriers and greenhouse gases. Therefore, our recommendation is to **focus further research and programmes primarily on other topics**, i.e. the optimization of cultivars as well as cultivation and conversion methods. Regarding the latter, special emphasis should be put on by-products such as Dried Distillers Grains with Solubles (DDGS). Although DDGS production results in less advantageous greenhouse gas and energy balances, it could have economic advantages since – in contrast to stillage – it can be stored, transported and sold even on international markets.

- The great variation and range of results of the energy and greenhouse gas balances and the numerous possible effects on humans and the environment show the **importance of a solid framework for assuring the sustainability of Sweet Sorghum production and use**. Therefore, the current FAO activities on the environmental assessment framework (BIAS programme), which is part of the more encompassing bioenergy and food security integration efforts (FAO's BEFS programme) – are to be strongly encouraged. They represent an indispensable part of the endeavours to attain sustainable production and use of Sweet Sorghum. The same is true also for other energy crops. However, it is already becoming clear that these activities will not be sufficient since, for example, a more specific guidance is necessary for correct and harmonized energy and greenhouse gas balancing. Therefore, the above-named activities should be urgently pursued and developed further and simultaneously be interconnected with and adapted to other, both international and national programmes and activities.

5.3 Recommendations regarding further research

- The yields of juice / sugar and grains still prove to be fairly variable. Therefore, further breeding efforts are necessary to develop variants that produce stable and more predictable yields while meeting different producer and customer requirements. Breeding efforts should emphasise on the adaptation to different climatic and / or agricultural conditions, on the optimized composition of Sweet Sorghum regarding grains, sugar and bagasse and on the optimized composition of the single crop parts. Special emphasis should be put on varieties with higher yields since yield is one of the most important parameters in positively influencing the energy and greenhouse gas balances. In general, the bigger the yields the more fossil energy and greenhouse gases can be saved. In addition, higher yields increase area efficiency which contributes to the reduction of trade-offs between the production of bioenergy and food crops.
- Since the yield of energy crops accounts for a high impact on their energy and greenhouse gas balances it should represent the starting point for optimizing cultivation methods and crop breeding. Further research and breeding efforts should also be directed at enhancing the potential of Sweet Sorghum as a low input crop and / or its integration into organic farming systems. Here, the relation between yields and reduced / organic fertilizer is an important issue. In the balances, the nitrogen demand plays a major role and in organic farming systems the negative impacts on the environment resulting from the production and use of mineral fertilizers can be minimized. Also generally, further environmental benefits of applying no-till or organic production methods – such as the impact on soil organic matter and agrobiodiversity – should be further evaluated. Special emphasis should be put on the research regarding the cultivation of Sweet Sorghum on carbon poor soils since this offers further enormous potentials of saving greenhouse gases.

- Double cropping and intercropping of Sweet Sorghum with additional crops would create additional positive effects especially for subsistence and small-scale farmers. In order to increase such potentials, research projects should pursue two main aims: (1) validate current knowledge on intercropping experience, and (2) strive to develop further combinations with different crops.
- For the exact calculation of the energy and greenhouse gas balances some data are not yet adequately available. Therefore, several parameters should be measured, determined or collected. This is the case especially for: conversion technologies, the amount of nitrogen, phosphor or organic fertilizer ensuring a sustainable Sweet Sorghum production, the yields under different climatic conditions and soil qualities and for the carbon stocks of different Sweet Sorghum production systems. The latter should include soil carbon stock changes due to different cultivation methods such as no-till or organic farming as well as exact amounts of carbon stocks in the crop itself. Even more helpful would be the assessment of carbon stocks in single crop parts (e.g. in the roots).
- In addition to the assessment of environmental impacts of Sweet Sorghum production, further research on economic potentials and constraints under various surrounding conditions is needed. In this context, general system specific interrelations and case-specific or country-specific conditions must be distinguished.
- If alternative energy crops are compared with Sweet Sorghum, a highly differentiated picture is delivered in which each crop has advantages and disadvantages under specific conditions. In order to make use of the specific advantages, Sweet Sorghum should be integrated in a system in which each energy crop is dealt with and optimized according to specific production conditions. To do so, the environmental performance should be assessed equally for other energy crops. This also applies to the optimization of a future use of Sweet Sorghum for second generation ethanol production.
- The integration of Sweet Sorghum in alternative energy systems and respective optimization possibilities should be investigated further and the potentials arising from an integration of this crop in local, regional, national and pan-national energy programmes should be explored. **In any such context the versatility, adaptability and efficiency of Sweet Sorghum is a considerable contribution and should be further enhanced.**

5.4 Recommendations for next FAO steps

- Though being expert judgements, the qualitative evaluation of environmental implications of Sweet Sorghum production and use systems other than “resource depletion” and “greenhouse gas emissions” could not be quantified and assessed in detail within the scope of this study. However, the assessment delivers a comprehensive overview and serves as an important and solid base for further, more detailed discussion on this topic. In order to stimulate and support such a discussion on international levels and to consolidate the respective results, we recommend holding an expert consultation or workshop as a follow-up to the FAO consultation in Rome in November 2007 (FAO 2007a) and taking this study as a base with emphasis on relevant environmental impacts connected with Sweet Sorghum production and use. Such a workshop could give the opportunity to round off the picture of Sweet Sorghum and to fill some of the gaps identified in this study. This report is a solid basis for further discussions, however, it was the first screening analysis thus it could not clarify all open issues in detail. Several steps worth pursuing have been identified. The workshop could give the platform to plan and prioritize next steps regarding research needs and to improve the cooperation with the BIAS activities as well as networking in general.

  Additionally, the consultation would also offer a possibility to deal more in depth with the comparison of Sweet Sorghum with other crop choices. As with the environmental impacts, only basic – though consistent and solid – judgements have been made in this study and therefore need to be confirmed as well.

- The interpretation of results derived from the quantitative results presented in this study is scientifically sound. However, single data – including yield and cultivation data – show high uncertainties and / or bandwidths. For exact calculations of energy and greenhouse gas balances, these data should be collected systematically. Concerning agronomic data, we recommend launching well directed country and crop specific case studies. The goal should be to assess data on inputs and outputs and the correlation of yields with different boundary conditions. The studies should cover different countries with different climatic and soil conditions and cultivations methods.

  Accompanying ecological research should complement these assessments for gaining more insight into further – non-GHG – environmental impacts of Sweet Sorghum cultivation.

  Besides assessing resource depletion and greenhouse gas emissions, the Sweet Sorghum production and use system should be assessed in a more comprehensive way where also economic and social aspects are taken into consideration. This would help recognizing the entire range of positive potentials of Sweet Sorghum to the fullest extent.

  These case studies – initiated and supported by FAO where appropriate – could have positive side effects beyond mere data collection. They could support local capacity building regarding the collection and evaluation of scientific data. Furthermore, direct data input into decision-making processes on different national and international levels could be realized.

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7 Glossary

Abbreviation / Expression	Explanation
BEFS	Bioenergy and Food Security; a project of the FAO (see references)
BIAS	Bioenergy Environmental Impact Analysis; a study funded by the FAO (see references)
DDGS	Dried Distillers Grains with Solubles: Cereal by-product of the grain fermentation process; created by drying and pelletizing the stillage; used as feed, especially for ruminants
dm	Dry matter: Here, all solids of a crop, i.e. all constituents excluding water of biomass
EtOH	Ethanol: Here, first generation Ethanol which is produced by fermenting sugary juice (from Sweet Sorghum or sugar cane) or starch (from Sweet Sorghum or wheat grains)
EtOH 2	Second generation ethanol: Here, cellulosic ethanol; after a pre-treatment, sugar molecule chains are broken down to glucose molecules with the help of enzymes; the sugar can then be fermented to bioethanol; by-product is lignin which can produce process power
fm	Fresh matter: Here, whole biomass including water
GJ	Gigajoule: Unit of energy measuring heat, electricity and mechanical work, 1 Gigajoule are 1 000 000 000 Joule
ha x yr	One hectare in one year
kWh	Kilowatt hour. Unit of energy which is most commonly used to express amounts of energy delivered by electric utilities
LCA	Life Cycle Assessment: Investigation and valuation of the environmental impacts of a given product or service taking into account the entire life cycle of the product from raw material acquisition through production to utilization of the products ("well to wheels" approach)
MJ	Megajoule: Unit of energy measuring heat, electricity and mechanical work, 1 Megajoule are 1 000 000 Joule
to x km	Ton-kilometre: Unit of measurement used to assess the environmental implications in LCA associated with transportation; the number of ton-kilometres is calculated by the weight in tons of a product multiplied by the number of kilometres transported
WUE	Water use efficiency: Production of dry matter divided by water loss

8 Annex

8.1 Detailed life cycles for all scenarios

Fig. 8-1 Scenario 1: Standard

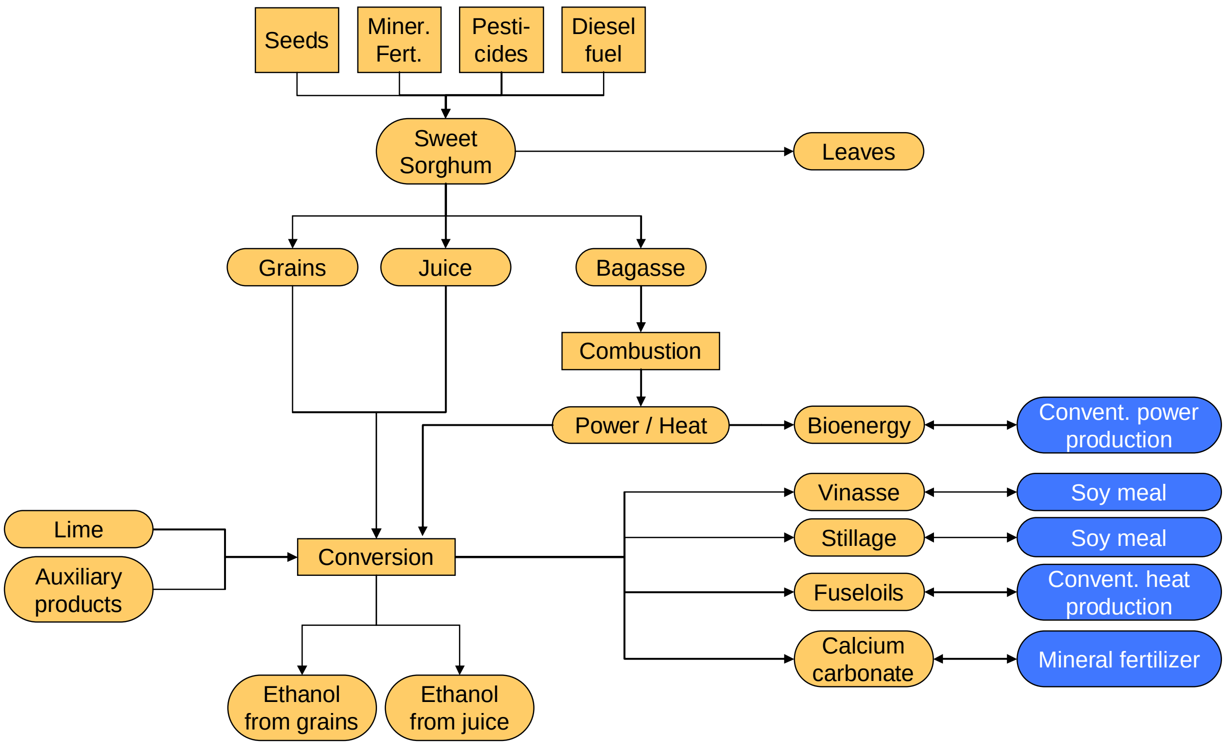


Fig. 8-2 Scenario 2: Grains to food

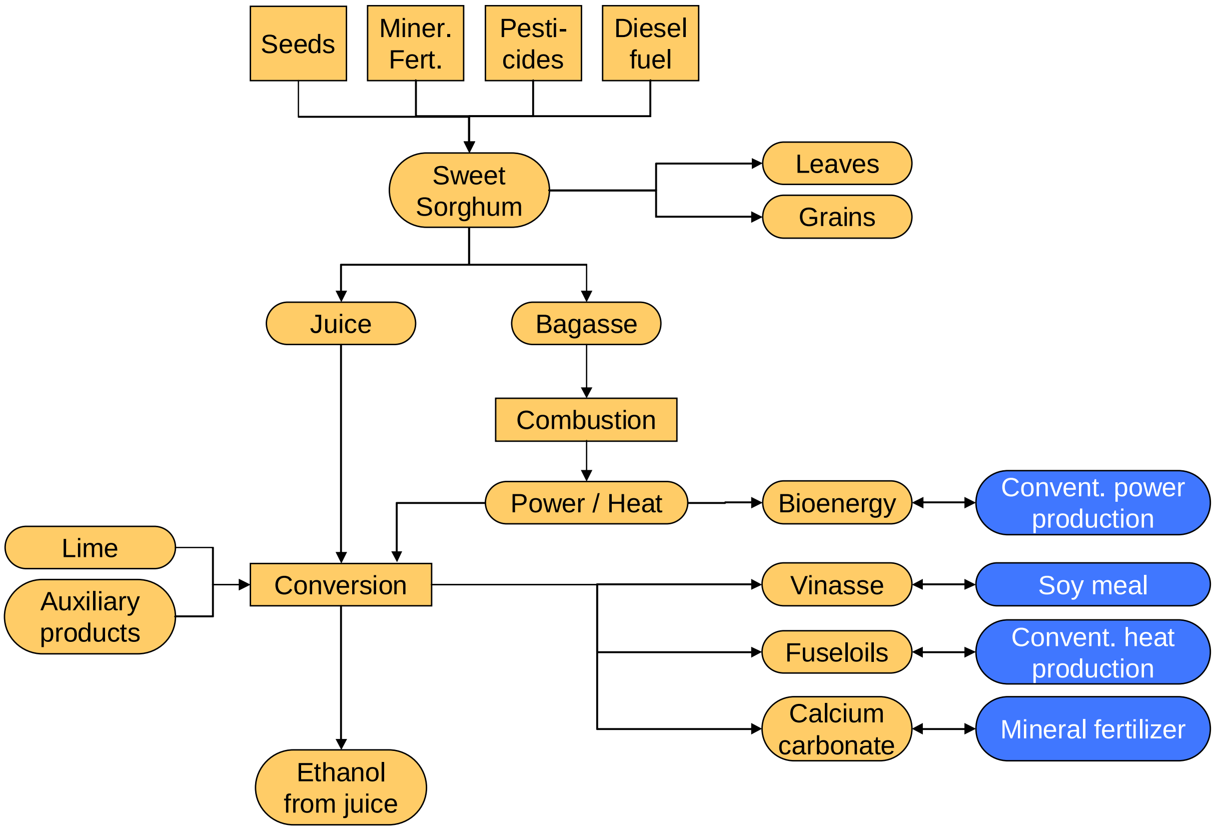


Fig. 8-3 Scenario 3: Food & EtOH 2

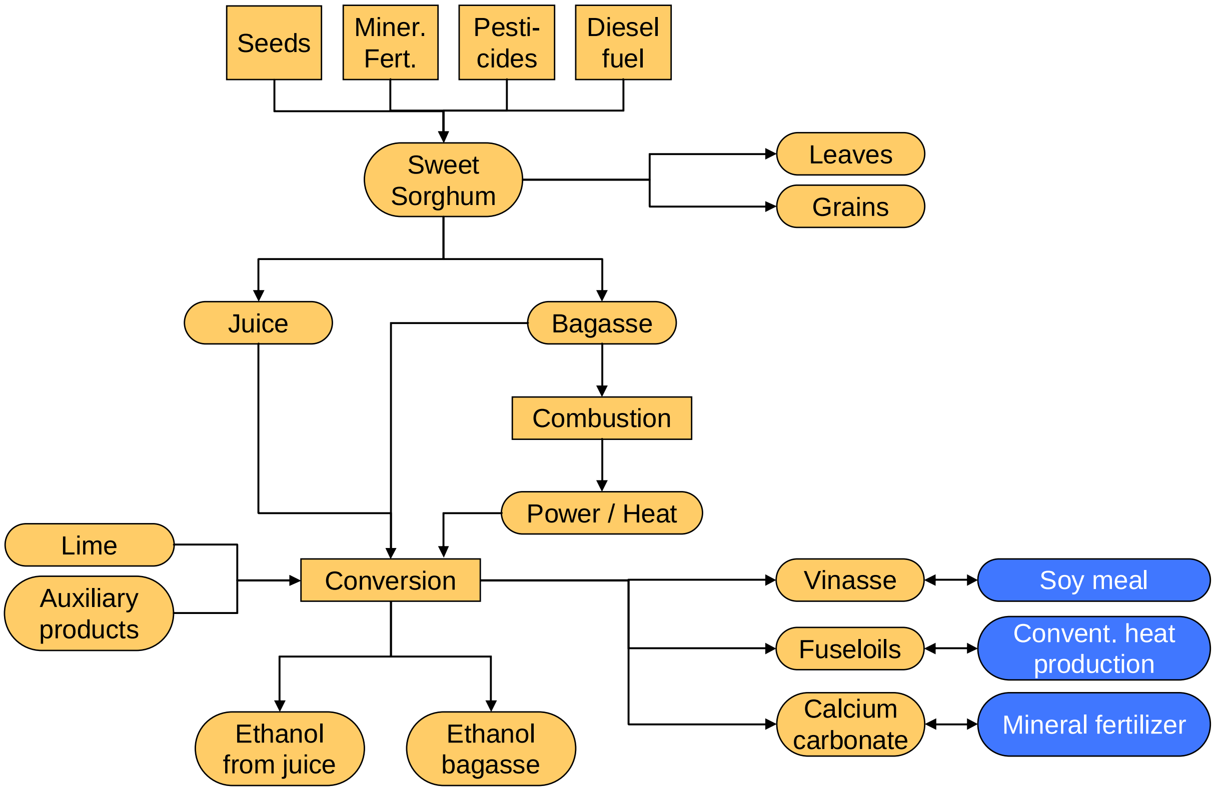


Fig. 8-4 Scenario 4: Grains & juice to food

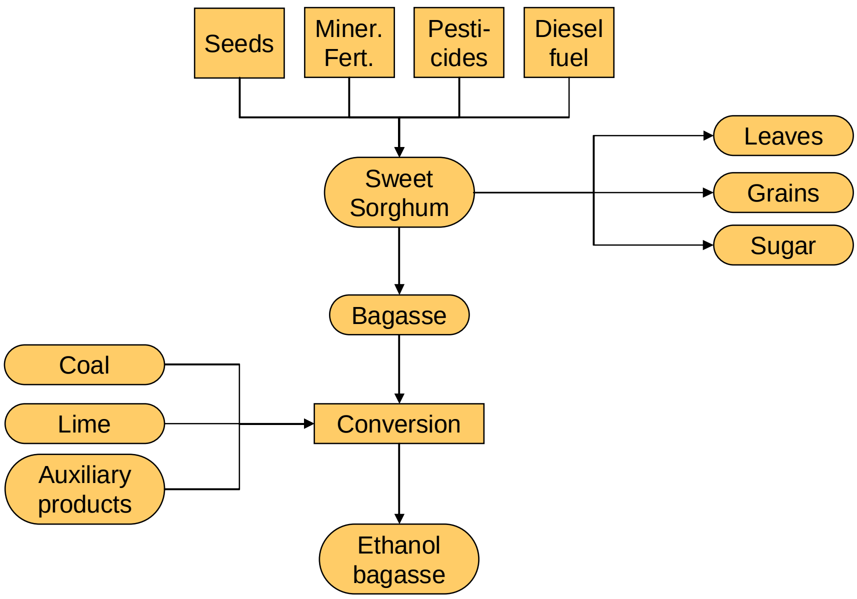


Fig. 8-5 Scenario 5: EtOH 2 extended autarkic

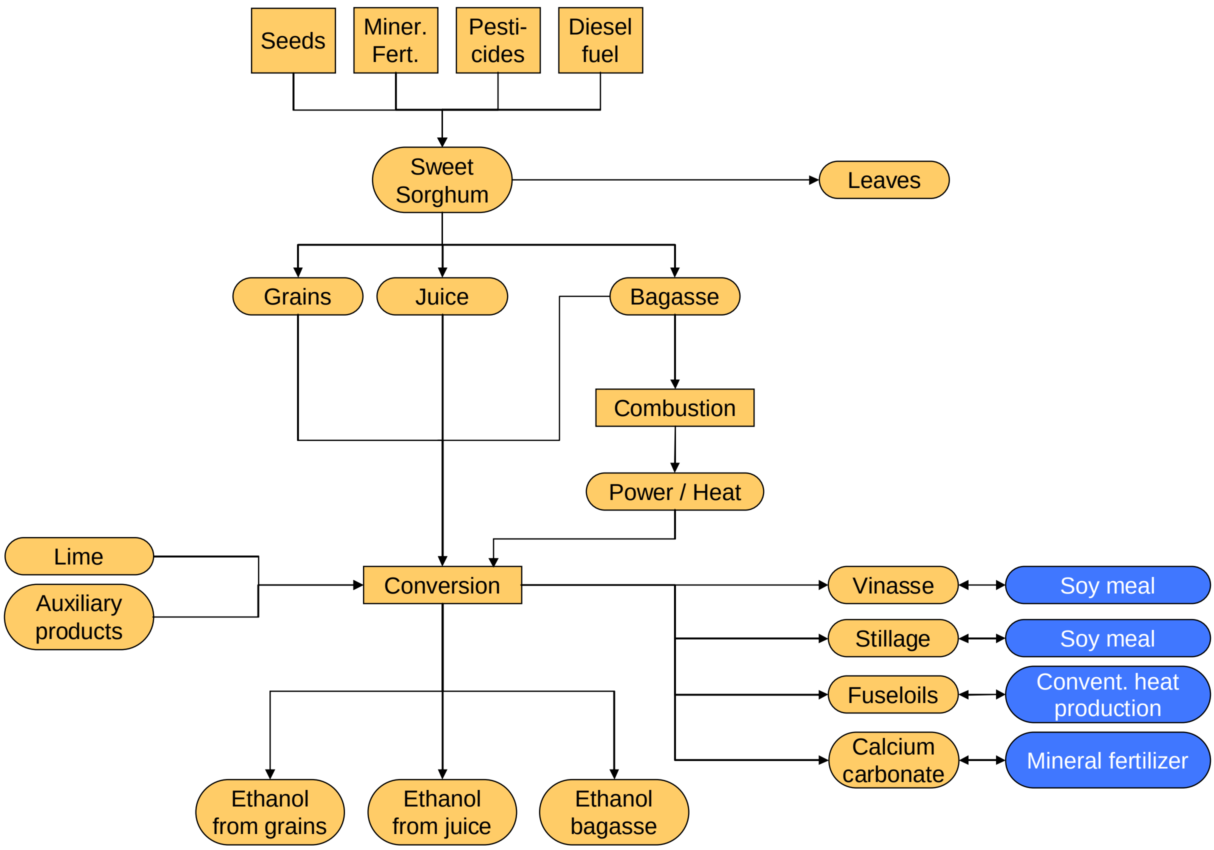
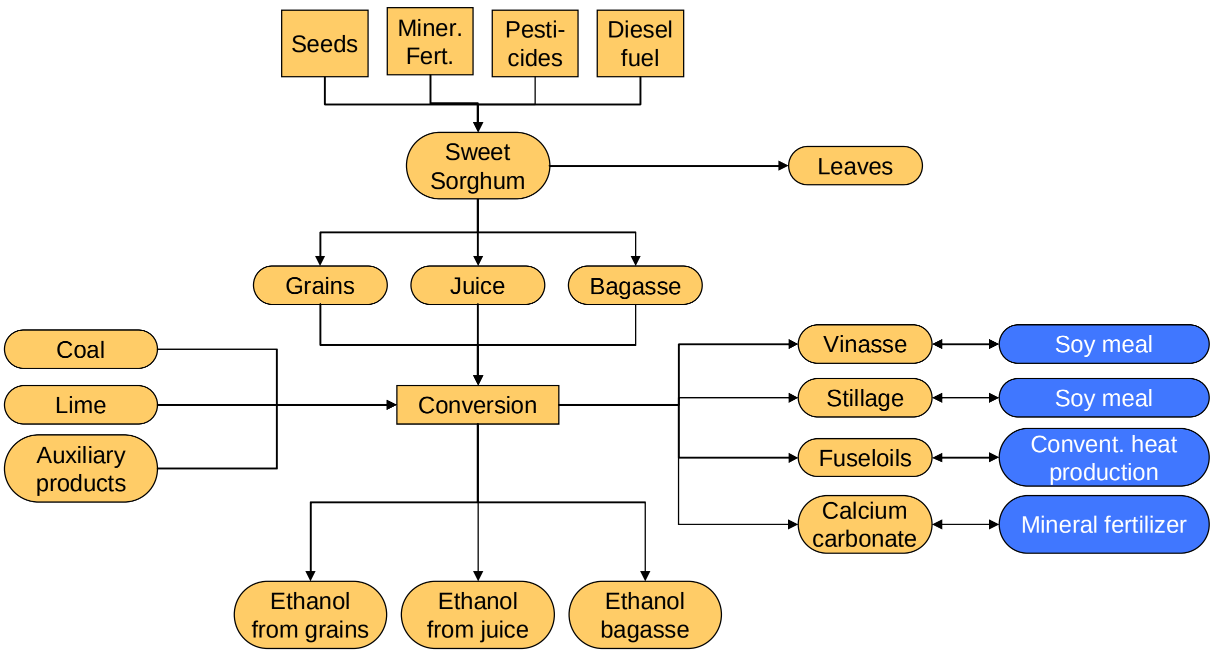


Fig. 8-6 Scenario 6: EtOH 2 maximum fossil



8.2 Additional basic data for chapter 3.2

Tab. 8-1 Basic data for average energy and greenhouse gas expenditures for seeds, pesticides and diesel fuel under consideration of three different yields (“Low”, “Medium” and “High”); IFEU 2008b

Basic data for seeds, pesticides and tractor fuel (Tab. 3-3)

	Yields	Seeds	Pesticides	Tractor (diesel fuel)
Primary energy consumption [GJ / (ha x yr)]	Low	0.03	1.4	4.4
	Medium	0.023	1.4	5.8
	High	0.02	1.4	8
Greenhouse gas emissions [tonnes CO_2 equiv. / (ha x yr)]	Low	0.03	0.063	0.33
	Medium	0.003	0.063	0.45
	High	0.0027	0.063	0.61

Tab. 8-2 Basic data for average energy and greenhouse gas expenditures for fertilizer requirements based on nutrient removal under consideration of three different yields (“Low”, “Medium” and “High”); IFEU 2008b

Basic data for fertilizer (Tab. 3-4)

	Yields	N	P_2O_5	K_2O
Primary energy consumption [GJ / (ha*yr)]	Low	2.4	0.35	0.1
	Medium	4.9	0.7	0.21
	High	8.6	1.2	0.36
Greenhouse gas emissions [tonnes CO_2 equiv. / (ha x yr)]	Low	0.32	0.024	0.0067
	Medium	0.65	0.048	0.013
	High	1.1	0.083	0.023

Tab. 8-3 Basic data for average energy and greenhouse gas expenditures for transport fuel and fertilizer when leaves are used as fertilizer or feed; IFEU 2008b

Basic data for the use of leaves as fertilizer or feed (Tab. 3-10)

		Transport (fuel)	N	P_2O_5	K_2O
Primary energy consumption [GJ / (ha x yr)]	**Leaves as fertilizer**	1.6	4.9	0.7	0.21
	Leaves as feed	1.8	5.4	0.84	0.042
Greenhouse gas emissions [tonnes CO_2 equiv. / (ha x yr)]	**Leaves as fertilizer**	0.12	0.65	0.048	0.013
	Leaves as feed	0.14	0.71	0.057	0.0027

8.3 Tables with precise data for each figure in chapter 4*

Tab. 8-4 Detailed expenditures and credits as well as balance results for the life cycle comparison between Sweet Sorghum first and second generation bioethanol and conventional fuel regarding **primary energy**; [GJ primary energy / (ha x yr)]

Results of the main scenarios – Primary energy (Fig. 4-1)

		Standard (1)	Grains food (2)	Food & EtOH 2 (3)	Grains & Juice food (4)	EtOH 2 extended autarkic (5)	EtOH 2 maximum fossil (6)
Credits Sorghum	*Credit ethanol*	-8	-3	-20	-20	-30	-30
	Credit power	-50	-50	0	0	0	0
Expenditures Sorghum	*Biomass tractor*	6	6	6	6	6	6
	Biomass N-fertilizer	5	5	5	5	5	5
	Biomass other aux. material	2	2	2	2	2	2
	Biomass transport	2	2	2	2	2	2
	Ethanol production	1	1	16	17	15	41
	Sugar food	0	0	0	14	0	0
	Ethanol transport	0.4	0.2	0.4	0.2	0.6	0.7
Expenditures fossil equivalent	*Foss. equiv. EtOH grains*	40	0	0	0	40	40
	Foss. equiv. EtOH sugar	40	40	40	0	40	40
	Foss. equiv. EtOH bagasse	0	0	33	38	31	38
	Balance	**-120**	**-79**	**-64**	**-15**	**-105**	**-91**

*** Abbreviations and explanations of the scenarios see chapter 3.2**

Tab. 8-5 Detailed expenditures and credits as well as balance results for the life cycle comparison between Sweet Sorghum first and second generation bioethanol and conventional fuel regarding **greenhouse gases**; [tonnes CO_2 equiv. / (ha x yr)]

Results of the main scenarios – Greenhouse gases (Fig. 4-2)

		Standard (1)	Grains food (2)	Food & EtOH 2 (3)	Grains & Juice food (4)	EtOH 2 extended autarkic (5)	EtOH 2 maximum fossil (6)
Credits Sorghum	***Credit ethanol***	-1	-0.41	-1.4	-1.2	-2	-2.2
	Credit power	-5.2	-5.4	0	0	0	0
Expenditures Sorghum	***Biomass tractor***	0.45	0.45	0.45	0.45	0.45	0.45
	Biomass N-fertilizer	0.65	0.65	0.65	0.65	0.65	0.65
	Biomass other aux. mat.	0.13	0.13	0.13	0.13	0.13	0.13
	Field emissions	0.47	0.47	0.47	0.47	0.47	0.47
	Biomass transport	0.12	0.12	0.12	0.12	0.12	0.12
	Ethanol production	0.2	0.19	1.2	1.2	1.2	3.7
	Sugar food	0	0	0	1.4	0	0
	Ethanol transport	0.033	0.017	0.03	0.016	0.046	0.049
	Ethanol usage	0.19	0.094	0.17	0.09	0.26	0.28
Expend. fossil equivalent	***Foss. equiv. EtOH grains***	3	0	0	0	3	3
	Foss. equiv. EtOH sugar	3	3	3	0	3	3
	Foss. equiv. EtOH bagasse	0	0	2.5	2.9	2.4	2.9
	Balance	**-9.9**	**-6.7**	**-3.7**	**0.42**	**-7**	**-5.3**

Tab. 8-6 Detailed credits and expenditures of **greenhouse gases** for the "Standard" scenario; [tonnes CO_2 equiv. / (ha x yr)]

Influence of the single production steps – Greenhouse gases (Fig. 4-3)		
Credits Sorghum	*Credit lime*	-0.037
	Credit vinasse/stillage	-0.8
	Credit fuseloil	-0.033
	Credit power	-5.2
Expenditures Sorghum	*Tractor*	0.45
	Nitrogen (N)	0.65
	Phosphor (P2O5)	0.048
	Kalium (K2O)	0.013
	Pesticides	0.063
	Seeds	0.003
	Field emissions	0.47
	Biomass transport	0.12
	Bagasse combustion	0.019
	Lime	0.18
	Ammoniak water	0.0056
	Enzymes	0.0006
	Water treatment	0.0002
	Fuseloil combustion	0.0004
	Ethanol transport	0.033
	Ethanol usage	0.19
Expend. fossil equiv.	*Fossil equiv. production*	0.95
	Fossil equiv. usage	5
	Balance	**-9.8**

Tab. 8-7 Credits, expenditures and balance results of **greenhouse gases** for Sweet Sorghum ethanol from the "Standard" production scenario under consideration of three different biomass yields and two different sugar yields; [tonnes CO_2 equiv. / (ha x yr)]

Different biomass and sugar yields – Greenhouse gases (Fig. 4-4)

		Low yield	Medium yield	High yield	Low juice	High juice
Credits Sorghum	*Credit Ethanol*	-0.51	-1	-1.8	-1	-1.4
	Credit power	-2.6	-5.2	-9	-5.2	-2.6
Expenditures Sorghum	*Biomass production*	0.99	1.7	2.7	1.7	1.7
	Biomass transport	0.059	0.12	0.21	0.12	0.14
	Ethanol production	0.1	0.2	0.35	0.2	0.39
	Ethanol transport	0.017	0.033	0.058	0.033	0.05
	Ethanol usage	0.094	0.19	0.33	0.19	0.28
Expend. fossil equiv.	*Foss. equiv. EtOH grain*	1.5	3	5.2	3	0
	Foss. equiv. EtOH juice	1.5	3	5.3	3	0
	Balance	**-4.8**	**-9.9**	**-18**	**-9.9**	**-10**

Tab. 8-8 Credits, expenditures and balance results of **primary energy** for Sweet Sorghum ethanol from the "Standard" production scenario under consideration of three different yields and three different carbon stock changes; [GJ primary energy / (ha x yr)]

Yield and land cover changes – Primary energy (Fig. 4-5)								
		Low yield, carbon neutral	**Low yield, carbon gain**	**Medium yield, carbon loss**	**Medium yield, carbon neutral**	**Medium yield, carbon gain**	**High yield, carbon loss**	**High yield, carbon neutral**
Credits Sorghum	***Credit ethanol***	-4	-4	-8	-8	-8	-13	-13
	Credit power	-25	-25	-50	-50	-50	-87	-87
Expenditures Sorghum	***Biomass production***	9	9	13	13	13	20	20
	Biomass transport	0.8	0.8	2	2	2	3	3
	Ethanol production	0.6	0.6	1	1	1	2	2
	Ethanol transport	0.2	0.2	0.4	0.4	0.4	0.8	0.8
Expend. fossil equiv.	***Foss. equiv. production***	6	6	13	13	13	22	22
	Foss. equiv. usage	33	33	66	66	66	116	116
	Balance	**-58**	**-58**	**-120**	**-120**	**- 120**	**-213**	**-213**

Tab. 8-9 Credits, expenditures and balance results of **greenhouse gases** for Sweet Sorghum ethanol from the "Standard" production scenario under consideration of three different yields and three different carbon stock changes; [tonnes CO_2 equiv. / (ha x yr)]

Yield and land cover changes – Greenhouse gases (Fig. 4-6)								
		Low yield, carbon neutral	**Low yield, carbon gain**	**Medium yield, carbon loss**	**Medium yield, carbon neutral**	**Medium yield, carbon gain**	**High yield, carbon loss**	**High yield, carbon neutral**
Credits Sorghum	***Credit ethanol***	-0.51	-0.51	-1	-1	-1	-1.8	-1.8
	Credit power	-2.6	-2.6	-5.2	-5.2	-5.2	-9	-9
Expenditures Sorghum	***Biomass production***	0.99	0.99	1.7	1.7	1.7	2.7	2.7
	Reference system	0	-1.8	6.4	0	-0.92	6.4	0
	Biomass transport	0.059	0.059	0.12	0.12	0.12	0.21	0.21
	Ethanol production	0.1	0.1	0.2	0.2	0.2	0.35	0.35
	Ethanol transport	0.017	0.017	0.033	0.033	0.033	0.058	0.058
	Ethanol usage	0.094	0.094	0.19	0.19	0.19	0.33	0.33
Expend. fossil equiv.	***Foss. equiv. production***	0.48	0.48	0.95	0.95	0.95	1.7	1.7
	Foss. equiv. usage	2.5	2.5	5	5	5	8.8	8.8
	Balance	**-4.8**	**-6.6**	**-3.5**	**-9.9**	**-11**	**-11**	**-18**

Tab. 8-10 Credits, expenditures and balance results of **primary energy** for the “Standard” scenario (scen. 1) and the “EtOH 2 extended” scenario (scen. 5) under consideration of two uses of the by-product of grain ethanol; [GJ primary energy / (ha x yr)]

DDGS instead of stillage as by-product – Primary energy (Fig. 4-7)					
		(1) Standard (stillage)	**(1) Standard (DDGS) - 1**	**(5) EtOH 2 ext. (stillage)**	**(5) EtOH 2 ext. (DDGS)**
Credits Sorghum	***Credit stillage/DDGS***	-3	-9	-3	-9
	Other credits	-4	-3	-26	-25
	Credit power	-50	-40	0	0
Expenditures Sorghum	***Biomass production***	13	13	13	13
	Biomass transport	2	2	2	2
	Ethanol production	1	1	41	60
	Ethanol transport	0.4	0.5	0.7	0.7
Expend. fossil equiv.	***Foss. equiv. production***	13	13	19	19
	Foss. equiv. usage	66	70	98	102
	Balance	**-120**	**-120**	**-91**	**-81**

Tab. 8-11 Credits, expenditures and balance results of **greenhouse gases** for the “Standard” scenario under consideration of two use options for leaves; [tonnes CO_2 equiv. / (ha x yr)]

Use of leaves as fertilizer or feed – Greenhouse gases (Fig. 4-8)			
		Leaves as feed	**Leaves as fertilizer**
Credits Sorghum	***Credit ethanol***	-1	-1
	Credit leaves	-1.5	0
	Credit power	-5.2	-5.2
Expenditures Sorghum	***Biomass tractor***	0.45	0.45
	Biomass N-fert.	0.71	0.65
	Biomass other aux. mat.	0.13	0.13
	Biomass field emissions	0.52	0.47
	Biomass transport	0.14	0.12
	Ethanol production	0.2	0.2
	Ethanol transport	0.033	0.033
	Ethanol usage	0.19	0.19
Expend. fossil equiv.	***Foss. equiv. production***	0.95	0.95
	Foss. equiv. usage	5	5
	Balance	**-11**	**-9.9**

Tab. 8-12 Credits, expenditures and balance result of **primary energy** for different substituted fossil energy carriers in the “Standard” scenario; [GJ primary energy / (ha x yr)]

Variation of substituted fossil energy carriers – Primary energy (Fig. 4-9)			
		Standard coal	**Natural gas**
Credits Sorghum	***Credit ethanol***	-8	-8
	Credit power	-50	-51
Expenditures Sorghum	***Biomass production***	13	13
	Biomass transport	2	2
	Ethanol production	1	1
	Ethanol transport	0.4	0.4
Expend. fossil equiv.	***Foss. equiv. production***	13	13
	Foss. equiv. usage	66	66
	Balance	**-120**	**-121**

Tab. 8-13 Credits, expenditures and balance results of **greenhouse gases** for different substituted fossil energy carriers in the “Standard” scenario; [tonnes CO_2 equiv. / (ha x yr)]

Variation of substituted fossil energy carriers – Greenhouse gases (Fig. 4-10)			
		Standard coal	**Natural gas**
Credits Sorghum	***Credit ethanol***	-1	-1
	Credit power	-5.2	-3.1
Expenditures Sorghum	***Biomass production***	1.7	1.7
	Biomass transport	0.12	0.12
	Ethanol production	0.2	0.2
	Ethanol transport	0.033	0.033
	Ethanol use	0.19	0.19
Expend. fossil equiv.	***Foss. equiv. production***	0.95	0.95
	Foss. equiv. usage	5	5
	Balance	**-9.9**	**-7.8**

Tab. 8-14 Credits, expenditures and balance results of **primary energy** for different external fossil energy carriers in the case of a maximized second generation ethanol production from bagasse; [GJ primary energy / (ha x yr)]

Variation of external fossil energy carrier – Primary energy (Fig. 4-11)			
		EtOH 2 max. coal	**EtOH 2 max. NG**
Credits Sorghum	***Credit ethanol***	-30	-30
Expenditures Sorghum	***Biomass production***	13	13
	Biomass transport	2	2
	Ethanol production	41	41
	Ethanol transport	0.7	0.7
Expend. fossil equiv.	***Foss. equiv. production***	19	19
	Foss. equiv. usage	98	98
	Balance	**-91**	**-90**

Tab. 8-15 Credits, expenditures and balance results of **greenhouse gases** for different external fossil energy carriers in the case of a maximized second generation ethanol production from bagasse; [tonnes CO_2 equiv. / (ha x yr)]

Variation of external fossil energy carrier – Greenhouse gases (Fig. 4-12)			
		EtOH 2 max. coal	**EtOH 2 max. NG**
Credits Sorghum	***Credit ethanol***	-2.2	-2.2
Expenditures Sorghum	***Biomass production***	1.7	1.7
	Biomass transport	0.12	0.12
	Ethanol production	3.7	2.8
	Ethanol transport	0.049	0.049
	Ethanol usage	0.28	0.28
Expend. fossil equiv.	***Foss. equiv. production***	1.4	1.4
	Foss. equiv. usage	7.4	7.4
	Balance	**-5.3**	**-6.2**

Tab. 8-16 Credits, expenditures and balance results of **greenhouse gases** for the "Standard" scenario under consideration of two different harvesting methods; [tonnes CO_2 equiv. / (ha x yr)]

Mechanical vs. manual harvest – Greenhouse gases (Fig. 4-13)

		Mechanical harvest	Manual harvest
Credits Sorghum	***Credit ethanol***	-1	-1
	Credit power	-5.2	-5.2
Expenditures Sorghum	***Biomass tractor***	0.45	0.22
	Biomass other aux. materials	1.2	1.2
	Biomass transport	0.12	0.12
	Ethanol production	0.2	0.2
	Ethanol transport	0.033	0.033
	Ethanol usage	0.19	0.19
Expend. fossil equiv.	***Foss. equiv. production***	0.95	0.95
	Foss. equiv. usage	5	5
	Balance	**-9.9**	**-10**

Tab. 8-17 Results of the **greenhouse gas** balances, if the credit or allocation method is used to consider the by-products of the "Standard" Sweet Sorghum production and use system; [tonnes CO_2 equiv. / (ha x yr)]

Allocation vs. credit – Greenhouse gases (Fig. 4-14)

	Standard Credit	Allocation Bagasse	Allocation Power
Balance results	-9.9	-5.1	-4.5

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