Resource Use Efficiency and Environmental Performance of Biofuel Cropping Systems

Thesis committee

Thesis supervisors
Prof. dr. ir. M.K. van Ittersum
Personal chair at the Plant Production Systems Group
Wageningen University

Prof. dr. K.E. Giller
Professor of Plant Production Systems
Wageningen University

Thesis co-supervisor
Dr. ir. G.W.J. van de Ven
Assistant Professor at the Plant Production Systems Group

Other members
Prof. dr. C. Kroeze, Wageningen University
Dr. ir. S. Nonhebel, University of Groningen
Dr. A. Voss, Shell, Rijswijk
Dr. E. Hoffland, Wageningen University

This research was conducted under the auspices of the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC)

Resource Use Efficiency and Environmental Performance of Biofuel Cropping Systems

Sander C. de Vries

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Friday 20 April 2012
at 11 a.m. in the Aula.

S.C. de Vries
Resource Use and Environmental Performance of Biofuel Cropping Systems

PhD thesis, Wageningen University, Wageningen, The Netherlands (2012).
With ref., with summary in English and Dutch.

ISBN 978-94-6173-117-3

"There are of course two kinds of natural resources. One is the kind which can only be used as part of a process of exhaustion; this is true of mines, natural oil and gas wells, and the like. The other, and of course ultimately by far the most important, includes the resources which can be improved in the process of wise use; the soil, the rivers, and the forests come under this head. Any really civilized nation will so use all of these three great national assets that the nation will have their benefit in the future. Just as a farmer, after all his life making his living from his farm, will, if he is an expert farmer, leave it as an asset of increased value to his son, so we should leave our national domain to our children, increased in value and not worn out."

President's annual address to Congress (State of the Union)

Theodore Roosevelt, 1908

Abstract

The world production of biofuels, i.e. liquid transport fuels produced from agricultural products, has shown an unprecedented growth over the past decade (2000-2010); this growth is projected to continue for the coming decade. The increased demand for biofuels is mainly caused by government targets, set because of concerns over climate change (Kyoto protocol), dependence on imported oil from politically unstable regions, and to create new markets for the agricultural sector. Soon after government targets were set, a hot scientific and societal debate arose on whether the large-scale production and use of biofuels is a sustainable endeavour, after all. A sustainable activity (i.e. biofuel production) meets the needs of the present generation without compromising the ability of future generations to meet their own needs.

This thesis aims to assess the production-ecological sustainability of biofuel production systems that represent as much as possible the diversity in feedstock crops, climatic and bio-physical environments in the world. Production-ecological sustainability is a part of the environmental dimension of sustainability; for the specific purpose of the current work, it was defined by a set of sustainability indicators relating to resource use efficiencies, soil quality, net energy production and greenhouse gas emissions. Secondly, the work aimed to provide a general methodology that enables such assessments of systems with minimum land use change, aid in their development and could potentially form a basis for sustainability certification of biofuels.

First a literature-based inventory of the production-ecological sustainability of nine major biofuel production systems was made, based on current practices in major production areas in the world. Crops that performed well or seemed promising in this inventory were analysed in more detail in three region-specific case studies. For these case studies, an assessment framework was developed, based on existing crop-soil models; it calculates the sustainability indicators and takes into account the effects of limited availability of water and nutrients on crop growth. Such limitations are particularly relevant in low-input smallholder systems.

From the work done, we conclude that under good agricultural practice and without adverse land use change, biofuel production systems using feedstock from sugarcane, oil palm and second generation crops Miscanthus and black locust perform much better than first generation production from arable crops in temperate areas. Sugarcane, oil palm, Miscanthus and black locust under good agricultural practice produce so much biomass that they have high gross energy yields, provide enough biomass for powering the conversion process which contributes to high net energy yields, and at the same time supply ample crop residues for maintaining or increasing soil organic carbon storage. In contrast, first generation systems in temperate areas generally have rather low net energy yields and poor resource use efficiencies and perform relatively poorly for the other sustainability indicators that we assessed. Therefore, their production is relatively land- and resource consuming and has relatively high environmental impact. Aspects that require further research are the frost tolerance of Miscanthus and invasive characteristics of black locust.

Results further indicate that yield increase through ecological intensification in existing plantations (oil palm, smallholder cassava) and rehabilitation of degraded lands (oil palm, black locust) are much more sustainable ways of increasing production than through directly or indirectly encroaching into tropical forest and other natural habitats. Ecological intensification may be defined as the achievement of substantially higher yields relative to both land area and time, involving concomitant improvements in nutrient use efficiency, water use efficiency and energy efficiency. Rehabilitation of degraded lands offers great potential for carbon sequestration in soil and biomass and hence could be considered for eligibility as a carbon sink in the UN's REDD+ programme (Reducing Emissions from Deforestation and forest Degradation + Conservation of forest carbon stocks, Sustainable management of forests & Enhancement of forest carbon stocks).

Table of contents

chapter 1

General Introduction

1.1 Biofuels

Biofuels, liquid transport fuels produced from agricultural products, can be produced from plant compounds in different ways. Ancient and simple is the conversion of starch and sugar into ethanol by fermentation. Henry Ford designed his automobiles, beginning with the 1908 Model T, to use ethanol (Werner, 2003). Sugar is readily extracted from e.g. sugarcane[$], sugar beet and sweet sorghum, or obtained by conversion of starch from crops such as cereals and cassava.

Extracting plant oil from crops such as oil palm, rapeseed and soybean is also simple; when Rudolph Diesel first demonstrated his engine at the *Exposition Universelle* (World's Fair) in Paris in 1900, he used peanut oil. To meet modern fuel standards, plant oil normally needs to be converted into biodiesel by a process called 'transesterification', however.

Biofuels can also be produced from lignocellulosic plant compounds, using more advanced ('second generation') technology, as opposed to the above-described 'first generation' technologies. Lignin and cellulose are main constituents of straw and other crop residues and of perennial non-food crops like *Miscanthus*, willow, poplar, switchgrass and black locust. The advantage of these crops is that they are not used for food production; hence food markets are not directly influenced by extra demand for these crops from biofuel producers. Nevertheless, competition for natural resources may in the end still result in higher food prices. At the time of writing, second generation fuels are much less cost-effective than first generation fuels, particularly sugarcane (Nauclér and Enkvist, 2009); sugarcane ethanol is already competitive with gasoline at oil prices above ~50 US$ per barrel (Deconti, 2008; Nauclér and Enkvist, 2009); the current oil price is ~100 US$ (Bloomberg, 2011). Although second generation biofuels are currently relatively expensive, it is expected that the cost of second generation biofuels will fall much more than of first generation fuels, since second generation technology is at an earlier stage of development and is therefore likely to benefit from greater learning curve cost reductions (Deconti, 2008).

[$] Scientific crop names in order of appearance: sugarcane: *Saccharum officinarum* L.; sugar beet: *Beta vulgaris* L.; sweet sorghum: *Sorghum bicolor* L. Moench; cassava: *Manihot esculenta* Crantz; oil palm: *Elaeis guineensis* Jacq.; rapeseed: *Brassica napus* L.; soybean: *Glycine max* L. Merr; Miscanthus: *Miscanthus x giganteus* Greef et. Deu. ex Hodkinson et Renvoize; willow: *Salix* spp.; poplar: *Populus* spp.; switchgrass: *Panicum virgatum* L.; black locust: *Robinia pseudoacacia* L.

1.2 Recent developments

Since the year 2000, world production of biofuels has shown unprecedented growth (Figure 1.1). In 2009, fuel ethanol production had increased more than fourfold of its volume in 2000, to 73 billion liters per year; biodiesel production increased more than fifteen-fold to 16 billion liters per year. Although in itself these volumes may be considered massive, jointly they only represent 0.002% of the world transport energy consumption (currently 2284 million ton oil equivalents or 95631 PJ y^{-1}; IEA, 2011). Rather than created by market forces, the increased demand for biofuels is caused mainly by government targets (cf. European Parliament, 2003; European Parliament, 2009; U.S. Congress, 2005). These targets have been set because of concerns over climate change (Kyoto protocol), dependence on imported oil from politically unstable regions and to create new markets for the agricultural sector (cf. European Parliament, 2003). Creating new markets for the agricultural sector is the oldest argument to support

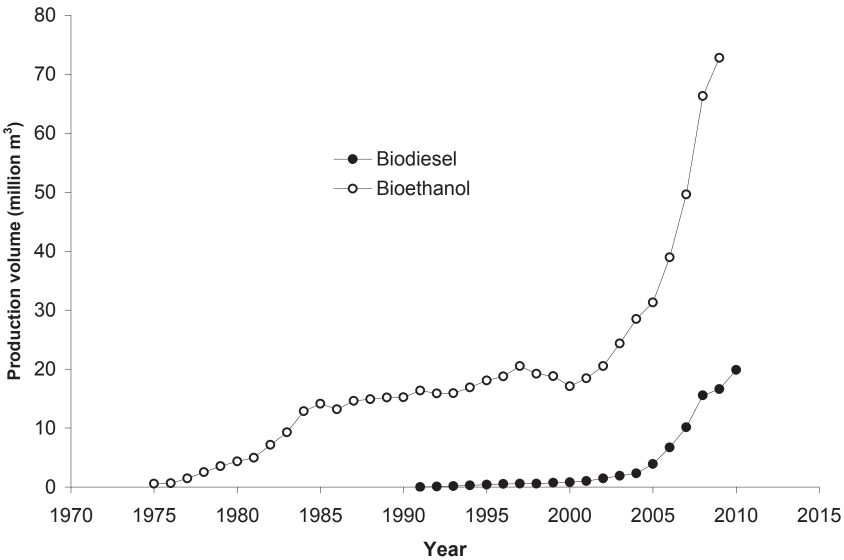


Figure 1.1 World production of bioethanol and biodiesel 1975-2010. Source: F.O. Licht, Worldwatch Institute.

biofuel production; it was the reason for removing the US federal beverage alcohol tax in 1906, during a period of agricultural price decline (Giebelhaus, 1980). Similarly, the “Motor Fuel Alcohol Committee”, a coordinating group of mid-western alcohol advocates, issued a statement in May 1933 arguing that “if alcohol from crops were allowed to supply two per cent of the nation’s consumption of motor fuel, a new use would be established for 120 to 130 million bushels of corn annually” (Giebelhaus, 1980).

In the European policy arena, the debate on biofuels started around 1983 in the era of surplus production of wine, grain and agricultural products in general in the EU. It was argued that the subsidies for dumping agricultural products on the world market should be redirected to produce biofuels (Londo and Deurwaarder, 2007). In the Netherlands, the search for non-food products from agricultural products was called *'agrificatie'*. Here and also elsewhere in Europe, an additional argument behind this development was the need for a so-called fourth major crop, next to cereals, potato and sugar beet, to widen the narrow crop rotations. This fourth crop could then be used for non-food applications (Bos, 2008). The 1997 Kyoto Climate Conference created more awareness of the possibilities to reduce greenhouse gas emissions with biofuels. In the preparation for the Biofuels Directive (European Parliament, 2003), the reduction of greenhouse gas emissions became a very important argument while, at the same time, possible negative side-effects of biofuels were hardly mentioned (Londo and Deurwaarder, 2007).

1.3 Side-effects of increased biofuel production

The side-effects of large-scale cultivation of energy crops started to attract more attention only after the biofuel targets had been in place for some time, despite the fact that some research had already touched on the subject in the 1990s (cf. Cook et al., 1991; Hanegraaf et al., 1998; Kaltschmitt et al., 1997). New issues that emerged comprised direct (Nellemann et al., 2007) and indirect (Sparovek et al., 2009) land use change and impact on food prices and food security (cf. Cassman and Liska, 2007; Ewing and Msangi, 2009). Also, more fundamentally, doubts emerged on the effectiveness of biofuels in reducing GHG emissions (Patzek and Pimentel, 2005). Due to these issues, the *sustainability* of biofuels became a key issue in the debate. One of the first and most general definitions of sustainability was formulated by chairman Gro Harlem Brundtland of the UN World Commission on Environment and Development in the report Our Common Future (1987): "an activity is sustainable when it meets the needs of the present generation without compromising the ability of future generations to meet their own needs". Biofuel blending targets forced oil companies to source biofuels, while the criteria by which sustainability should be measured were still unclear and not legally established. The initiative was left to the oil companies. Shell, for instance, introduced a sustainable sourcing policy to help provide responsible biofuels in September 2007, including environmental and social safeguards (Royal Dutch Shell plc, 2008). However, there was a definite need for more knowledge on biofuels sustainability, especially on the potentials to produce sustainable biofuels from different crops, cultivation systems and regions of the world, to secure future supply; this was the driver behind the funding of the current research.

1.4 This thesis

1.4.1 Production-ecological sustainability

Before the sustainability of an activity like biofuels production can be assessed, it needs to be clarified what exactly is meant with sustainability, which aspects of sustainability are taken into account and how they can be measured. Sustainability normally involves three dimensions: the social, the environmental and the economic dimension (Zhen and Routray, 2003), also known as the 'people, planet and profit' dimensions, respectively.

In this research, the focus is on the *production-ecological* sustainability of biofuel production chains, which may be considered part of the environmental dimension of sustainability (Figure 1.2). Production ecology studies the integration of basic information on physical, chemical, physiological and ecological processes to elucidate the functioning of agricultural production systems (Van Ittersum and Rabbinge, 1997). For the specific purpose of the current work, production-ecological sustainability is defined by a set of sustainability indicators relating to resource use efficiency, soil quality, net energy production and greenhouse gas emissions.

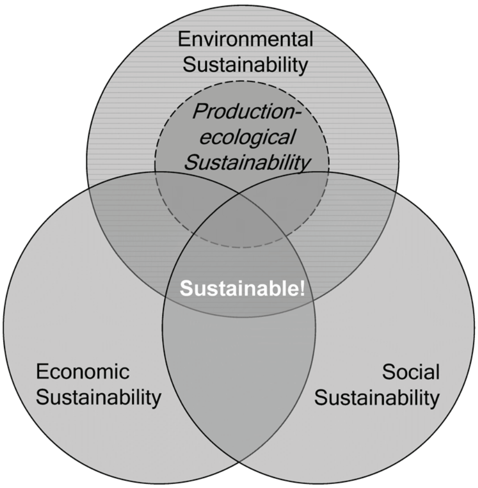


Figure 1.2 The place of production-ecological sustainability in the three dimensions of sustainability of biofuel production systems: social (people), environment (planet) and economic (profit). A system is sustainable where environmental, economic and social sustainability overlap.

1.4.2 A methodology for assessing the production-ecological sustainability of biofuel production systems

This thesis aims to assess the production-ecological sustainability of biofuel production systems that represent as much as possible the diversity in feedstock crops, climatic and bio-physical environments in the world. Secondly, the work should result in a general methodology that enables such assessments of systems with minimum land use change, aid in the development of such systems and could potentially form a basis for sustainability certification of biofuels.

When the proposal for the current research was written, research on the sustainability of biofuels strongly focused on environmental emissions but rarely integrated insights on the effects of water and nutrient limitations, pests and diseases, (sub-optimal) crop management and largely ignored heterogeneity in soil properties, climate conditions and land management history. The aim is to address these issues in the current thesis. A prime aim of the developed methodology will be to support decision making of biofuel producing oil companies and local or national policy makers, and to aid in planning and design of sustainable biofuel production systems.

1.5 Sustainability indicators employed in this thesis: rationale and relevance

When studying the sustainability of a certain land use, the natural resources that need consideration are those that are affected by this land use, and that in their turn affect this or other land uses (Jansen et al., 1995). These natural resources can be identified, for example, by the three rules compiled by Pearce and Turner (1990, cited by Jansen et al., 1995): (i) renewable resources should be used at rates less than or equal to the natural rate at which they regenerate; (ii) waste flows to the environment should be kept at or below the assimilative capacity of the environment and (iii) the efficiency of use of non-renewable resources should be optimised. A resource may be characterised as non-renewable if it is consumed at rates much quicker than the natural rate at which it regenerates; fossil fuels are an important example.

The most important environmental impacts of biofuels occur not at a car's tailpipe or biorefinery's smokestack, but on the farms that grow the crops to be rendered into liquid transportation fuels (Martin, 2011). Soil, water, atmosphere and biodiversity are the natural resources affected by the agriculture carried out on these farms (Eckert et al., 2000; Lewandowski et al.; McBride et al., 2011; OECD, 2001; Pieri et al., 1995; Scherr and Summit, 2008; Van Cauwenbergh et al., 2007; Van der Werf and Petit, 2002); additionally landscape quality may also change (Eckert et al., 2000;

OECD, 2001). The impact of agriculture on these resources is normally much greater than that of the ecosystems that it once replaced. The impact can be quantified by means of sustainability indicators, which quantitatively describe the (change in) the condition of the (agro-) ecosystem or its components affected (Lewandowski et al., 1999). Sustainability indicators used in this thesis were selected based on the work by the list of authors cited above, based on work describing criteria for selecting useful indicators (cf. Azapagic and Perdan, 2005; Lewandowski et al., 1999; Zhen and Routray, 2003) and on the selection of similar indicators by multi-stakeholder platforms such as the roundtables for sustainable biofuels, palm oil and responsible soy (RSB, 2009; RSPO, 2007; RTRS, 2010).

Burning of fossil fuels and deforestation (Baede et al., 2001) currently create GHG emissions that are much greater than the sequestration that is occurring globally, hence contribute to global warming; one of the main goals of biofuels is to reduce GHG emissions. Furthermore, agriculture may pollute the atmosphere by burning of residues, denitrification of fertiliser N, fossil fuel consumption, and volatilisation of fertiliser in ammonia form. We included *GHG emission reduction* as a sustainability indicator in this study; as part of these emissions, N_2O emissions were also calculated. Relating to fossil energy consumption, the *energy efficiency* (energy produced/energy consumed) was used as an indicator. Although it is not really consumed, land is an increasingly scarce resource on our planet and subject to competing claims from food production, urban use, industry and nature conservation. Therefore, the *net energy yield* per ha was also included as a sustainability indicator. The higher the net energy yield, the more land is potentially left for other purposes.

Soil nutrients in agricultural soils may be exhausted more rapidly than they are replenished due to the export of agricultural products, if insufficient fertilisation is practised; topsoil may disappear more rapidly than it is formed due to soil erosion and more soil organic carbon (SOC) may decompose than is formed from supplied crop residues and roots. Finally, due to imbalanced crop rotations and monoculture, populations of pathogenic organisms may increase, rendering soils less suitable for the cultivation of certain crops. To take all these issues into account, *nutrient (N) use efficiency, soil erosion, SOC change* and the *risk of soil borne diseases* were used as indicators in this thesis. Freshwater reserves may be depleted more quickly than they are replenished, especially where industry and consumers compete with agriculture for water or in areas of low rainfall. Also, water may be polluted by leaching of nutrients and biocides applied in agriculture and then become unsuitable for human consumption. These issues were quantified by including indicators of *water productivity, N leaching and pesticide use efficiency*. Each of these indicators is also included in several other frameworks for assessing or certifying the sustainability of biomass, biofuels, or agricultural products (Table 1.1).

1.6 The four assessments in this thesis

First the indicators are assessed in a literature-based inventory of the sustainability of nine major biofuel production systems, based on current production practices in major production areas (Chapter 2). Crops that performed well in this inventory

Table 1.1 The sustainability indicators employed in this thesis and their incorporation in major frameworks for assessing or certifying the sustainability of biomass, biofuels, or agricultural products

	Roundtable on sustainable biofuels (RSB, 2009)	**Roundtable on responsible palm oil (RSPO, 2007)**	**Assessment framework for sustainable biomass (Cramer et al., 2007)**	**EU Directive 2009/28/EC on the promotion of the use of energy from renewable sources (European Parliament, 2009)**	**Roundtable on responsible soy (RTRS, 2010)**
GHG emission reduction	Criterion 3a,b,c,	Criterion 5.6	Criterion 1.1	Article 17-2	Principle 4.3
Net energy yield, energy efficiency	Principle 11 (implicit)	Criterion 5.4	-	-	Principle 4.3.1, 4.3.2, (implicit)
N use efficiency	Principle 11 (implicit)	Criterion 5.3, (implicit)	Criterion 6.2 (implicit)	-	-
Soil erosion	Criterion 8a	Criterion 4.3	Criterion 5.1, 5.2	Reference to Council Regulation (EC) No 73/2009, Annex III (¶)	Principle 5.1.1, 5.3.2
SOC change	Criterion 8a	Criterion 4.2	Criterion 2.2, 5.2, 5.3	Reference to Council Regulation (EC) No 73/2009, Annex III (¶)	Principle 5.3.3
Risk of soil borne diseases[$]	Criterion 8a	Criterion 4.5	Criterion 5.2, (implicit)	-	Principle 5.3.1
Water Productivity	Criterion 9b	Criterion 4.4 (implicit)	Criterion 6.2	-	Principle 5.1.1, 5.1.4, (implicit)
N leaching	Criterion 9d (implicit)	Criterion 4.4, (implicit)	Criterion 5.1, 6.2 (implicit)	Reference to Council Directive 91/676/EEC (from ¶)	Principle 5.1.1
Pesticide use efficiency[&]	Criterion 8a1, 8a2	Criterion 4.5, 4.6 (implicit)	Criterion 5.1, 6.2 (implicit)	Reference to Council Directive 80/68/EEC (from ¶)	Principle 5.4, 5.9

[$] only in Chapter 2
[&] only in Chapters 2, 5

are analysed in more detail in three subsequent region-specific case studies. For these studies, geographic regions were chosen that represent as much as possible the diversity in climate, bio-physical and socio-economic environments existing in the world. Also, it was attempted to study as much as possible the variation that exists among plant species that may be used for the production of biofuels: perennials and annuals are included, species with C3 and C4 photosynthesis, food (first-generation) and non-food (second generation) producing species, and biodiesel and bio-ethanol yielding species. Further, smallholder systems as well as large-scale plantations are assessed (Figure 1.3).

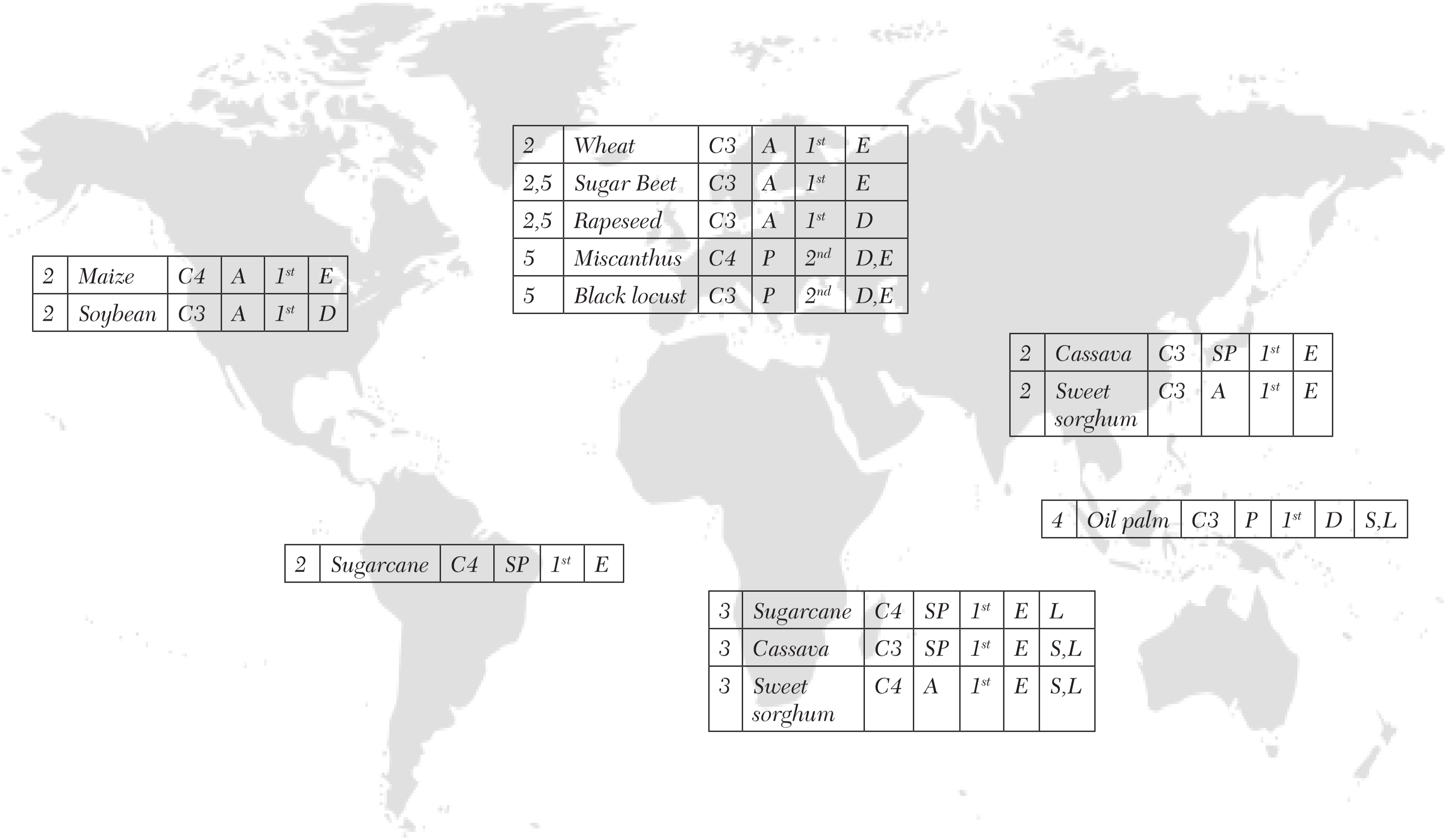
Chapter 3 analysed agricultural production systems on smallholdings and large-scale plantations in Mozambique, where climate is mostly semi-arid, soils are poor and, in the case of smallholder agriculture, insufficient inputs are supplied. Crops considered are cassava, a C3 root crop that can still produce on poor soils, sweet sorghum which is relatively drought resistant and irrigated sugarcane. The latter two crops are members of the *Poaceae* group and possess C4 photosynthetic mechanisms.

Chapter 4 assesses different production systems of palm oil biodiesel in Indonesia, situated in the humid tropics. Again, production by smallholdings and large plantations are assessed and compared. Furthermore, different previous land uses are considered; in oil palm previous land use plays a crucial role in among others GHG emissions.

Chapter 5 assesses and compares first and second generation biofuel production systems in Brandenburg, Germany. In second generation systems, the lignin and cellulose compounds of plant biomass are converted into biofuels; this requires more advanced and costly processing techniques than first-generation conversion of starch, sugar or plant oil. Climate in Brandenburg is dry-temperate; crops studied are *Miscanthus* and black locust as perennial ligno-cellulosic species, and rapeseed and sugar beet. This chapter also contains an uncertainty analysis.

In the case studies in Chapters 2-5, issues could be addressed that were not analysed in the broad initial assessment since it was not sufficiently location-specific for doing so. These issues comprise the sustainability impact of land use change, of soil fertility and of different, improved crop management practices, including fertilisation, residue mulching and irrigation. Moreover, due to the more mechanistic nature of the case study assessments, several options for improving the performance of the assessed systems could be identified.

Chapter 6, finally, discusses the findings and limitations of the work, and the relevance of these matters for society and science. Also, based on the work in Chapters 2-5, we formulate a general methodology ('framework') for assessing the production-ecological sustainability of biofuel production systems.



2	*Maize*	C4	A	1st	E
2	*Soybean*	C3	A	1st	D

2	*Wheat*	C3	A	1st	E
2,5	*Sugar Beet*	C3	A	1st	E
2,5	*Rapeseed*	C3	A	1st	D
5	*Miscanthus*	C4	P	2nd	D,E
5	*Black locust*	C3	P	2nd	D,E

2	*Cassava*	C3	SP	1st	E
2	*Sweet sorghum*	C3	A	1st	E

4	*Oil palm*	C3	P	1st	D	S,L

2	*Sugarcane*	C4	SP	1st	E

3	*Sugarcane*	C4	SP	1st	E	L
3	*Cassava*	C3	SP	1st	E	S,L
3	*Sweet sorghum*	C4	A	1st	E	S,L

Figure 1.3. Crops, crop traits and geographic locations for which the production-ecological sustainability of biofuel production was assessed. Columns in the tables from left to right respectively indicate chapter number, crop name, crop photosynthetic mechanism (C3 or C4), crop habit (P = perennial, SP = semi-perennial, A = annual), type of processing (1st /2nd generation), produced fuel type (E = bioethanol, D = biodiesel), and, where taken into account, farm size (S = smallholder, L = large plantation) are given.

chapter 2

Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques

We compared the production-ecological sustainability of biofuel production from several major crops that are also commonly used for production of food or feed, based on current production practices in major production areas. The set of nine sustainability indicators focused on resource use efficiency, soil quality, net energy production and greenhouse gas emissions, disregarding socio-economic or biodiversity aspects and land use change. Based on these nine production-ecological indicators and attributing equal importance to each indicator, biofuel produced from oil palm, sugarcane and sweet sorghum appeared most sustainable: these crops make the most efficient use of land, water, nitrogen and energy resources, while pesticide applications are relatively low in relation to the net energy produced. Provided there is no land use change, greenhouse gas emissions of these three biofuels are substantially reduced compared with fossil fuels. Oil palm was most sustainable with respect to the maintenance of soil quality. Maize (USA) and wheat (Northwest Europe) as feedstock for ethanol perform poorly on nearly all indicators. Sugar beet (Northwest Europe), cassava (Thailand), rapeseed (Northwest Europe) and soybean (USA) take an intermediate position.

This chapter was published as:
De Vries SC, Van de Ven GWJ, Van Ittersum MK, Giller KE (2010). Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. Biomass and Bioenergy 34:588–601.

2.1 Introduction

Recent policy targets (European Parliament, 2003; U.S. Congress, 2005) are boosting the demand for biofuel and its production starts to claim increasingly large areas of agricultural land and large quantities of other resources. Substantial impacts of the increased use of resources on the environment, food security and markets for agricultural commodities (OECD and FAO, 2008) are to be expected. It is important to know to what extent the currently emerging biomass production systems are sustainable or contributing to the ability of future generations to meet their own needs (Brundtland, 1987). To this end, scientists have formulated criteria and indicators for assessing the sustainability of biofuel production systems (Cramer et al., 2007; Hanegraaf et al., 1998; Lewandowski and Faaij, 2006; Mattsson et al., 2000; Reijnders, 2006; Turner et al., 2007). In general, one can distinguish social, economic and ecological sustainability criteria (Lewandowski and Faaij, 2006). So far, most studies on the sustainability of biofuels exclusively focused on environmental emissions (LCA studies) or dealt with limited numbers of indicators and feedstock crops. The aim of the present paper is to give a full picture of the production-ecological sustainability of nine major first generation biofuel production chains. We concentrate on sustainability indicators relating to energy use and the quality of soil and water resources and their ability to sustain agricultural production. The paper focuses on the use of these nine crops for producing first generation biofuels, since other known alternatives (e.g. the second generation biofuels) are still under development and unlikely to have impact before 2020 (Jesse and Van der Linde, 2008). We assess the crops used for bio-ethanol and biodiesel production which are most important in different parts of the world. Data on best practice production methods for these crops have been derived from the literature. Our work aims to improve understanding of the pros and cons of certain types of feedstocks for the production of biofuels, which can assist better-founded choices in the future.

2.2 Methods

The partial sustainability assessment presented here was based on calculations using data from the literature. We analysed different biofuel production systems in geographical regions where they are currently important or successful: for ethanol the main crops are maize (USA), wheat (Northwest Europe), sugar beet (Northwest Europe), cassava (Thailand), sweet sorghum (China), sugarcane (Brazil). We analysed production of biodiesel from winter oilseed rape (Northwest Europe), soybean (USA) and oil palm (Malaysia). All of these crops are commonly categorised as 'first generation' biomass crops: they contain either plant oil that may readily be extracted and converted into biodiesel, or starch or sugar that can easily be converted into ethanol by fermentation. In addition, these crops are currently more important as food crops than as biofuel crops; in this respect, a lot is already known about their environmental impacts (Clay, 2003). We reviewed the literature for studies on energy balance and GHG emissions of the above-mentioned crop-region combinations; since reducing fossil energy consumption and greenhouse gas (GHG) emissions are the main reasons for embarking on biofuel production, these are important indicators of sustainability for biofuel production systems. If not readily provided by the authors, we calculated the net energy yield: the energy content of the biofuel and its co-products minus the total fossil energy used throughout the full chain of production and transportation of the feedstock, and its conversion to biofuel (after Schnoor et al., 2008); in case of multiple sources of information, averages and standard deviations were calculated. The analysed system and its boundaries are displayed in Figure 2.1.

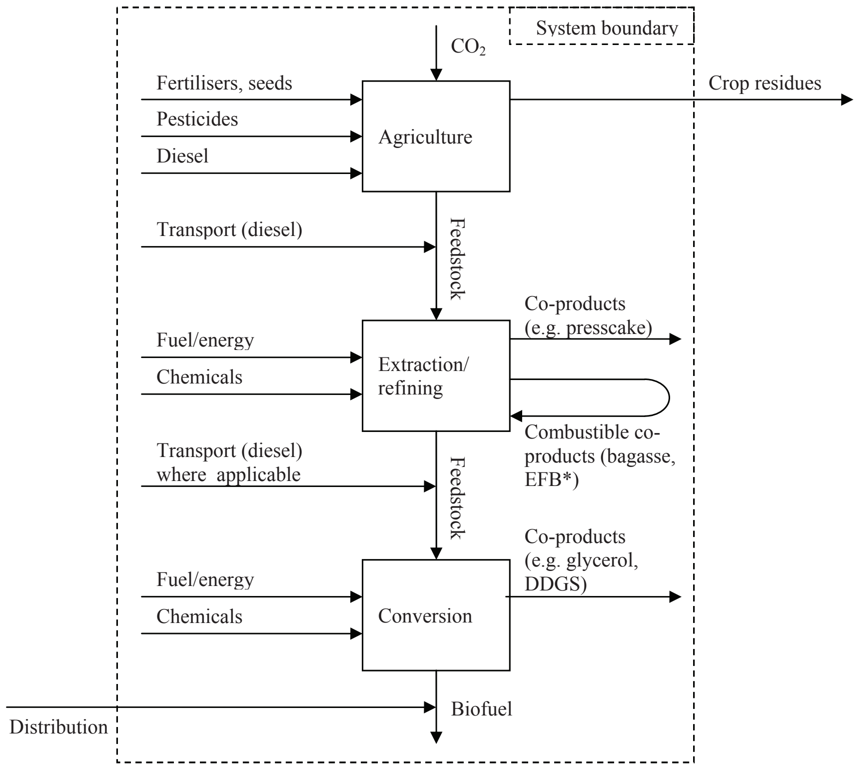


Figure 2.1 *Biofuel production systems and boundaries as analysed in the GHG and energy-related indicators (* EFB: Empty Fruit Bunches of oil palm). Co-products generate energy credits by their replacement value.*

Where co-products are normally used for generating processing energy (bagasse, fibres and shells), their energetic value was not added to the output, but subtracted from the fossil energy required for processing instead.

The obtained average net energy yields of each crop-region combination were used for calculating the use of fertilisers and pesticides per unit of the net energy gain captured in a biofuel, which is a suitable index for comparing environmental effects of different biomass types (Hill et al., 2006; Schnoor et al., 2008). We also assessed average GHG emissions of the biofuels and indicators for the quality of the agricultural resource base such as soil organic matter content, soil erosion hazard, soil borne diseases and water use. They are briefly discussed below.

2.2.1 Energy yield

A high output ('return') of biofuel energy per unit of fossil energy spent is desirable: the energy output/input ratio (briefly 'energy ratio') is used as an indicator of energy efficiency. This ratio is defined here as the energy in the biofuel and its co-products divided by the fossil energy used in agriculture, transport and processing, after Farrell et al. (after Farrell et al., 2006). Apart from fossil energy, another increasingly scarce resource employed in biofuel feedstock production is land. Therefore we also consider the net energy production per unit of land (i.e. per hectare) as an indicator. Based on selected references (Appendix I), we calculated average net energy yields per hectare, and standard deviations where possible. To improve comparability of these two energy indicators over the different systems and source publications, we assumed supply of energy for conversion by natural gas and grid electricity and use of co-products (sugar beet pulp, dried distillers' grains with solubles) as animal feed, wherever possible.

For calculating energy credits from co-products, a 'replacement' or 'system expansion' approach was followed. In the production of ethanol from sugarcane and sweet sorghum, bagasse (the biomass remaining after sugarcane or sorghum stalks are crushed to extract their juice) supplies ample energy to cover the entire processing energy requirement (Dias de Oliveira et al., 2005; Gnansounou et al., 2005; Macedo et al., 2004). Since sweet sorghum for ethanol has remained a relatively minor crop until today, no comprehensive studies on its energy balance and GHG emissions are available. Especially data on agricultural practices are scarce. As sweet sorghum and sugarcane both are C4 sugar crops in the *Gramineae* of which most of the aboveground biomass is harvested, we assume the energy required (and GHG emissions) for growing a hectare of sweet sorghum to be similar to that for growing a hectare of sugarcane, as calculated by Macedo et al. (2004). Transport energy requirements were also derived from Macedo et al. (2004). To compensate for the smaller yield of sweet sorghum as compared with sugarcane, they were reduced proportionally.

Similar to production of ethanol from sugarcane and sweet sorghum, energy required for extracting and refining palm oil is generally derived from combustion of crop residues (fibres and shells, Pleanjai and Gheewala, 2009; Wood and Corley, 1991). Subsequent transesterification of palm oil into biodiesel requires additional (fossil) energy however, among others for producing the required methanol, which is assumed to be produced from fossil sources. Since one reference (Wood and Corley, 1991) considered production of pure palm oil instead of biodiesel, we added the energy required for transport to the biodiesel plant and subsequent transesterification (Pleanjai and Gheewala, 2009) to the energy inputs; their estimate of the energy content of the co-produced glycerine was added to the overall output energy of the system.

2.2.2 GHG emissions

We compared GHGs emitted from biofuel production with those from production and combustion of fossil fuels. CO_2 emitted during *combustion* of biofuel is not taken into account as this CO_2 had earlier been captured from the atmosphere by photosynthesis during the agricultural production phase. Therefore, fossil energy use and field (N_2O) emissions are the main determinants of GHG emissions from biofuel production. In this paper, the significance of the GHG emission indicator is restricted to scenarios without land use change: converting rainforests, peatlands, savannas, or grasslands to produce food-based biofuel may create a 'biofuel carbon debt' by releasing much more CO_2 than the annual GHG emission reductions these biofuels provide by displacing fossil fuels (Fargione et al., 2008).

For each system, we calculated the average GHG emission per unit of energy produced and the accompanying standard deviation for the various literature sources (Appendix I). Figures on emissions from production and combustion of fossil fuels (i.e. diesel and gasoline) were derived from (LBST, 2002); we assumed that a volume of fossil fuel can simply be replaced by a volume of biofuel with equal energetic value. For allocating emissions to main product and co-products, we used the same methods as with the energy indicators discussed in Section 2.2.1.

2.2.3 The agro-environment

Large-scale production of biomass crops may affect the (agro-) environment in several ways: we have taken six aspects into account:

Soil erosion

Soil erosion is a major environmental threat to the sustainability and productive capacity of agriculture. Since it is difficult to compare erosion in different feedstock crops based on experiments conducted under different circumstances (soil type, climate, crop management, slope), we attempted to rank crops qualitatively, in order of erosion hazard. For temperate areas, maize, sugar beet, winter wheat and winter rapeseed were ranked based on factors for crop cover ('C-factors') from the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) combined with rainfall erosivity data (Gabriels et al., 2003; Wischmeier and Smith, 1978), and on crop cover data from literature. The ranking was then extended with the tropical crops. Maize is grown in both regions and was used as the reference for combining tropical and temperate crops in one ranking.

Soil organic matter

Soil organic carbon is often viewed as the most important indicator of soil quality because of its impact on physical, chemical and biological indicators of soil quality (Reeves, 1997). Recently, the role of soil carbon storage for the global carbon budget has also become a topic of importance (Van Noordwijk et al., 1997). Soil organic matter content in cropping systems is determined by the amount of residues that is added, and by soil type, tillage practices and climate. We use the *effective organic matter (EOM)* of each crop as an indicator. It is defined as the quantity of organic matter that is still present in the soil one year after application of the residues (Timmer et al., 2004). Estimated average quantities of EOM obtained from the different crops were obtained from literature (Appendix I) and adjusted according to our yield data (Table 2.1) with harvest indices unchanged.

Risk of soil borne diseases

Soil borne diseases may reduce the frequency with which biofuel crops can be grown on a certain field: the maximum share of crops in rotations effectively limits their production potential. Qualitative data on susceptibility of different biofuel crops to soil-borne diseases was obtained from literature. Sustainability of different crops was ranked according to the maximum frequency of cultivation and our impression of the financial impact of soil-borne diseases. Higher impact was attributed to rotation constraints (sugar beet, rapeseed) than to yield reduction.

Eutrophication

Part of the nutrients applied in agricultural production drains to aquatic systems, where it may damage ecosystems (Turner et al., 2007) and endanger drinking water quality. The main fertiliser compounds responsible for these processes are phosphate and nitrate. We focused on nitrate, as it is easier to make general (non location-specific) assumptions on nitrogen applications in a certain crop than on phosphorus applications: the latter are much more dependent on soil type and long-term management. Further, leaching of phosphorus is minimal except in soils where excessive amounts of organic manures are added.

Table 2.1 *Some average characteristics of the assessed biofuel production systems (based on the reviewed source publications) a.i.: active ingredient; f.w.: fresh weight.*

	Crop yield, fresh	**Average fertilizer application**	**Pesticide usage**	**Fuel yield**	**Conversion efficiency**	**Virtual water content of product**
	(Mg ha^{-1})	**(kg ha^{-1} of N)**	**(kg ha^{-1} of a.i.)**	**(m^3 ha^{-1})**	**(liters of fuel Mg^{-1} of fresh product)**	**(m^3 Mg^{-1} of f.w.)**
Ethanol crops						
Maize (USA)	8.2	149	3.8	3.2	386	489
Wheat (NW Europe)	8.2	191	4.8	2.9	357	501 (UK) 895 (France) 757 (Germany)
Sugarbeet (NW Europe)	61.2	107	3.5	6.0	97	56 (UK) 67 (France) 77 (Germany)
Cassava (Thailand)	27.0	49	3.9	3.7	137	387
Sweet sorghum (China)	47.1	58	3.0	4.1	87	131
Sugarcane (Brazil)	74.4	75	3.5	6.2	83	155
Biodiesel crops						
Rapeseed (NW Europe)	3.3	166	2.4	1.4	429	876 (UK) 1390 (France) 1128 (Germany)
Soybean (USA)	2.6	7	1.2	0.5	203	1869
Oil palm (SE Asia)	18.0	88	3.0	5.1	286	552 (Malaysia) 779 (Thailand)

The use of nitrogen impacts several aspects of sustainability. Nitrogen may be applied in synthetic forms or in animal manure. Compared with other fertilisers, production of synthetic nitrogen fertiliser is an energy consuming process (Mortimer et al., 2003) during which large amounts of GHGs are emitted. Production and transport of N fertiliser may claim between 5% (soybean, Hill et al., 2006) and 65% (rapeseed, Kaltschmitt et al., 1997; Mortimer et al., 2003) of the total fossil energy required for agricultural production. After application emissions are roughly proportional to the quantity of N applied (IPCC, 2006) and consist of N_2O, a GHG which is 296 times more active than CO_2 (Ehhalt et al., 2001). Since biophysical modelling of nitrogen emissions to the environment is beyond the scope of this paper, we used the quantity of N applied as an indicator for environmental risk. Fertiliser applications in Table 2.1 stem from practice and may be assumed sufficient for sustaining the accompanying yields. Comparing different crops is facilitated (Schnoor et al., 2008) by introducing a nitrogen fertiliser use efficiency (NUE):

$$NUE = E_{net} / N_{fert} \tag{2.1}$$

where *NUE* is the Nitrogen Use Efficiency (GJ kg^{-1} of N); E_{net} is the net energy yield (GJ ha^{-1}) and N_{fert} is the typical N fertilizer application for this crop (kg ha^{-1} of N, Table 2.1).

Pesticide usage

A particular biomass crop may be considered less sustainable than other biomass crops if its production entails comparatively large quantities of pesticides. Similar to the abovementioned NUE, we introduce a 'pesticide use efficiency' (PUE) for comparing different biofuel production systems:

$$PUE = E_{net} / PC_{applied} \tag{2.2}$$

where *PUE* is the Pesticide Use Efficiency (GJ kg^{-1} of a.i.); E_{net} is the net energy yield (GJ ha^{-1}) and $PC_{applied}$ the typical pesticide usage for this crop (kg ha^{-1} of a.i., Table 2.1). This indicator only informs us on the *amount* of pesticides used for producing a certain biofuel; calculation of a more advanced ecotoxicity indicator (Tzilivakis et al., 2005) is beyond the scope of this paper. We derived average pesticide application figures for each crop-region combination from the literature (Appendix I).

Water use.

A useful measure of performance from a water-efficiency standpoint is the net energy yield per unit of water withdrawn or consumed (Schnoor et al., 2008). We used the *virtual water contents (VWC)* of crop products (m^3 t^{-1} of fresh matter, f.m.) as calculated by Chapagain and Hoekstra (2004) for calculating the water productivity of biofuels (WPB) from the different systems. The VWC is defined as the volume of water used to produce the product, measured at the place where it was actually produced (Chapagain and Hoekstra, 2004); for our purpose, we defined the water productivity of a biofuel as the amount of net biofuel energy that is produced with 1 m^3 of water lost through evapotranspiration:

$$WPB = NETNRG / (VWC \cdot YLD) \quad (2.3)$$

where WPB is the water productivity of the concerning biofuel (GJ m^{-3}); NETNRG the net energy yield (GJ ha^{-1}); YLD the crop yield (t ha^{-1} of f.m.) and VWC the *virtual water content (VWC)* of the crop product (m^3 t^{-1} of f.m.). We did not take into account water use during processing, since compared with water use during feedstock production, water use in biorefineries is quite small. For example, a maize crop in the U.S. may transpire 411 mm of water (Chapagain and Hoekstra, 2004), equal to 4110 m^3 ha^{-1}. Water use in U.S. biorefineries is estimated at 7 l l^{-1} of ethanol, in the least favourable case (Schnoor et al., 2008). With an ethanol yield of 3.2 m^3 ha^{-1} (Table 2.1), water use in biorefineries is then just 0.5% of that lost through evapotranspiration of the crop. Biodiesel refining requires much less water per unit of energy produced than bioethanol (Schnoor et al., 2008).

2.3. Results

2.3.1 Energy yield

Figure 2.2 displays average energy ratios and standard deviations that were calculated from literature data. It is obvious that biofuel production from sugarcane, sweet sorghum and oil palm delivers substantially more energy per unit energy spent than from the other crops. With these crops, crop residues are the primary source of processing energy hence fossil energy consumption is greatly reduced. In temperate regions, biofuels from oil crops (rapeseed, soybean) appear more efficient than from ethanol crops. For ethanol crops, the conversion process is more energy consuming (Richards, 2000) due to the need for distillation. Low N fertiliser requirement for soybean (due to its ability to fix N_2 from the air) is an additional factor contributing to the favourable energy ratio for soybean biodiesel. It should be kept in mind that differences between systems (e.g. between ethanol from maize and from wheat) do not necessarily mean that one feedstock crop is intrinsically better than the other, since they may in part stem from differences in overall energy efficiencies of agriculture and industry between different regions (USA, Northwest Europe).

Average values for the second indicator, net energy production per hectare, are displayed in Figure 2.3. Wheat, corn and soybean on average produce little net energy per hectare. From the large standard deviations, it becomes also clear that between source studies, net energy estimates vary greatly (for maize and wheat-based systems the CV is over 100%). Underlying causes are different estimates of processing energy

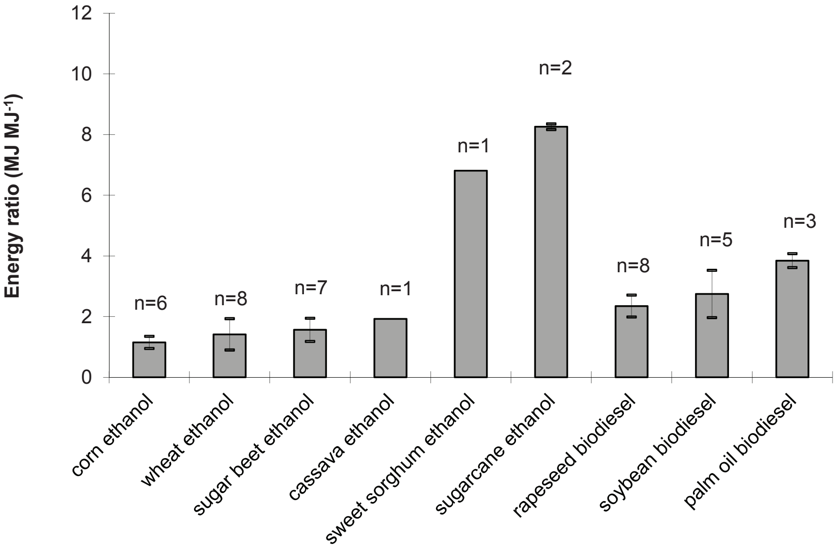


Figure 2.2 *Energy ratio of the assessed systems (MJ MJ^{-1}), based on source publications listed in the Appendix. Definition and calculation are explained in Section 2.2.1.*

requirements, differing coefficients for calculating energy use and GHG emissions, and in some cases different allocation methods. Compared with wheat and maize ethanol, net energy yields per hectare obtained from the tuber crops (cassava and sugar beet), and from rapeseed were more favourable, but systems based on sugarcane, sweet sorghum and oil palm performed best, hence these make the most efficient use of land resources. Crops with favourable energy ratios (Figure 2.2) do not necessarily produce high energy yields on a land area basis and *vice versa*; this applies especially to soybean, which produces only little net energy per hectare (Figure 2.3).

2.3.2 GHG emissions

Since GHG emissions are strongly linked to fossil fuel use (and N_2O emissions), the GHG emission indicator displays similar trends as the energy indicators: production of biofuel from sweet sorghum, sugarcane, soybean and oil palm strongly reduce GHG emissions compared with fossil fuels (Figure 2.4), again, this may be attributed to the use of crop residues as the main source of processing energy. Low fertiliser applications, especially in soybean cultivation, reduce emissions from fertiliser production. Systems relying on the other crops produced higher GHG emissions, with maize ethanol producing even higher GHG emissions than gasoline, on average.

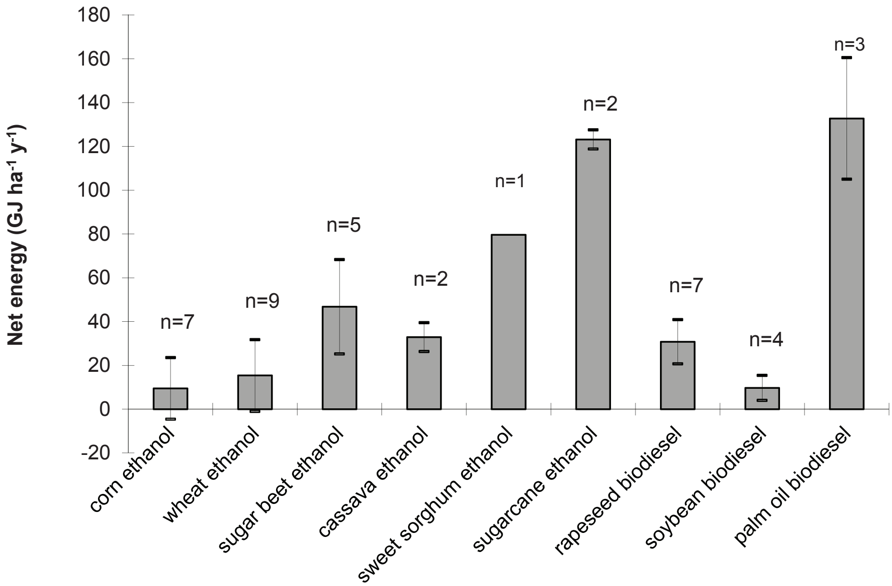


Figure 2.3 *Average net energy production (GJ ha^{-1}) of the assessed systems, based on source publications listed in the Appendix.Definition and calculation are explained in Section 2.2.1.*

2.3.3 The (agro-) environment

Soil erosion.

Based on USLE C-factors and reviewed literature, we ranked the feedstock crops that we consider in order of decreasing soil erosion hazard as follows: cassava > soybean > sugarcane > sorghum > maize > sugar beet > winter wheat > oil palm > winter rapeseed.

Winter wheat, and to a lesser extent sugar beet, develop their foliage early in the season, hence protect the soil during the summer season when rains are often most erosive; for maize this is much less the case. This was confirmed by a comparison of USLE C-factors (Gabriels et al., 2003; Wischmeier and Smith, 1978). Under a completely developed canopy, soil loss ratios were lowest for wheat and highest for maize, sugar beet was intermediate. Winter varieties of rapeseed and canola can provide more than 80% ground cover during the winter (Haramoto and Gallandt, 2004), compared with less than 50% in winter wheat during this period (Gabriels et al., 2003). Therefore, erosion in rapeseed is expected to be less than in winter wheat.

Over a 50-month period, Putthacharoen et al. (1998) determined erosion losses for a number of tropical crops, grown in replicated plots on 7% slope on a sandy loam soil in Thailand. Crops can be ranked in order of decreasing erosion as follows: cassava > sugarcane > sorghum > maize (residues of all crops were returned to the field).

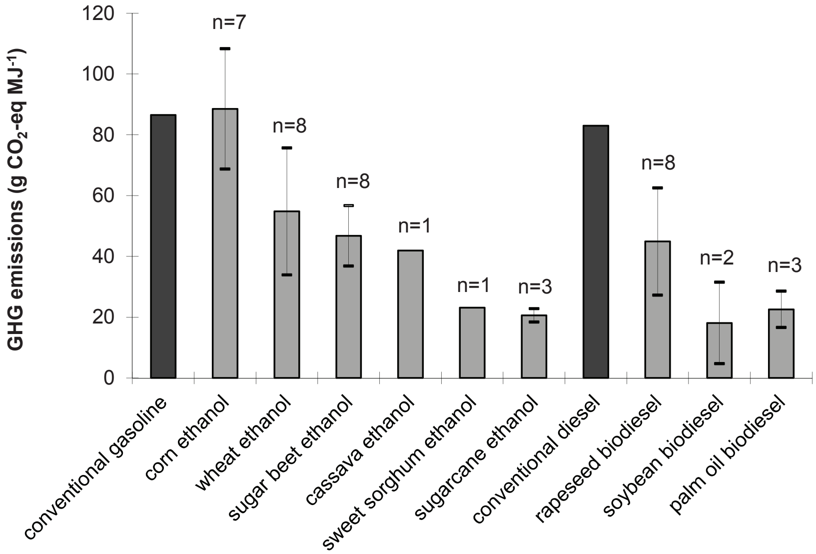


Figure 2.4 *Average GHG emissions from the assessed biofuel production systems (g CO_2 eq. MJ^{-1}; based on source publications listed in the Appendix). Details on calculations are provided in Section 2.2.2.*

The place of sugarcane in this list depends on ratoon practices: if the crop is ratooned several times, long-term soil losses are less than under short-cycle (annual) crops (Putthacharoen et al., 1998). Also, where a longer wet season permits the planting of two successive crops in one year, more frequent land preparation and weeding tend to increase soil losses from short-cycle crops (Putthacharoen et al., 1998). Taking this into account, based on Quintiliano et al. (1961), cited by Howeler et al. (2000), we ranked the (sub) tropical arable crops as: cassava > soybean > sugarcane ~ maize.
Soil erosion is generally less severe in land-use systems with perennial crops than under annual cropping simply because the soil is covered throughout the whole year (Hartemink, 2006). Under conditions rather similar to those encountered by Putthacharoen et al. (1998) and a slope of 9% instead of 7%, Maene et al. (1997) mention measured erosion rates in oil palm about half of those found for maize (Putthacharoen et al., 1998); with similar slopes the difference might have been larger. Based on Mattsson et al. (2000), erosion in oil palm is normally higher than in rapeseed, however.

Soil organic matter
Estimates of the EOM obtained from the temperate crops are displayed in Table 2.2. These figures are valid for conditions in the Netherlands, where it is assumed that each year, some 1.6 – 2.0 tonnes of (dry) organic matter are mineralised in arable land, and that sustainable crop rotations should provide at least this quantity of organic matter

(Hanegraaf et al., 2007). Annual decomposition rates of organic matter in arable land in the Netherlands are estimated at 2-3% (Vleeshouwers and Verhagen, 2002), with the average SOM content in a similar range. In tropical areas, higher temperature and relative humidity may acvcelerate decomposition, hence more organic matter is needed to prevent decline.

Table 2.2 shows that under these assumptions only oil palm, winter wheat and maize produce enough residues to prevent a decline in soil organic matter, provided the crop residues are left in the field. For winter wheat, sugar beet and winter rapeseed the estimations have been derived directly from the references listed in the table; below we underpin the estimates for the remaining crops.

Compared with other tropical farming systems, the amount of above ground organic residues (pruned fronds) returned to soil in oil palm plantations is large at about 10-15 t ha^{-1} y^{-1} of dry matter (DM) (Fairhurst and Mutert, 1997; Santoso, 1996) and exceeds the basic requirement of about 8 t ha^{-1} yr^{-1} of DM to sustain soil organic matter concentrations in humid tropical environments (Fairhurst and Mutert, 1997). Assuming a humification coefficient of 0.20, addition of 12.5 t DM of pruned fronds and 1.4 t ha^{-1} (DM) of empty fruit bunches (Wood and Corley, 1991) would yield about 2.8 t ha^{-1} of EOM. With a yield of 8.2 t ha^{-1}, maize may provide sufficient EOM in temperate areas if

Table 2.2 *Estimated Effective Organic Matter (EOM) obtained from feedstock crops assuming average yields as in Table 2.1. Estimates for cassava and sweet sorghum are not related to yield estimates but based on those for sugarcane and maize.*

	Fresh yield (t ha^{-1})	EOM (t ha^{-1} of DM)
Oil palm	18.0 (fresh fruit bunches)	2.8
Winter wheat	8.2	2.3
Maize (grains)	8.2	2.1
Sugar beet (incl. leaves and beet tops)	61.2	1.2
Sugarcane	74.4	0.9
Winter rapeseed	3.4	0.9
Cassava	(EOM estimate related to sugarcane value, refer to Table 2)	< 0.9
Sweet sorghum	(EOM estimate related to maize/ sugarcane values, refer to Table 2)	0.8*
Pea (assumed comparable to soybean)	5.7	< 0.8*

stover is not harvested; this claim is supported e.g. by Blanco-Canqui and Lal (2007). However, in tropical areas, probably more than 2.1 t ha^{-1} of EOM is required while (residue) yields are often smaller.

Sugarcane production with 'trash' (foliage) burning returns virtually no organic matter to the system (Garside, 1997). No consensus exists on EOM supply if trash is retained. From Robertson (2003) we calculated an EOM of between 0.1 and 2.3 t ha^{-1} of DM with a fresh cane yield of 100t ha^{-1}. Given a lower yield of 74 t ha^{-1} (Table 2.1), maximum EOM supply would be 1.7 t ha^{-1} of DM (assuming the same residue/product ratio); not enough to compensate for the decomposition in tropical climates.

Several studies have reported negative soil carbon balances for continuous cassava cultivation (Hairiah et al., 2005; Shirato et al., 2005). The balance was reported to be more negative than for sugarcane (Howeler et al., 2000; Vityakon, 2007). Smaller quantities of residues produced by cassava and frequent and severe soil disturbance are the likely underlying causes (Hairiah et al., 2005).

We assume the amount of crop residues (trash) obtained from sweet sorghum to be similar to or lower than that from sugarcane, since its biomass production is generally smaller. If foliage is removed/burnt we expect it to give a similar amount of residues as silage maize (0.7 t ha^{-1} of DM; (Timmer et al., 2004)), In Table 2.2, the average of these two values is given.

For soybean, no figure was available. Therefore, we assumed its EOM to be similar to that of pea, although this is probably optimistic, as biomass production of pea is higher than that of soybean, while harvest indices are similar (Lecoeur, 2001).

Risk of soil borne diseases
We ranked the feedstock crops in order of decreasing vulnerability to soil-borne diseases, based on the information below. The highest impact was attributed to rotation constraints (sugar beet, rapeseed), followed by yield reduction (crops were ranked in order of decreasing yield reduction). This resulted in the following ranking: sugar beet > rapeseed > cassava > wheat > soybean > maize ~ sweet sorghum > oil palm > sugarcane.

Two important soil-borne problems in sugar beet production are the beet cyst nematode (*Heterodera schachtii*) and rhizomania (Märländer et al., 2003). The former may become problematic in crop rotations that include beet at least every third year or more; since rapeseed is an alternative host (Märländer et al., 2003), it cannot be rotated with sugar beet. Rhizomania causes substantial reductions in yield and quality of sugar beet crops and is very persistent once a field has been infected. Apart from the fact that rapeseed should not be grown in rotation with sugar beet due to the earlier mentioned nematode problem, it is affected by clubroot (*Plasmodiophora brassicae*), if grown too frequently.

Cassava bacterial blight (CBB), caused by the bacterium *Xanthomonas campestris*, is a major constraint to cassava cultivation worldwide; yield losses due to CBB in Africa in the 1990's are estimated up to 7.5 million tonnes (Wydra and Verdier, 2002); this is around 10% of the annual African cassava production (FAO, 2007). However, an interval of 6 months is already sufficient to prevent carry-over of the pathogen in the soil (Lozano, 1986), and the use of clean planting material may stop it from spreading.

Take-all disease (*Gaeumannomyces graminis*), rhizoctonia root rot (*Rhizoctonia solani*) and pythium root rot (*Pythium* spp.) are soil-borne diseases in wheat which are favoured by a lack of crop rotation (Cook and Haglund, 1991) and presence of wheat residues (Bockus and Shroyer, 1998). Three-year rotations are often considered the safest practice in wheat production, especially where reduced tillage is common (James Cook, 1992; Lipps et al., 2008).

In the north central regions of the United States, maize and soybean have been grown in rotation with each other for decades (Zhang and Yang, 2000). However, this practice may reduce yields. A 10-year field study by Porter et al. (1997) indicates an approximately 8% lower yield of soybean grown in continous rotation with maize compared to first-year soybean after multiple years of maize. For maize the effect was less significant: first year maize after multiple years of soybean yielded only 1-2% more than maize in continuous rotation with soybean. Sorghum occupies a similar niche in agriculture as maize (Aref and Pike, 1998) and shares several of its soil borne diseases (e.g. rhizoctonia root rot, *Pythium* spp., *Fusarium* spp.).

Basal stem rot (BSR) caused by *Ganoderma boninense* remains the most significant constraint to sustainable oil palm production in South East Asia ; debris left in the field from the previous crop is a very important source of infection (Flood et al., 2005). In comparison to some other crops discussed here, the relative damage is limited: in 2008, an estimated three percent of the Malaysian oil palm acreage was affected (Anonymous, 2008). Provided that sugarcane cropping cycles (which may last several years, depending on the number of ratoon crops) are alternated with legume crops, pasture or fallow, as is currently done in Australia (Stirling, 2008), little evidence of serious problems was found in the literature.

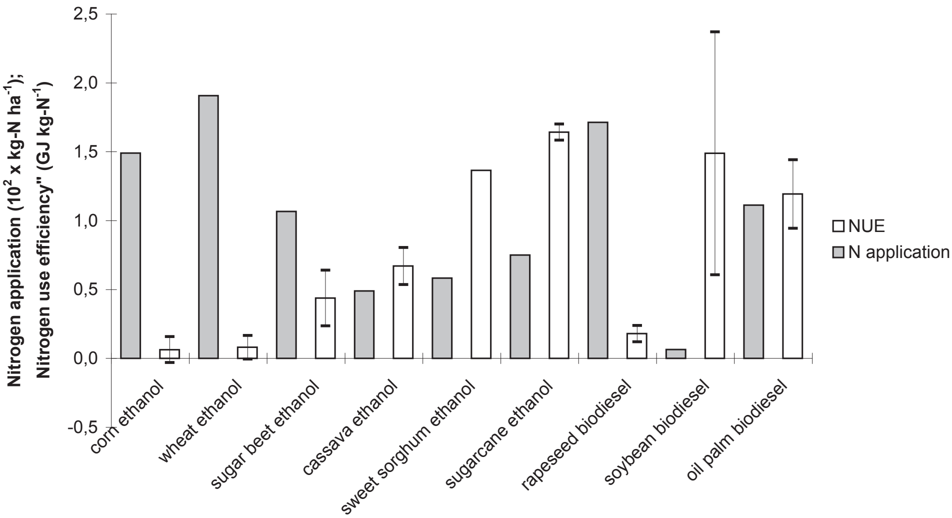


Figure 2.5 *Nitrogen use efficiency (GJ kg^{-1} of N, Equation 2.1) and nitrogen application (10^2 x kg ha^{-1} of N) of the assessed biofuel production systems, based on average data from source publications (Appendix).*

Eutrophication

Nitrogen use efficiencies (NUEs) of several first generation biofuel production systems are displayed in Figure 2.5. Although a large share of the variation may be attributed to differing net energy estimates (Figure 2.3), soybean performed well on this indicator due to its ability to fix nitrogen from the atmosphere in symbiosis with rhizobium bacteria: it needs little fertiliser. All temperate first generation crops analysed here perform poorly, due to high-input cultivation practices and low net energy production. Some undesirable properties of these crops from the perspective of biofuel production are relatively low harvest indices and relatively high protein content (hence high nitrogen requirement), either in the product (wheat grains) or in the residue (sugar beet foliage).

Pesticide usage

For most crops reviewed, pesticide application rates were between 3 and 5 kg ha^{-1} of a.i. with rapeseed and soybean being exceptions: they generally receive applications between 1 and 2.5 kg ha^{-1} of a.i.. Hence most of the differences in PUE in Figure 2.6 were determined by differences in net energy yield (Figure 2.3).

Water use

Figure 2.7 displays values of WPB that were calculated according to Equation (3). Similar to the described trends for NUE and PUE, biofuel production from oil palm,

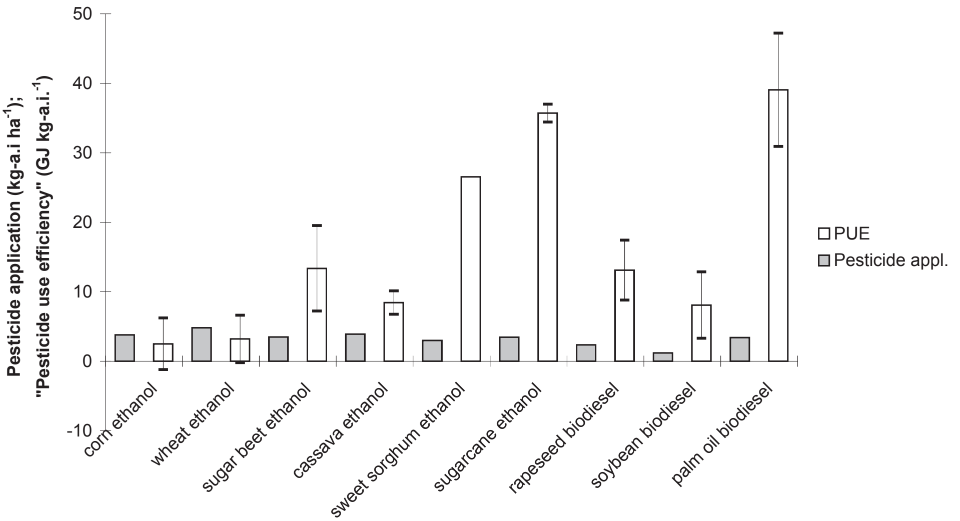


Figure 2.6 *'Pesticide use efficiency' (Equation 2.2) and pesticide application (kg ha^{-1} of a.i.) of the assessed biofuel production systems, based on average data from source publications (Appendix).*

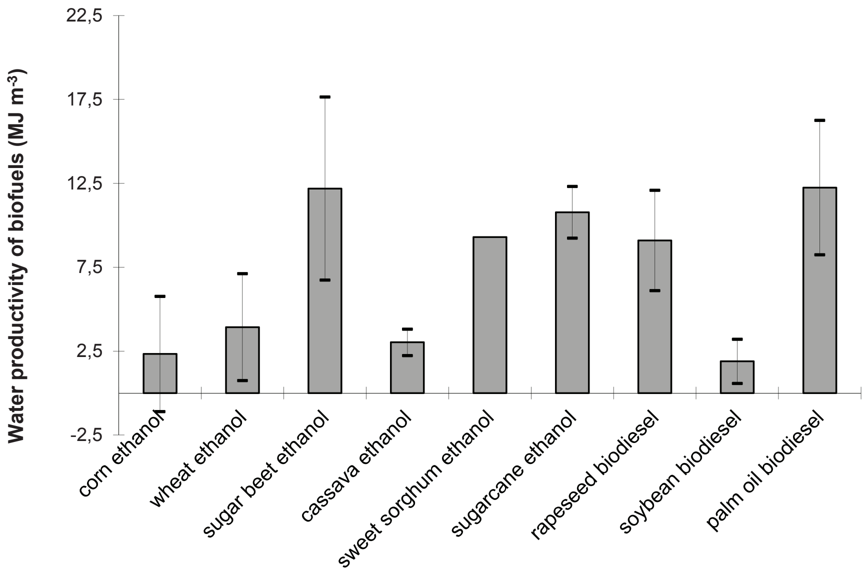


Figure 2.7 *Water productivity of the assessed biofuel production systems (GJ m^{-3}, Equation 2.3).*

sweet sorghum and sugarcane was relatively water efficient. It is striking that sugar beet and rapeseed also performed relatively well. Sugar beet is characterised by a high (fresh) biomass production per volume of water consumed: about double that of sugarcane. However, net energy production of sugar beet ethanol is relatively low, due to consumption of large quantities of fossil fuels during processing while in contrast, energy required for processing of sugarcane is mostly supplied by crop residues (bagasse). Rapeseed can hardly be called a water efficient crop (Table 2.1); the favourable WUE that characterises its biofuel product may be attributed to a favourable net energy yield of 9.1 GJ per tonne of processed rapeseed.

Comparison of the assessed systems, attributing equal importance to all indicators
We indexed the obtained values for each indicator (except GHG emissions) in percentages relative to the best (i.e. most sustainable) value found for that indicator across all crops, valued 100. However, GHG emission reduction (in percentages) were calculated relative to those of the replaced fossil fuels. For the soil erosion hazard indicator, the crop with the greatest soil erosion hazard (cassava) received a score of 10, while the best performing crop in our assessment (oil palm) received a score of 90. The other crops were ranked equidistantly in between. The same approach was applied for soil borne diseases where sugar beet received a value of 10 and sugarcane was valued 80, indicating that the latter crop is not entirely free from soil borne diseases. The values obtained in this way are displayed in Figure 2.8. Polygon areas in these figures are correlated to the overall sustainability based on our nine indicators; each indicator exerts the same amount of influence on the area, and thus all are represented as being equally important.

2.4 Discussion and conclusion

The set of indicators that we employed is not exhaustive and therefore, definite conclusions on the sustainability of the assessed biofuel production systems cannot be drawn. Important issues relating to social and economic sustainability, land use change, biodiversity and habitat destruction have not been taken into account. Some emissions which are estimated in life cycle analysis (e.g. ozone formation, emission of fine particles and NO_x) were ignored since, apart from the energy and GHG indicators, we narrowed our focus to the agricultural production systems.

With respect to the set of nine production-ecological indicators (Figure 2.8), biofuel production from oil palm, sugarcane and sweet sorghum appeared most sustainable. High net energy yields per hectare are obtained from these systems, which result in good nitrogen use efficiency, pesticide use efficiency and water productivity, and imply efficient use of land resources. With production of the same amount of net energy, more resources may be left for e.g. production of food, compared with the other systems. In addition, GHG emissions are greatly reduced compared with fossil fuels, provided these reductions are not overruled by carbon emissions from land use change (Fargione et al., 2008). There is also a trade-off: residues of oil palm, sugarcane and sweet sorghum are combusted for processing energy, while in the latter two cases, not enough are supplied to the soil for maintenance of SOM. Instead of generating excess energy and exporting it to the grid (Gnansounou et al., 2005; Macedo et al., 2004), it could be more advisable to return sufficient bagasse to the field for maintenance of soil quality and to use the remainder for power generation.

In temperate areas, first generation biofuels from wheat and maize ethanol appear not sustainable, especially since they hardly meet their prime goals: reduction of fossil energy use and GHG emissions. For maintaining soil organic matter and soil erosion (in the case of wheat), they perform relatively well. Relatively low harvest indices of these crops imply production of large quantities of residues but, on the other hand, are unfavourable with respect to energy efficiency, nitrogen use efficiency, pesticide use efficiency and water productivity. Sustainability of wheat- and maize-based systems could be improved by leaving enough straw in the field for maintaining SOM and using the remainder (Blanco-Canqui and Lal, 2007) for the supply of processing energy, similar to e.g. sugarcane. Although their net energy yields are generally modest, sugar beet ethanol and biodiesel from rapeseed and soybean are relatively water efficient, while soybean biodiesel is also highly nitrogen efficient. Due to its small N fertilisation requirement, soybean is the only crop with low net energy yield and a high energy ratio; for the other systems a strong correlation exists between the two, hence one energy indicator would be sufficient. Estimates of energy consumption and GHG emissions generally varied widely for all crops, demonstrating that there is still little consensus among authors in this respect.

Compared with our base-case estimates, introduction of reduced tillage practices may reduce energy use, soil erosion and SOM decomposition in arable crops. In cassava and oil palm, planting cover crops and application of crop residues may reduce soil erosion (Howeler et al., 2000; Kee and Chew, 1996; Suharmoko et al., 2007), on steeper slopes, construction of contour bunds or terraces may be advisable (Caliman and De Kochko, 1987). Planting legumes in rotation with e.g. cereals may improve the energy balance of the cereals (Nemecek et al., 2008). Depending on their economic value, residues may be left in the field, contributing to the build-up of SOM and erosion control, or be used for other purposes, including energy generation. Energy ratios can, if financially worthwhile, further be improved by introducing biogas production from wastewater, combined heat and power (CHP) generation and by using crop residues or other biomass as fuel (LBST, 2002; Punter et al., 2004). This could improve sustainability of biofuel production from temperate annual crops and cassava vis-à-vis that from oil palm, sweet sorghum and sugarcane, where CHP and combustion of residues is already common practice.

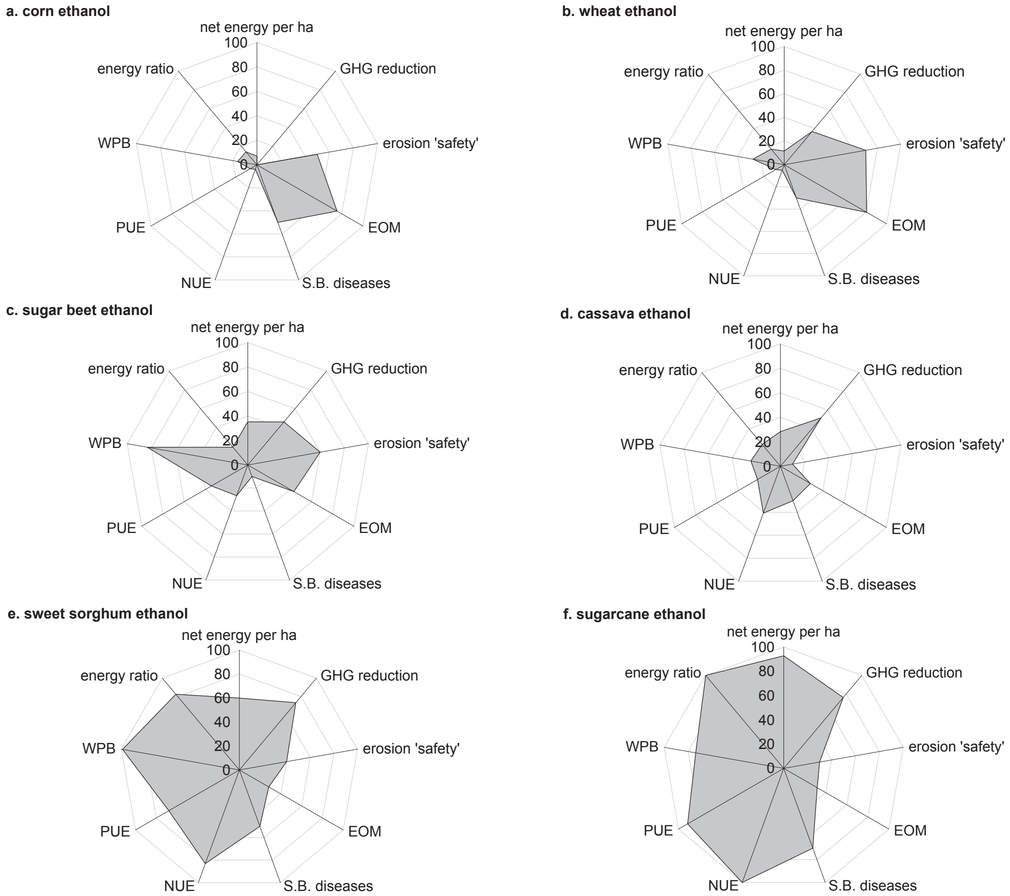


Figure 2.8 *Relative sustainability of the assessed systems, based on nine indicators. Values are indexed in percentages relative to the best (i.e. most sustainable) indicator value found for that indicator across all nine systems. 'GHG reduction' is emission reduction relative to replaced fossil fuels. 'Soil erosion' and 'soil borne diseases' (S.B.) indicators have been ranked.*

Although the sustainability of temperate first generation biofuels can certainly be improved, it is the question whether this is desirable: it may be more sustainable and economically sound for countries in the North to import biofuels from e.g. Brazil or Southeast Asia, since transport costs, GHG emissions and energy requirements are generally small (Hamelinck et al., 2005). In our assessment, the biofuels produced in those regions are currently more sustainable with respect to the use of (natural) resources. Depending on technology development, sooner or later the second generation (ligno-cellulosic) biofuels will become a viable alternative in temperate regions. For instance, the net energy yield of ethanol from switchgrass (*Panicum*

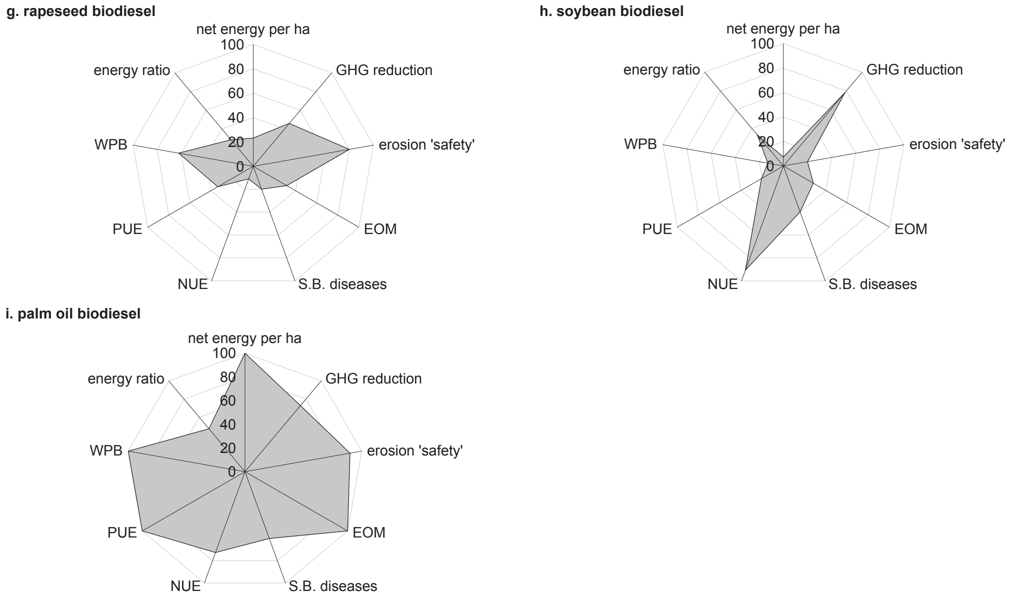


Figure 2.8 - continued

virgatum) is estimated at 60 GJ ha^{-1} y^{-1} (Schmer et al., 2008), more than all temperate options that we assessed, while use of fertilisers and pesticides on a hectare basis is much less.

Appendix I - Consulted Source Publications by Feedstock Crop

	Net energy, energy ratio, GHG emissions, eutrophication	Soil erosion	Soil organic matter	Soil borne diseases	Pesticide usage	Water use
Ethanol						
Maize	Farrell et al., 2006	Based on USLE 'C-factor' and rainfall erosivity data (Gabriels et al., 2003; Wischmeier and Smith, 1978)	Mulier et al., 2006	Porter et al., 1997	Kleter et al., 2007	Chapagain and Hoekstra, 2004
Wheat	ADEME, 2002; Armstrong et al., 2002; Department for Transport, 2007; Edwards et al., 2007; Elsayed et al., 2003; Malça and Freire, 2006; Mortimer et al., 2004; Punter et al., 2004; Richards, 2000	Based on USLE 'C-factor' and rainfall erosivity data (Gabriels et al., 2003; Wischmeier and Smith, 1978)	Hanegraaf et al., 1998	Bockus and Shroyer, 1998; Cook and Haglund, 1991; James Cook, 1992; Lipps et al., 2008	Webster et al., 1999	Chapagain and Hoekstra, 2004
Sugar beet	ADEME, 2002; Armstrong et al., 2002; Cariolle and Molard, 2004; Department for Transport, 2007; Edwards et al., 1992; Elsayed et al., 2003; LBST, 2002; Malça and Freire, 2006; Mortimer et al., 2004	Based on USLE 'C-factor' and rainfall erosivity data (Gabriels et al., 2003; Wischmeier and Smith, 1978)	Timmer et al., 2004	Märländer et al., 2003	Cariolle and Molard, 2004; Naaktgeboren and van Swaaij, 2007	Chapagain and Hoekstra, 2004
Cassava	Nguyen et al., 2007a; Nguyen et al., 2007b	Putthacharoen et al., 1998	Based on comparison with sugarcane (Howeler et al., 2000; Vityakon, 2007)	Wydra and Verdier, 2002	Nguyen et al., 2007a	Chapagain and Hoekstra, 2004

	Net energy, energy ratio, GHG emissions, eutrophication	Soil erosion	Soil organic matter	Soil borne diseases	Pesticide usage	Water use
Ethanol						
Sweet sorghum	Gnansounou et al., 2005; Macedo et al., 2004; TNAU, 2007; Worley et al., 1992	Putthacharoen et al., 1998	Assumed between sugarcane (Robertson, 2003) and silage maize (Timmer et al., 2004)	Aref and Pike, 1998	Worley et al., 1992	Chapagain and Hoekstra, 2004
Sugar-cane	Dias de Oliveira et al., 2005; Macedo et al., 2004; Patzek and Pimentel, 2005	Putthacharoen et al., 1998	Robertson, 2003	Stirling, 2008	(Dias de Oliveira et al., 2005; Patzek and Pimentel, 2005)	Chapagain and Hoekstra, 2004
Bio-diesel						
Rape-seed	ADEME, 2002; Armstrong et al., 2002; Department for Transport, 2007; Edwards et al., 2007; Kaltschmitt et al., 1997; LBST, 2002; Mortimer et al., 2003; Richards, 2000; Scharmer, 2001	Based on comparison of rapeseed soil cover (Haramoto and Gallandt, 2004) with that of wheat (Gabriels et al., 2003)	Timmer et al., 2004	Märländer et al., 2003	Kempenaar et al., 2003; McManus et al., 2003	Chapagain and Hoekstra, 2004
Soybean	Ahmed et al., 1994; Department for Transport, 2007; Hill et al., 2006; Huo et al., 2008; Sheehan et al., 1998; Smith et al., 2007	Howeler et al., 2000	Assumed similar to pea (Mulier et al., 2006; Timmer et al., 2004)	Porter et al., 1997	Kleter et al., 2007	Chapagain and Hoekstra, 2004
Oil palm	Pleanjai and Gheewala, 2009; Reinhardt et al., 2007; Wicke et al., 2007; Wood and Corley, 1991	Maene et al., 1997; Mattsson et al., 2000	Calculated from Fairhurst and Mutert (1997) and Santoso (1996)	Anonymous, 2008; Flood et al., 2005	Palaniappan et al., 2004; Wood and Corley, 1991	Chapagain and Hoekstra, 2004

chapter 3

The production-ecological sustainability of cassava, sugarcane and sweet sorghum cultivation for bioethanol in Mozambique

We present an approach for providing quantitative insight into the production-ecological sustainability of biofuel feedstock production systems. The approach is based on a simple crop-soil model and was used for assessing feedstock from current and improved production systems of cassava for bioethanol. Assessments were done for a study area in Mozambique, a country considered promising for biomass production. Our focus is on the potential role of smallholders in the production of feedstock for biofuels. We take cassava as the crop for this purpose and compare it with feedstock production on plantations using sugarcane, sweet sorghum and cassava as benchmarks. Production-ecological sustainability was defined by seven indicators related to resource use efficiency, soil quality, net energy production and greenhouse gas emissions. Results indicate that of the assessed systems, sugarcane performed better than cassava, although it requires substantial water for irrigation. Targeted use of nutrient inputs improved sustainability of smallholder cassava. Cassava production systems on more fertile soils were more sustainable than those on less fertile soils; the latter required more external inputs for achieving the same output, affecting most indicators negatively and reducing the feasibility for smallholders. Cassava and sweet sorghum performed similarly. Cassava production requires much more labour per hectare than production of sugarcane or sweet sorghum. Production of bioethanol feedstock on cultivated lands was more sustainable and had potential for carbon sequestration, avoiding GHG emissions from clearing natural vegetation if new land is opened.

This chapter was published as:
De Vries SC, Van de Ven GWJ, Van Ittersum MK, Giller KE (2012). The production-ecological sustainability of cassava, sugarcane and sweet sorghum cultivation for bioethanol in Mozambique. GCB Bioenergy 4:20-35.

3.1 Introduction

The importance of biofuels is increasing rapidly, mainly due to renewable energy targets in transport set by several governments (e.g. European Parliament, 2009; U.S. Congress, 2005). One country considered promising for biomass production is Mozambique, due to its relative abundance of land resources, favourable environmental conditions and low population density (Batidzirai et al., 2006); only one-sixth of its 30 million hectares of arable land are currently cultivated (Arndt et al., 2009). Although it is one of the fastest growing economies in sub-Saharan Africa and poverty rates are dropping, Mozambique is still among the world's poorest countries (Schut et al., 2010). Biofuels investment may help enhancing growth and poverty reduction, although food prices may also increase due to competition for land and labour (Arndt et al., 2009). Mozambique is listed as a country where there is high risk of deteriorating food security due to increased food prices (FAO, 2008). Apart from pressing policy questions that these issues raise, the environmental implications of large-scale biofuels production also matter for the sustainability of an emerging biofuels sector and of Mozambican agriculture in general. Changes in relative or absolute acreage of different biomass crops may impact production-ecological sustainability in different ways. Two examples: first, cultivation of sugarcane (*Saccharum officinarum* L.) relies on irrigation in Mozambique, and there are competing demands for the available water resources (Cheesman, 2004). On the other hand, sugarcane with so-called green cane trash blanketing contributes to carbon sequestration and improved soil quality through increase in soil organic carbon (SOC) content (Razafimbelo et al., 2006; Robertson and Thorburn, 2007). Secondly, cultivation on slopes of cassava (*Manihot esculenta* Crantz), a starch crop that may be used for producing bioethanol (cf. Dai et al., 2006), generally causes more erosion on an annual basis than other crops grown under the same circumstances (Howeler et al., 2000). On the other hand, it is a low-cost feedstock and has a pro-poor profile (Arndt et al., 2010; Econergy et al., 2008).

In this study, we examine the production-ecological sustainability of current and improved cropping and management options in Mozambique. Our focus is on the potential role of smallholders in the production of feedstock for biofuels. We take cassava as the crop for this purpose and compare it with feedstock production on plantations using sugarcane, sweet sorghum and cassava. Cassava was chosen because of its pro-poor profile (Arndt et al., 2010), its low cost (Econergy et al., 2008) and because it is a crop that is familiar to Mozambican smallholders (Worldbank, 2006). Sugarcane and sweet sorghum were selected due to existing interest from investors (Schut et al., 2010) and scientists, and they are among the officially approved biofuel crops in Mozambique (Conselho do Ministros, 2009).

Cassava is mostly produced by smallholders (Howeler et al., 2000); in Mozambique, smallholders make up 95% of the country's agricultural GDP and few use any fertilisers or other inputs (ca. 4%; Worldbank, 2006). Yields are mostly low (on average 6.5 Mg ha^{-1} over 2003-2007; FAO, 2010) or, where they are higher, soil fertility is effectively mined (Folmer et al., 1998).

Sugarcane, contrary to cassava, is currently mostly grown on large-scale plantations with a high degree of mechanisation where substantial amounts of inputs are normally used, particularly water and fertilisers (Cheesman, 2004). Sweet sorghum has been researched as a sugarcane 'off-crop' for sugarcane plantations, since it is often able to produce sugar at times when sugarcane does not accumulate enough sugar for harvesting due to its photoperiod sensitive nature (Woods, 2000). It then presents an opportunity to utilise otherwise idle equipment (e.g. the sugarmill).

Using the methods of Chapter 1, we concentrated on sustainability indicators relating to energy use and the quality of soil and water resources, and their ability to sustain agricultural production. The indicators that we employed are relevant within the 'Principles and Criteria for Sustainable Biofuel Production' set by RSB (2009) and comprise greenhouse gas emissions (Principle 3, GHG emissions) , soil organic matter (Criterion 8.a.1), water productivity (Criterion 9.c.), nitrogen leaching (Criterion 9.d.), soil erosion (Criterion 8.a.1.), employment creation (Criterion 5.a.), net energy yield and nitrogen use efficiency.

3.2 Methods

3.2.1 Study sites

The assessment was conducted for three locations in Mozambique. For smallholder cassava we selected Gafaria (15°43'S, 37°38'E, 600 m.a.s.l., sandy clay loam) and Nacuaca (15°41'S, 37°49'E, 500 m.a.s.l., loamy sand), two villages in Alto Molocue district, Zambezia province which is an important cassava producing region. For plantation-scale cultivation of sugarcane, sweet sorghum and cassava we selected Dombe village, Sussundenga district, Manica province (19°58'S, 33°23'E, 150 m.a.s.l., sand). An extensive new sugarcane plantation has been established here that specifically aims at the production of bioethanol (Principle Energy, 2009). In all locations soil samples were collected and analysed in the soil laboratory of Eduardo Mondlane University, Maputo for pH, soil organic carbon (SOC), total N, exchangeable K, CEC, P Olsen and soil texture (Table 3.1).

***Table 3.1** Average characteristics for the three study sites (standard deviations in parentheses)*

		Gafaria (n = 58)		Nacuaca (n = 76)		Dombe (n = 2)
Rainfall	mm	1416		1416		1079
Soil type		Sandy clay loam		Loamy Sand		Sand
clay	%	25.08	(8.65)	12.53	(7.07)	8.42
silt	%	7.82	(5.22)	6.55	(4.01)	2.12
sand	%	67.11	(10.17)	80.92	(8.11)	89.46
pH H_2O	-	5.68	(0.53)	5.87	(0.36)	6.10
C	g kg^{-1}	10.69	(4.8)	8.53	(2.97)	8.35
N	g kg^{-1}	1.32	(0.31)	1.06	(0.38)	1.20
K	$cmol^+ kg^{-1}$	0.45	(0.17)	0.19	(0.13)	0.18
H^++Al^{3+}	$cmol^+ kg^{-1}$	3.30	(1.34)	3.27	(1.79)	1.75
ECEC	$cmol^+ kg^{-1}$	9.77	(2.73)	9.56	(3.17)	7.42
P	mg kg^{-1}	20.6	(21.1)	35.3	(37.8)	16.0

3.2.2 Assessed cropping systems and crop management options

For smallholder cassava production we assessed a current production system without fertilisation and improved systems with fertilisation and/or residue mulching (Table 3.2). Introduction of irrigation and agricultural machinery were not considered feasible for smallholders. All fertiliser rates for cassava in Table 3.2 are sufficient to overcome yield limitations of macro-nutrients and were formulated based on a simulation exercise carried out before the actual assessment. We estimated that 70% of the cassava residues were available for mulching and the remainder required as planting material.

In plantations, cassava is usually grown with substantial inputs (cf. Dai et al., 2006). We assessed a production system (Table 3.2) where sufficient fertilisers are applied for removing yield limitations by macro-nutrients and included two types of irrigation, drip and surface irrigation. Agricultural operations were assumed to be carried out mechanically, except harvesting.

For sugarcane (Table 3.2), we assessed two fertiliser rates, three types of irrigation (drip, pivot and furrow) and two residue management strategies (residue mulching, commonly called 'green cane trash retention' and residue burning). Mulching is normally combined with mechanical harvesting (Wood, 1991) and residue or trash burning with manual harvesting. Agricultural operations other than harvesting were assumed to be mechanised.

Table 3.2 *Crop management of the assessed production systems of cassava, sugarcane and sweet sorghum*

Crop	Location	Crop yield Mg ha^{-1}	Fertilisation (kg ha^{-1} of N:P:K)	Irrigation	Mulching of residues?	Harvesting	Other agricultural operations
			0:00:00		N		
Cassava	Gafaria	Simulated			Y		
			40:150:0		N		
				-	Y	Manual	Manual
			0:00:00		N		
	Nacuaca	Simulated			Y		
			100:150:200		N		
					Y		
				470 mm drip			
	Dombe	Simulated	200:300:400		Y		Mechanised
				750 mm surface			
					N	Manual	
Sugarcane	Dombe	76	120:40:200	-			
					Y	Mechanised	
				650 mm furrow			
				380 mm pivot	N	Manual	
				340 mm drip			
				-			
		100	170:60:285				
				650 mm furrow			
				380 mm pivot	Y	Mechanised	
				340 mm drip			
				-			
Sweet sorghum	Dombe	46	90:60:60	-	Y	Manual	

Only one sweet sorghum production system was assessed due to limited data: fertilised, rainfed cultivation (Table 3.2). Rainfall during the rainy season is normally sufficient to attain a good sweet sorghum yield and if irrigation is available, sugarcane is the preferred crop. In Mozambique, the optimal time for sweet sorghum harvesting coincides with the end of the rainy season and the soil generally is too wet to allow any machinery in-field, hence we assumed manual harvesting. In addition, at that time the leaves are still green and not burnt. Therefore they must be removed before transporting the stalks to the mill (Woods, 2000) and we assumed they are left in the field as mulch.

3.2.3 Crop production

Response of cassava production to crop management was simulated by a simulation model of the soil-crop system with a seasonal time step: 'FIELD' (Field-scale Interactions, use Efficiencies and Long-Term soil fertility Development; (Tittonell et al., 2010). This model satisfactorily simulated maize response to application of manure and fertilizers on smallholder farms in Kenya (Tittonell et al., 2008) and has also been applied to e.g. seed cotton and sweetpotato (Tittonell et al., 2010). A simplified representation of the structure of the crop-soil model and the way it is integrated with the calculation of the sustainability indicators (discussed in detail further on) is provided in Figure 3.1. FIELD consists of submodels for crop ('CROPSIM') and soil ('SOILSIM') that can be either used separately or combined. In this study, SOILSIM was used for all three crops, while we ran CROPSIM only for cassava, due to limited data availability for sweet sorghum and sugarcane. CROPSIM calculates crop production based on seasonal availability of light, water, nitrogen (N), phosphorus (P) and potassium (K) and their interactions. Potential yields are estimated through a radiation use efficiency approach, while the integrated effect of the relative availability of the other resources on crop productivity is calculated according to a methodology developed by Janssen et al. (1990) for N, P and K. Solar radiation data were derived from Jones et al. (2002). Resource availability in the soil is kept track of by a seasonal bookkeeping approach in SOILSIM. Crop available N, P and K are estimated from soil parameters using functions developed by (Janssen et al., 1990); N availability is strongly linked to SOC content which is simulated as the net effect of annual SOC decomposition and the addition of organic resources like crop residues. Crop available N may be further improved by addition of residues and/or fertilisers. To account for the residual effect of P fertilisers, we applied the approach described by Wolf *et al.* (1987) and Janssen et al. (1987). In their model, a labile and a stable P pool are distinguished; the model calculates the P transfers between the pools, the uptake of P by the crop, and the resulting pool sizes. Regarding soil K, we assumed that after addition of fertilisers, exchangeable K returns to its previous 'base level' within one year after application, similar to findings by e.g. Cox and Uribe (1992).

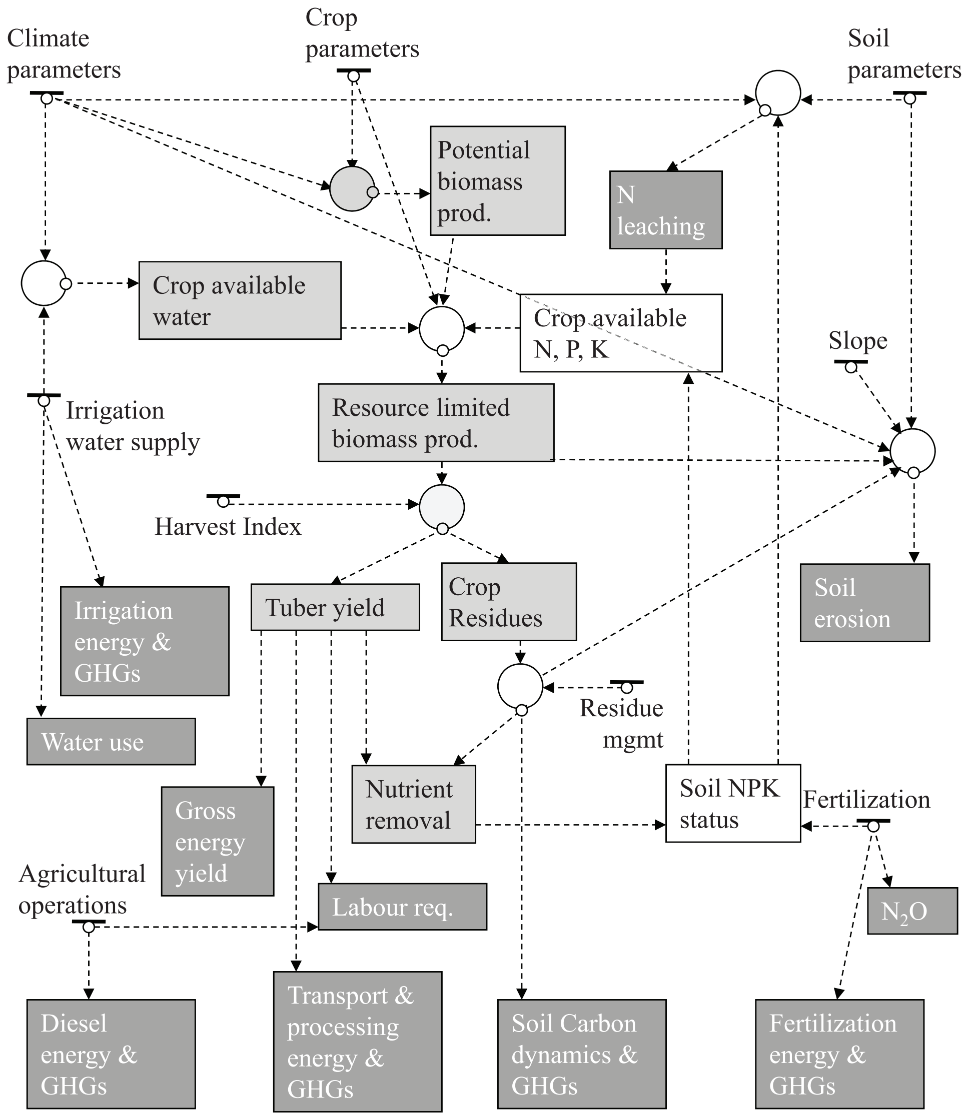


Figure 3.1 *Simplified representation of the crop-soil model ('FIELD') and the way it is integrated with the calculation of the sustainability indicators. Dotted arrows represent flows of information, circles represent calculation processes and boxes represent (intermediate) results of calculations. Dark grey boxes relate to the indicators used in this paper, light grey boxes are part of CROPSIM and white boxes belong to SOILSIM.*

Model parameters specific for cassava, e.g. minimum and maximum N, P and K contents of roots and crop residues were derived from the literature (Table 3 A1). We assumed that roots are harvested after 12 months, average practice in sub-Saharan Africa (Fermont, 2009). Using data from (Fermont, 2009), we minimised the root mean squared error (RMSE) between measured and simulated dry total cassava biomass by inverse modelling. The 'tuning' parameters comprised adjustment factors to the estimated supply of N, P and K from the soil (Janssen et al., 1990).

Simulated cassava yields for the no input systems (see Results section) were in the same range as actual yields reported for Gafaria and Nacuaca by Van den Dungen (2010). However, the yields that our model simulated are nutrient- and water limited yields in absence of pests and diseases. In the study area, estimated yield losses due to among others cassava brown streak, cassava mosaic virus and termites are between 21-33% (Van den Dungen, 2010). In this light, simulated yields seem somewhat low.

For sugarcane we lacked site-specific data for calibrating FIELD, hence instead of using the model for simulating fertiliser response, we used fixed combinations of yields and fertiliser applications (76 Mg ha $^{-1}$ of fresh cane with 120:40:200 kg ha^{-1} of N:P:K and 100 Mg ha^{-1} fresh cane with 170:60:285 kg ha^{-1} of N:P:K; Table 3.2), based on Tongaat Hulett (2010); Lewis (1984); Ndlovu (2000); Principle Energy (2009). The same approach was applied for sweet sorghum production, using data from Woods (2000): crop yield was set at 46 Mg ha^{-1} of fresh stems with fertiliser application of 90:60:60 kg ha^{-1} of N:P:K.

3.2.4 Soil organic carbon simulation

The model FIELD (Figure 3.1), in particular the SOILSIM component, was also used for simulating SOC dynamics; changes in SOC are the net effect of addition of carbon in crop residues and the ongoing decomposition of added residues and SOC. Tittonell et al. (2007) successfully used it for simulating long term soil organic carbon dynamics in agricultural soils in Zimbabwe. We used the calibration of Tittonell et al. (2007), based on chronosequence data for similar soils in Zimbabwe (Zingore et al., 2005).

In our sustainability assessments we used two sets of initial conditions: SOC contents that we actually measured in the field (Table 3.1) and simulated equilibrium SOC contents 20 years after clearing. In all simulations FIELD was run for 25 years within which new equilibriums were established in all cases.

3.2.5 Sustainability indicators

Calculation methods for the sustainability indicators are provided below. System boundaries and N, P, K and C flows of the systems assessed are displayed in Figure 3.2. For additional details and values of coefficients, see Table 3 A1.

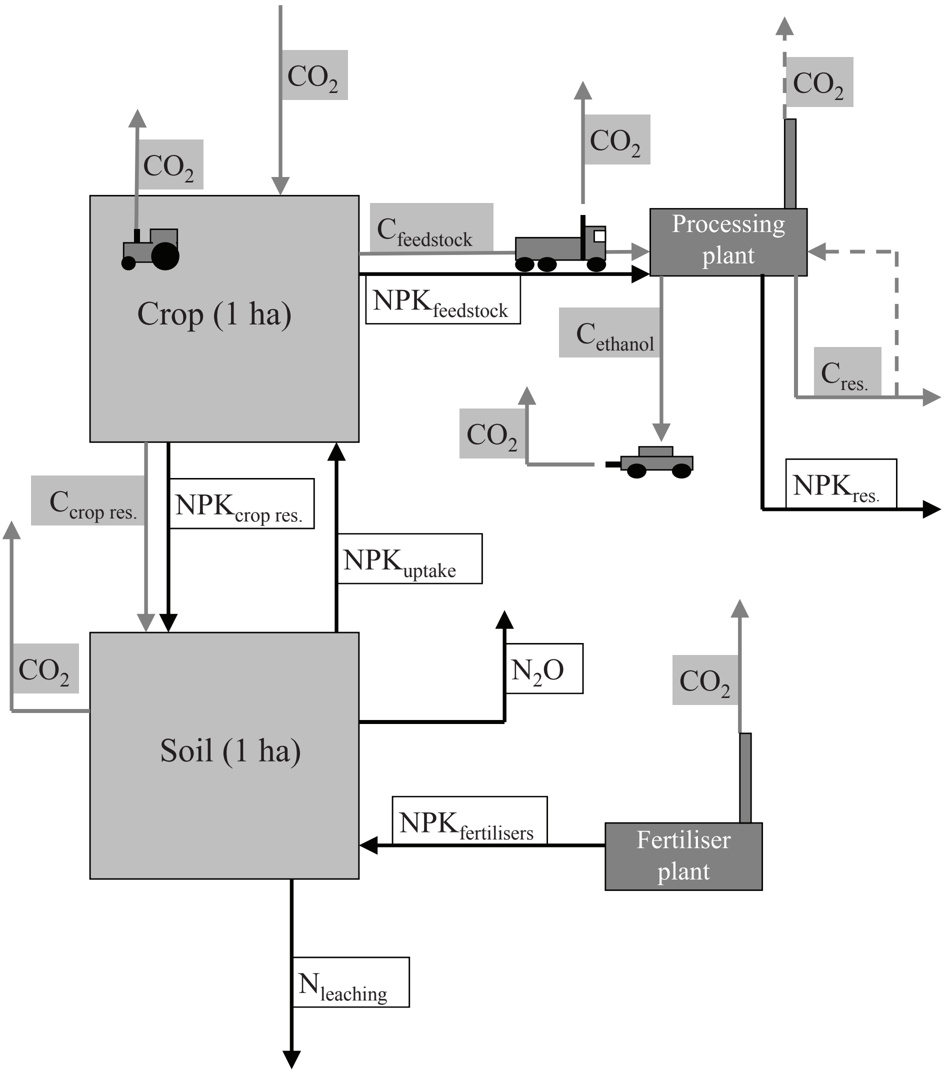


Figure 3.2 *The assessed system with the nutrient and carbon flows taken into account. Dotted lines for CO_2 emissions and cycling of residue C from the processing plant indicates that for sugarcane and sweet sorghum, processing energy is entirely supplied by residues (Res.) hence is carbon neutral while for cassava additional fossil energy is required since residues leave the system, generating additional CO_2 emissions.*

The *net energy yield per hectare* is calculated by subtracting the energy requirements for producing and transporting fertilisers, agricultural operations, pumping irrigation water, harvesting and transporting feedstock to the mill from the gross energy yield (the energy present in the produced ethanol). For conversion of feedstock into ethanol, fixed efficiencies were used: 137, 90 and 60 l ethanol Mg^{-1} of fresh product for cassava, sugarcane and sweet sorghum, respectively (Table 3 A1). It was assumed that for sugarcane and sweet sorghum, energy requirement for processing can fully be covered by burning bagasse, i.e. the biomass remaining after stalks are crushed to extract their juice (cf.Gnansounou et al., 2005; Macedo *et al.*, 2004). With cassava, only part of the processing energy requirements is met by biogas produced from the distilled mash. Taking this into account, the energy consumption for processing cassava is about 6.7 MJ l^{-1} ethanol (Nguyen et al., 2007). The effect of this extra energy requirement for cassava is demonstrated by calculating net energy with and without taking into account processing energy.

The *greenhouse gas (GHG) emissions* indicator was calculated on a *gross* energy basis (kg CO_2 eq. GJ^{-1} gross energy), similar to e.g. Farrell *et al.* (2006). We took into account emissions from production and transport of fertilisers, N_2O emissions from the soil, emissions from production and combustion of fossil fuel, and simulated net emission or sequestration of carbon by the soil (simulated by the FIELD model). Changes in aboveground carbon stocks were not taken into account. We used the annual average GHG emission over 25 years as indicator value. For cassava, processing requires additional fossil energy hence emits additional GHGs. Nguyen et al. (2007) estimated emissions from converting cassava feedstock into bioethanol at 23.5 kg CO_2 eq. GJ^{-1} ethanol.

Soil erosion (Mg soil loss ha^{-1} yr^{-1}) was estimated by implementation of the Revised Universal Soil Loss Equation (Renard et al., 1996; Table 3 A1). For sweet sorghum and sugarcane, we used annual average crop factors from literature (Table 3 A1). Cassava yielded poorly in some simulations for smallholder systems hence standard values are not applicable. Roose (1977) indicated that crop factors for cassava vary between 0.2-0.8. We assumed this factor was proportional to biomass yield, where the seasonal crop factor was estimated at 0.8 for root yields of ≥ 25 tons and above and 0.2 for yields of ≤ 2 tons; in between these values the C factor is interpolated linearly.

The change in soil organic matter (Mg SOC ha^{-1}) over 25 years was simulated by the FIELD model (Tittonell et al., 2007) as explained above.

Nitrogen use efficiency was calculated as:

$$NUE = \frac{E_{net}}{N_{available}} \quad (3.1)$$

where
NUE the nitrogen use efficiency (GJ net energy kg^{-1} available N); E_{net} the net energy yield (GJ ha^{-1}); $N_{available}$ the crop available N (kg N ha^{-1}), comprising applied fertiliser N and N mineralised from soil organic matter and crop residues calculated by the FIELD model.

N leaching (kg N ha^{-1} yr^{-1}) is estimated as:

$$N_{leached} = F_{leached} \cdot N_{available} \quad (3.2)$$

where
$N_{leached}$ the quantity of nitrogen lost through leaching (kg N ha^{-1}); $F_{leached}$ the fraction of mineral nitrogen lost by leaching, estimated from soil texture and rainfall by transfer functions derived by Smaling et al. (1993) (Appendix)

Water Productivity (MJ net energy m^{-3} of MJ) was calculated as:

$$P_{water} = \frac{E_{net}}{W_{available}} \quad (3.3)$$

where
P_{water} the water productivity of the biofuel (*MJ net energy m^{-3}*); $W_{available}$ the volume of water potentially available to the crop ($m^3 y^{-1}$), hence before e.g. conveyance losses and runoff occur. It includes both precipitation and supplied irrigation water. Irrigation water requirements were calculated as the water required to bridge the gap between rainfed and target yield; we used fixed water use efficiencies for rain and the types of different irrigation (see Appendix).

Labour demand for agricultural operations and harvesting was estimated from literature data (Table 3 A2). Labour requirements for harvesting were assumed to be proportional to yield (manual harvesting) or acreage (mechanised harvesting): 35 man hour Mg^{-1} cassava (manual); 2.7 man hour Mg^{-1} of fresh sorghum stems (manual) and 1.6 man hours Mg^{-1} of fresh cane (manual) or 2 man hours ha^{-1} of cane (mechanised). Labour requirements of all other agricultural operations were assumed to be constant at 1226 man hours ha^{-1} (cassava, manual) 100 man hours ha^{-1} (sweet sorghum, partly mechanised) and 14 man hours ha^{-1} (sugarcane, mechanised).

3.3 Results

3.3.1 Soil organic carbon

Simulated SOC dynamics depend strongly on the initial SOC content of the soil: at equilibrium or recently cleared. For plantation systems of sugarcane, sweet sorghum and cassava with residue mulching on recently cleared soils, SOC declined, while in the cultivated soils that started at base equilibrium, SOC content increased (Figure 3.3a). After about 15 years, simulations for both initial conditions reached the same equilibrium. The largest equilibrium SOC content was obtained with sugarcane, due to the largest input of organic material (10 Mg DM ha^{-1}), followed by cassava and sweet sorghum with residue inputs of 8.9 and 6.0 Mg DM ha^{-1}, respectively.

Even though fertilized cassava in Nacuaca yielded the same quantity of residue mulch as in Gafaria (see next section), simulated equilibrium SOC contents in Gafaria were higher due to a higher clay content (Figure 3.3b). In Nacuaca, unfertilised cassava yielded little residues for mulching, hence simulated SOC of this system with residue mulching was similar to the 'no inputs' treatment. Fertilisation strongly increased the amount of mulch, hence simulated SOC content (100:150:200, mulch) was higher than the 'no inputs' treatment with mulch. In Gafaria, residues of unfertilised cassava had a relatively strong effect due to more fertile soil, hence more residues and slower decomposition of SOC due to higher clay content. Fertilisation resulted in a further increase of (tuber and) residue yield, hence a further improvement in SOC content. In Dombe, irrigation almost doubled the amount of mulch available in Gafaria and Nacuaca. However, the effect of these residues on SOC is limited, due to rapid decomposition on the very sandy soils.

3.3.2 Simulated cassava root yields

Simulated *potential* cassava yields (in absence of nutrient and water shortages) were 76.8 Mg ha^{-1} of fresh roots for all locations; *water-limited* yields (in absence of nutrient shortages) were 28.6 Mg ha^{-1} of fresh roots for Gafaria and Nacuaca and 25.7 Mg ha^{-1} for Dombe.

Taking into account soil fertility, for unfertilized cassava in Gafaria we simulated a *resource-limited* yield of 19.0 Mg ha^{-1} fresh roots for recently cleared soils (Figure 3.4a). This yield starts declining slightly in year 10, when soil N supply becomes limiting due to declining N availability. N mineralization, which is proportional to SOC content, decreases due to lack of organic inputs. In the new equilibrium, reached after about 20 years, N limitation is only moderate and yields remain rather good. The soil has a relatively high clay content hence protects a large SOC content that sustains N supply. Nevertheless, the yield decline may be prevented by applying

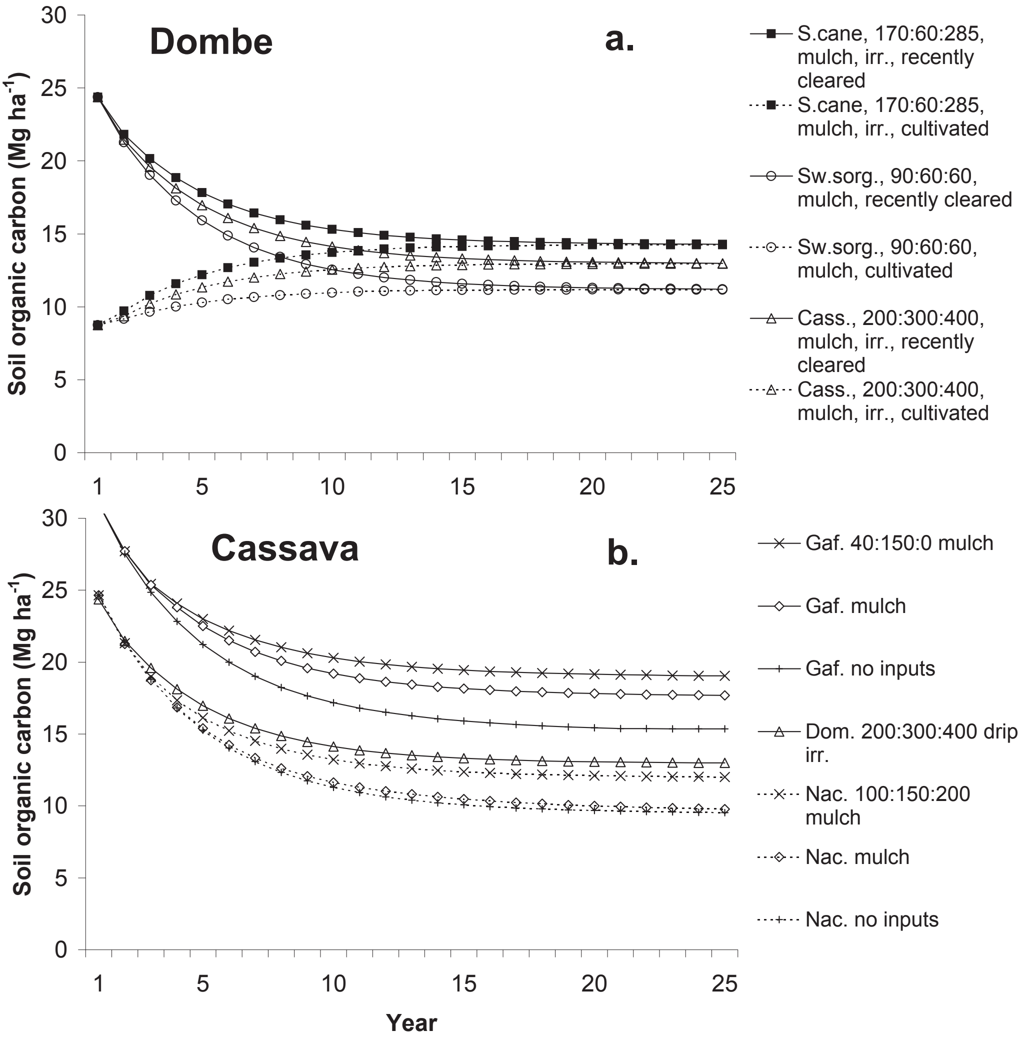


Figure 3.3 *Simulated soil organic carbon (SOC) content: (a) on recently cleared (solid lines) and cultivated soils (dotted lines) for sugarcane, sweet sorghum and cassava in Dombe, all with residue mulching; (b) in cassava fields with different crop management in Gafaria (Gaf), Nacuaca (Nac) and Dombe (Dom); recently cleared soils.*

70% of the available crop residues (containing 62 kg N, 6 kg of P and 62 kg of K[$]) or 40 kg ha^{-1} yr^{-1} of N fertilizer (Figure 3.4a); larger N applications do not result in further yield increase (data not shown). Yield improvement can only be achieved by P fertilisation (Figure 3.4a, 40:150:0). Due to the very low P-status of the soil (Table 3.1), annual application of 150 kg P ha^{-1} initially leads to a yield increase and build-up

[$] Nutrient contents in roots and residues are simulated by CROPSIM

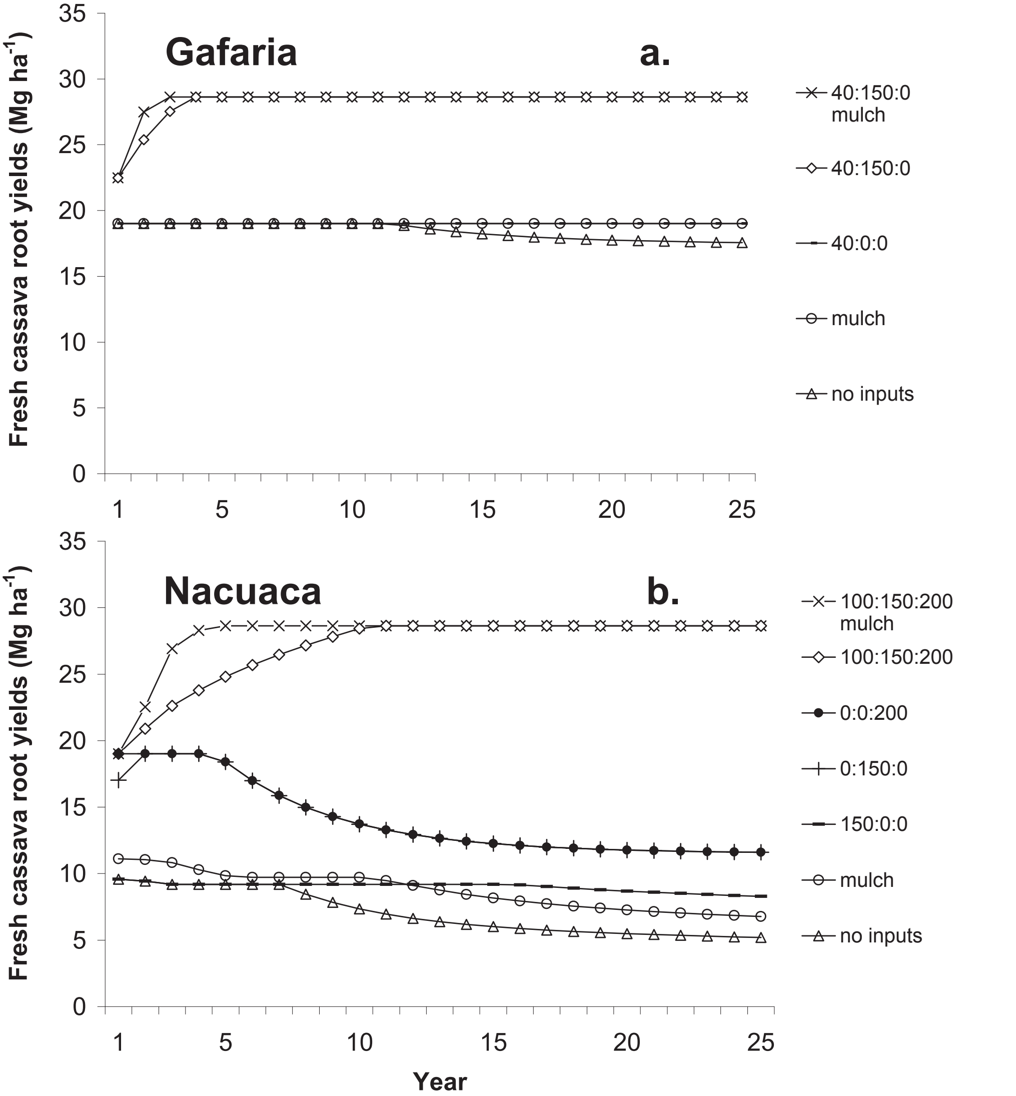


Figure 3.4 *Simulated fresh cassava root yields with different crop management on recently cleared soil in Gafaria (a) and Nacuaca (b).*

of the stable soil P pool. After 4 years sufficient P is exchanged with the labile (crop available) P pool, P limitations are removed and the water limited yield of 28.6 Mg ha^{-1} is attained. Combining P application with residue mulch (70% of the residues left on the soil, containing 68 kg N, 17 kg P and 89 kg of K[a]) led to a somewhat faster yield increase due to the additional nutrients supplied by the crop residues. After reaching the yield plateau, yields could be maintained with less P fertilizer (data not shown).

Smaller P application rates lead to a longer period of P buildup in the soil before the water limited yield is achieved. Due to the high K status of the soil in Gafaria (Table 3.1), fertilization with this nutrient is not immediately required.

In Nacuaca unfertilised resource-limited yield on recently cleared soils was 9.5 Mg ha^{-1} of fresh roots (Figure 3.4b), substantially lower than in Gafaria due to poorer soil fertility. Over time, root yield decreases further to about half its initial value; the decline starts after year 7, when soil N supply starts to fall below crop requirements; the mechanism is similar to that described above for Gafaria. Due to the small amount of residues produced, mulch contributed little to cassava yield. Simulations indicated that 150 kg N ha^{-1} (150:0:0, Fig. 3.4b) was required for preventing this decline, while higher applications did not further improve yields (not shown). The crop also responded to P applications up to 150 kg ha^{-1} (0:150:0, Fig. 3.4b[$]) and K applications up to 200 kg ha^{-1} (0:0:200, Fig. 3.4b[b]), hence both P and K severely limited crop growth (see cf. Table 3.1). However, after some years P-only or K-only fertilised yields are affected by the declining availability of N, hence illustrating the need for balanced fertilisation. The use efficiency of the macro-nutrients was much enhanced when applied jointly: 100:150:200 was sufficient for achieving the water-limited yield of 28.6 Mg ha^{-1} (Figure 3.4b). Reaching this yield took a number of years, depending on the amount of P applied and whether or not mulch was applied. Again, after reaching the yield plateau, yields could be maintained with less P (data not shown).

For Dombe, we investigated commercial cassava production with fertilisation, mulching and irrigation. For reaching a yield of 50 Mg ha^{-1} of fresh roots, the maximum yield recorded in East Africa (Fermont, 2009), 200:300:400 kg ha^{-1} of N:P:K and 470 mm of drip irrigation or 750 mm of surface irrigation were required (not shown).

3.3.3 Net energy yields

Cassava and sweet sorghum systems yielded less net energy per hectare than sugarcane systems (Figure 3.5a). Fertilisation, although also consuming energy, improved net energy yield of cassava systems, especially in Nacuaca where it more than tripled. In Dombe, where soils were the least fertile, combining fertilisation with 470 mm of drip irrigation resulted in a better net energy yield (116 GJ ha^{-1}) than was obtained on more fertile soils in Gafaria and Nacuaca without irrigation. With surface irrigation nearly the same net energy yield was obtained (not shown); it required more water (750 mm) but less energy per volume of water due to the lower pressure requirement hence the net result was similar. Taking into account the processing

[$] *These fertilizer applications only serve for demonstration and are not part of the sustainability assessment* energy consumption (Nguyen *et al.*, 2007) reduced the net energy yield of cassava (Figure 3.5a) in comparison with the other crops since with this crop additional fossil energy is required.

Irrigated sugarcane systems perform best for net energy yield (Figure 3.5a). The differences among the irrigated sugarcane systems were due to different energy requirements for irrigation of 4.1 (drip), 7.0 (surface, not displayed) or 13.9 GJ ha^{-1} (pivot), and for harvesting:1.1 (manual) or 3.8 GJ ha^{-1} (mechanical); they remain relatively small compared to the differences with the other systems however. Rainfed sugarcane produces less net energy than irrigated sugarcane, due to the smaller crop yield.

Sweet sorghum performs similar to cassava: it produced less biomass and contains less sugar than sugarcane while still requiring substantial N fertilisation. Transport energy requirements were higher than for cassava; the latter crop can be transported as (sun-)dried chips while sweet sorghum stalks have to be transported fresh; this also applies to sugarcane.

3.3.4 GHG emissions

For recently cleared soils, GHG emissions of the no-inputs treatment in Nacuaca (Figure 3.5b) were much larger than in Gafaria due to the very low net energy yield in Nacuaca. Balanced fertilisation improved GHG performance since the increase in cassava yield was greater than the additional emissions from fertilization. Emissions of fertilised treatments in Gafaria were somewhat lower than in Nacuaca where, due to poorer soil fertility, more fertilisers were needed to achieve the same yield. The largest share of the emissions was caused by SOC decomposition, as becomes evident from comparison with emissions from cultivated soils (Figure 3.5b). Application of crop residues had a beneficial effect due to higher equilibrium SOC levels hence reduced net emissions.

Emissions of sugarcane systems where generally slightly lower than those of the cassava systems. Sweet sorghum on recently cleared soils produced rather high emissions: net energy yield is equal to e.g. cassava with no inputs in Gafaria, however, in sweet sorghum substantial inputs (e.g. fertilisers) are used. Emissions of all treatments, except no-input cassava on recently cleared soils in Nacuaca were lower than those from production and combustion of conventional gasoline (Figure 3.5b).

3.3.5 Nitrogen Use Efficiency

Of the three crops, sugarcane had the best NUE, followed by cassava and sweet sorghum, respectively (Figure 3.5c). Due to the very low availability of P from

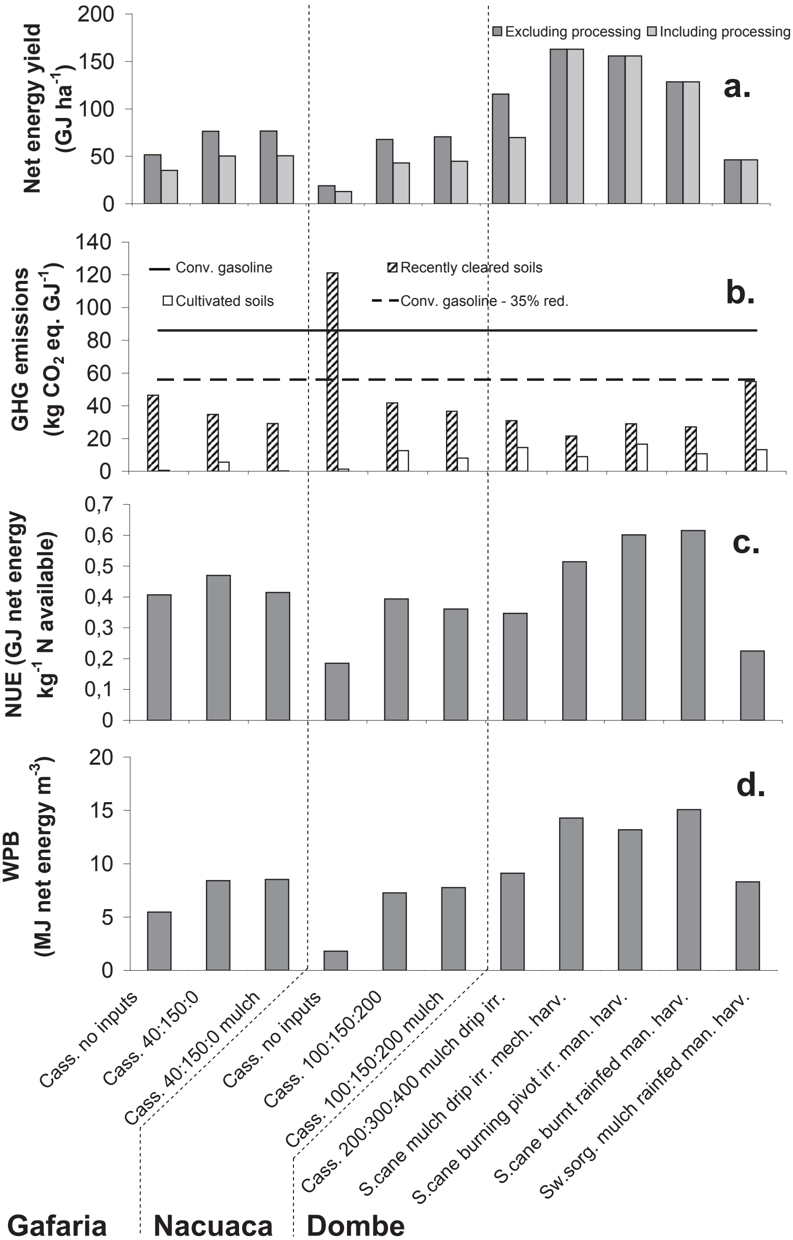


Figure 3.5 *Simulated energy-related sustainability indicators for some of the assessed systems: net energy yields at equilibrium with and without taking into account processing energy requirements (a); average greenhouse gas (GHG) emissions over 25 years for recently cleared soils and for cultivated soils and the reference emission from producing and combusting conventional gasoline (b); nitrogen use efficiency at equilibrium (NUE, c); and water productivity of the biofuels (Pwater, d).*

unfertilised soil in Nacuaca, N efficiency for the no input system was the poorest. Mulching combined with fertilisation had a poorer NUE than fertilisation only; apparently, the extra N mineralising from the residues was used less efficiently by the crop.

3.3.6 Water productivity

For zero-input systems, nutrient-limited yields fell below water-limited yields, hence only a fraction of the effective rainfall was utilised, resulting in poor P_{water} (Figure 3.5d). Fertilisation was such that water-limited yields were attained, hence the crop fully utilised the effective rainfall. For sugarcane, target yields (Table 3.2) were greater than the water-limited yields, hence the effective rainfall is fully utilised by this crop. The effect of irrigation on overall P_{water} depends on the method; sugarcane with drip irrigation had the best P_{water} (14.3 MJ m^{-3}), followed by pivot (13.0 MJ m^{-3}) and furrow irrigation (11.0 MJ m^{-3}, not shown), respectively. Sweet sorghum performed similarly to the fertilized cassava systems.

3.3.7 Nitrogen leaching

Since rainfall in Gafaria and Nacuaca is similar, differences in N leaching between these two villages depended on crop growth and management and soil texture. Therefore, the larger N fertiliser rates in Nacuaca led to more N leaching, as did application of crop residues also led to increased leaching (Figure 3.6a). Sugarcane with mulching gave more leaching than when sugarcane residue was burned due to the additional N mineralized from the trash.

3.3.8 Soil erosion

Soil erosion was strongly related to crop yield and soil cover (Figure 3.6b). Erosion was greatest for zero-input cassava in Nacuaca, the poorest yielding system with least soil cover. Fertilisation increased crop growth and thereby reduced erosion due to better soil cover. Residue mulching further reduced soil erosion. Sugarcane and sweet sorghum performed better than cassava, although the differences largely disappeared for high-input cassava systems.

3.3.9 Labour requirement

Cassava systems required much more labour than systems based on sugarcane or sweet sorghum (Figure 3.6c); cassava required around one person year ha^{-1}. In contrast, for sugarcane and sweet sorghum that are harvested manually, requirements are 4-5 person weeks ha^{-1}, while for mechanically harvesting it is less than 0.5 person week ha^{-1}. Labour requirement for harvesting and agricultural operations were in the same order of magnitude if harvesting was manual.

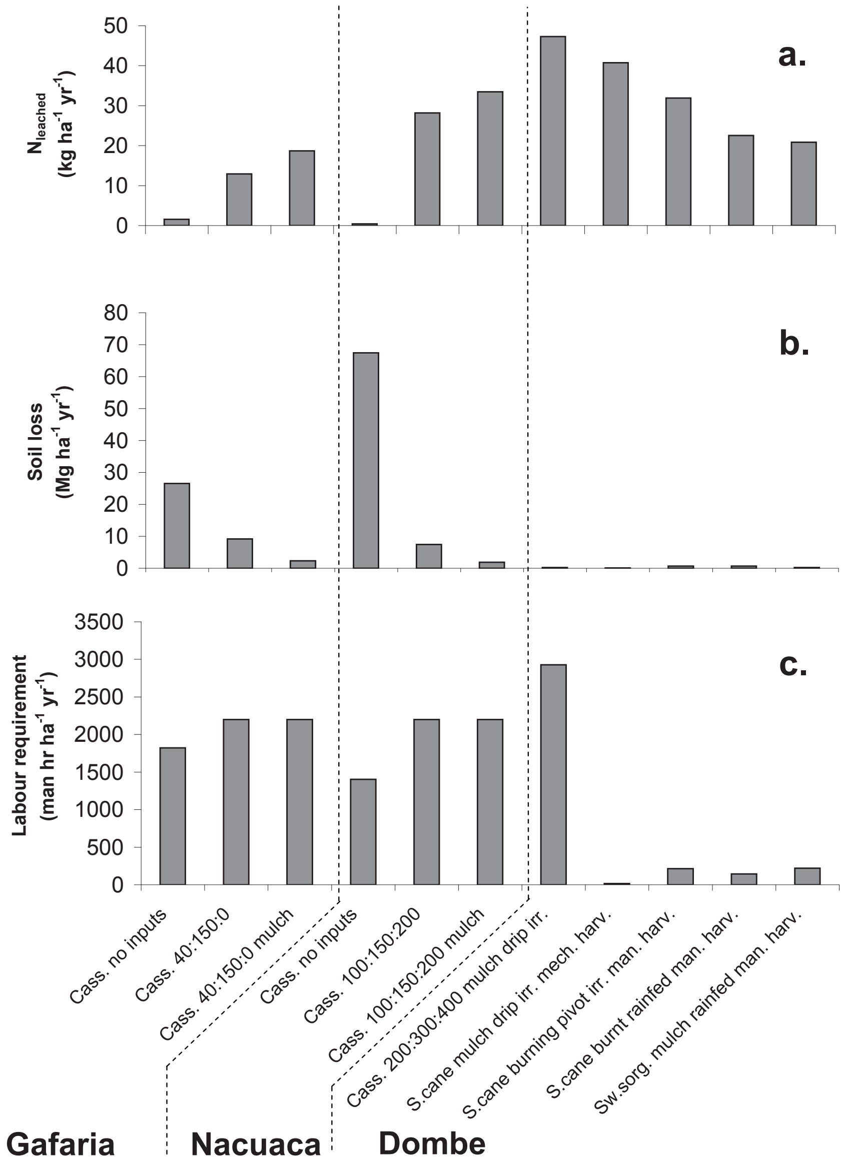


Figure 3.6 *Simulated area-based sustainability indicators of the assessed systems at equilibrium: N leaching (a); soil erosion (b) and labour requirements (c).*

3.3.10 Synthesis of results

We indexed the obtained values for each indicator except GHG emissions in percentages relative to the most sustainable value found for that indicator across all crops and locations, which was set to 100. Only GHG emission reduction (in percentages) was calculated relative to that of the replaced gasoline. Results for selected systems are displayed in Figure 3.7 a) – i); since not all systems are displayed, the '100%' value for the best indicator cannot always be found in the figure. The GHG indicator is displayed for cultivated soils; SOC dynamics were captured in a single figure by taking the difference between soil C stocks at year 25 and at year 1 for cultivated soils.

3.4 Discussion

3.4.1 Comparison of crops

Smallholder cassava systems (Figure 3.7 a-d) were outperformed by sugarcane in plantations (Figure 3.7 f-h) with respect to net energy yield, SOC build-up if residues of both crops are mulched, NUE, soil erosion and water productivity. Only for N leaching cassava performed better, due to lower N fertiliser rates. The improved smallholder cassava systems performed similarly or somewhat better than sweet sorghum in plantations (Figure 3.7 b,d vs. 7i).

Taking into account the energy requirements of cassava processing changes the energy- and GHG related indicators in favour of sugarcane and sweet sorghum, since these crops generate sufficient energy for this purpose by burning bagasse. Although sugarcane performed better than cassava for production-ecological sustainability, Arndt et al. (2010) found that ethanol production from cassava grown by smallholders has stronger economic growth effects than sugarcane ethanol. On the other hand, while cane sugar is mostly an export product, cassava is a vital domestic food security

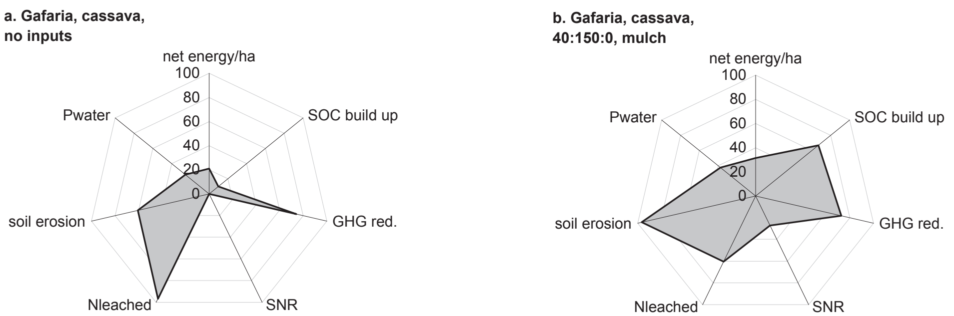


Figure 3.7(a)–(i) *Relative sustainability of the assessed systems, based on seven indicators. Values are indexed in percentages relative to the best indicator value calculated for that indicator across all 10 systems. 'GHG reduction' is emission reduction relative to replaced fossil fuels. GHG, greenhouse gas.*

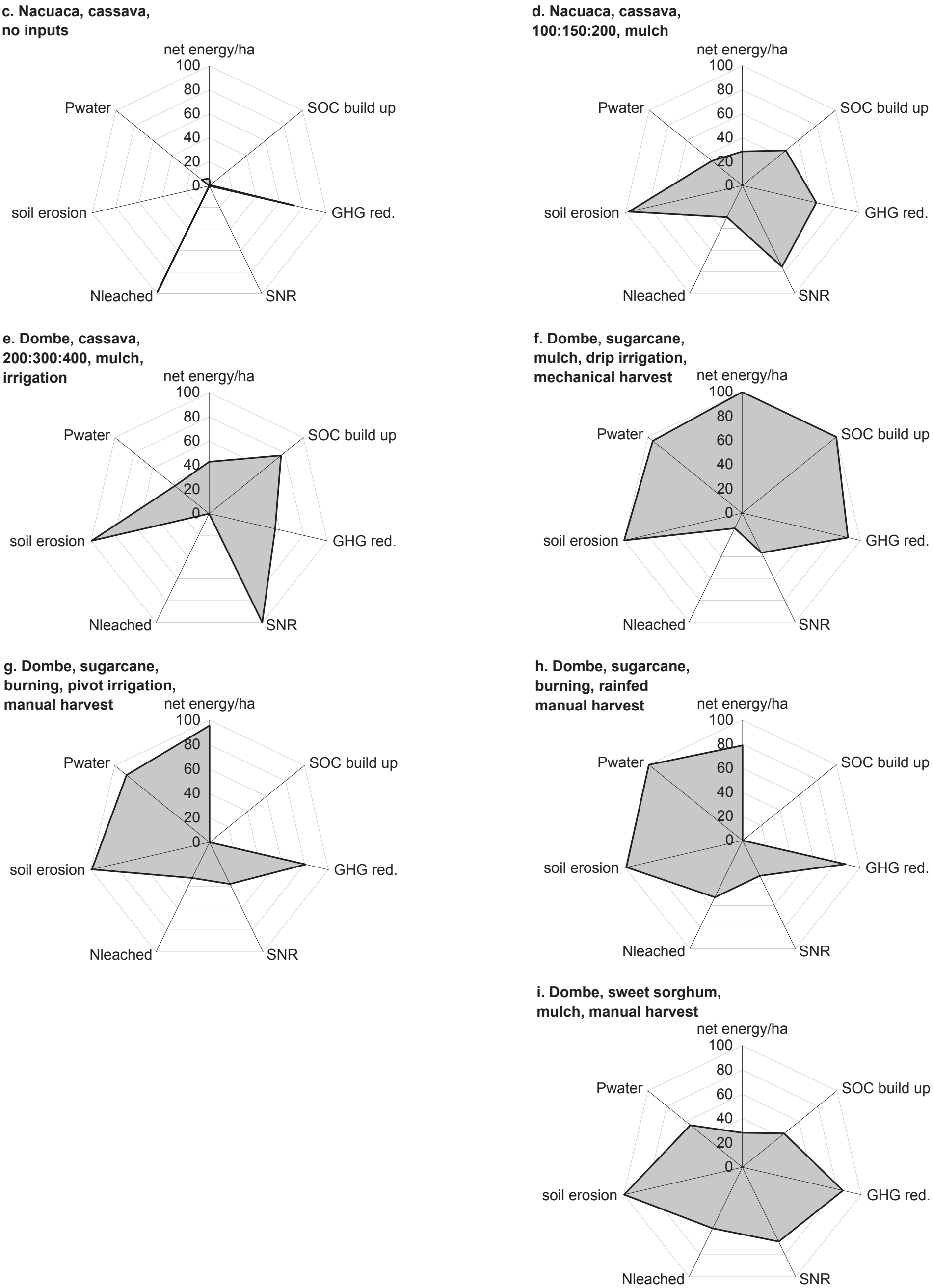


Figure 3.7 **- continued**

crop in Mozambique and increased demand could easily lead to price hikes. In formulating policies, a balance should be struck between environmental aspects, poverty reduction goals and food security considerations.

We analysed systems in which one crop is cultivated continuously. Sustainability could also be improved by, for example, rotating biofuel crops with crops that have low harvest indices and high residue yields for maintaining SOC at favourable levels, managing GHG emissions and even fixing nitrogen (e.g. pigeonpea). Pigeonpea is currently a common crop among smallholders in the study area.

3.4.2 Cassava

Cassava cultivation in Gafaria performed better than in Nacuaca due to better soil fertility. Fertilisation and residue mulching (Figure 3.7b and d) for both locations resulted in a substantial improvement compared to the zero-input system (Figure 3.7a and c). Fertilisation and residue mulching (Figure 3.7b and d) substantially improve the system: net energy yield, SOC sequestration, NUE and P_{water} increase, while soil erosion is strongly reduced.

A practical problem with the improved systems is that mulching large quantities of cassava tops, especially stems, may obstruct preparation of the field for the next crop: this was mentioned by smallholders in a rapid farm survey in the study area (Van den Dungen, 2010). A shredding device could be the solution, but getting such an implement adopted among smallholders may be difficult or expensive compared to just removing or burning residues.

Cassava yields can be boosted further by introducing irrigation and increasing fertiliser rates (Figure 3.7e). The result is that net energy yield and SOC sequestration improve, while GHG reduction and N leaching are less favourable due to increased input use. This type of system is more feasible for plantations than poor smallholders.

3.4.3 Sugarcane and sweet sorghum

Sugarcane cultivation with residue mulching, drip irrigation and mechanical harvesting yielding 100 Mg ha^{-1} emerged as the most sustainable production system in our comparison; it only performed sub-optimal for N leaching. Burning sugarcane residues (Figure 3.7g) negatively affected GHG performance and virtually eliminated SOC build up (Garside, 1997), but reduced N leaching. We did not reduce N applications to compensate for the simulated extra N mineralised from residues. Robertson and Thorburn (2007) found that fertiliser N application should not be reduced in the first 6 years after adoption of residue mulching in sugarcane because of immobilisation, and that small reductions may only be possible in the longer term (>15 years).

Water requirements of furrow irrigation were highest, followed by pivot and drip, respectively. Lower yielding rainfed cane with residue burning (Figure 3.7h) performed rather similar to irrigated, high yielding sugarcane with burning (Figure 3.7g) ; the main difference was that N leaching was reduced due to lower fertiliser application and that net energy yields were slightly reduced due to lower crop yield. Since it fully utilised the effective rainfall, P_{water} was somewhat better. Due to uneven rainfall distribution, the majority of the Mozambican sugar estates are irrigated however (Instituto Nacional do Açúcar, 2000).

Regarding sweet sorghum, Figure 3.7i displays the performance of mechanised cultivation on plantations, where fossil fuel use contributes to GHG emissions and reduces net energy yield. Sweet sorghum cultivation in smallholders systems with predominantly manual labour may perform better. Also, the N fertilisation rate in sweet sorghum (Woods, 2000) was based on US practices and could well be too high, contributing to a low NUE; often, response to N is absent in sweet sorghum (cf. Barbanti et al., 2006). Yields could also be increased by ratooning; two crops a year may then be obtained, provided there is enough water. Due to much lower labour requirements of sweet sorghum as compared to cassava (Figure 3.6c), this crop might be more suitable for smallholders in Gafaria and Nacuaca than cassava.

3.4.4 Cultivated vs. recently cleared soils

On cultivated soils, all analysed systems met the EU standard of 35% GHG reduction (European Parliament, 2009) compared with the emissions of conventional gasoline of 86 kg CO_2 eq. GJ^{-1} (Figure 3.5b, Punter et al., 2004), even when cassava processing was taken into account. On recently cleared soils, cassava with no inputs in Nacuaca does not meet the standard, due to the small net energy yield. If emissions from processing were taken into account, GHG emissions in Figure 3.5b would increase by 23.5 kg CO_2 eq. GJ^{-1} (not shown); in that case only cassava with fertilisation and residue mulching in Gafaria and irrigated cassava in Dombe would meet the 35% reduction target.

When land is allotted to biofuel production in the tropics, it will often be somewhere on the trajectory between clearing and equilibrium; clearing natural vegetation for biofuel production is not preferred, among others to avoid creation of a 'carbon debt' (Fargione et al., 2008) and to preserve biodiversity. For indicators that differed strongly between cultivated and recently cleared soils (GHG emissions, SOC dynamics), actual values will be between the two simulated extremes.

3.5 Conclusions

The approach presented provides quantitative insight into the production-ecological sustainability of biofuel feedstock production systems with different crops and crop management, on different soil types and for different land use histories. For our set of production-ecological sustainability indicators, cassava for bioethanol both in smallholder and plantation systems performed more poorly than plantation-style cultivation of sugarcane. The latter system requires substantial volumes of surface water for irrigation however, which in the future may also be needed for other purposes. Also, it has a less pronounced pro-poor effect and generates less labour than smallholder cassava production. Cassava and sweet sorghum performed similarly.

For smallholder cassava, increased but targeted use of inputs improved sustainability, e.g. through greater net energy yield, greater production of crop residues and better erosion control. With increased N fertilisation, N leaching increased however. If smallholders are to be involved in production of feedstock for biofuels, sweet sorghum has the advantage of requiring far less labour than cassava. In the study area, labour shortage of rural households often limits the acreage cropped and hence, agricultural output.

Cassava production systems on more fertile soils (Gafaria) were more sustainable than those on less fertile soils; the latter required more agricultural inputs, affecting most indicators negatively. Increased input requirements on less fertile soils also reduce the financial feasibility of achieving yield improvement for smallholders. However, instead of producing biofuel feedstock, it is often preferred to use the more fertile (clayey) soils for production of food crops. In contrast, relatively sustainable sugarcane systems can be achieved on poor sandy soils if irrigation is available. Production of bioethanol feedstock on cultivated lands is more sustainable than on newly cleared land as large GHG emissions after clearing natural vegetation are avoided and instead there is a potential for carbon sequestration, which can be realised through suitable management of crop residues. New SOC equilibrium levels are established within 15 years. After this time, further sequestration is only possible by increasing carbon inputs.

Overall, sugarcane systems performed better than cassava and sweet sorghum systems for our set of seven production-ecological sustainability indicators.

Appendix I: additional model description

In this section, additional details on the calculations of the sustainability indicators are provided, as well as values of coefficients used in these calculations and their sources.

Sustainability indicators
The *net energy yield per hectare* is calculated as:

$$E_{net} = E_{gross} - E_{fert} - E_{mech} - E_{harv} - E_{irr} - E_{transp} \quad (1)$$

where
E_{net}: net energy yield in (GJ ha^{-1} yr^{-1});
E_{gross}: gross energy yield: the energy present in the produced ethanol (GJ ha^{-1} yr^{-1})
E_{fert}: energy for producing and transporting fertilisers (GJ ha^{-1} yr^{-1})
E_{mech}: energy required for agricultural operations (GJ ha^{-1} yr^{-1})
E_{irr}: energy required by irrigation pumps (GJ ha^{-1} yr^{-1})
E_{harv}: energy required for harvesting (GJ ha^{-1} yr^{-1})
E_{transp}: energy required for transporting feedstock to the mill (GJ ha^{-1} yr^{-1})
For conversion of feedstock into ethanol, fixed efficiencies were used (Table 3 A1).

E_{irr} was calculated according to Sloggett (1992) as:

$$E_{irr} = \frac{98.1 \cdot 0.001 \cdot TDH \cdot W_{irr}}{\eta_{PU} \cdot \eta_{LD} \cdot \eta_{field} \cdot \eta_{cnv}} \quad (2)$$

where
TDH: total dynamic head (m)
W_{irr}: irrigation water supply in mm ha^{-1}
η_{PU}: efficiency of the employed power unit (-)
η_{LD}: efficiency of the lifting device (-)
η_{field}: field efficiency (-); it was set equal to the application efficiency (η_{app}, see 'water use' indicator).
η_{cnv}: conveyance and distribution efficiency (-)

The *greenhouse gas (GHG) emissions* indicator was calculated on a *gross* energy basis; this is commonly done in other studies (Farrell *et al.*, 2006) and facilitates comparison with other results:

$$GHG_{Egross} = \frac{CO_{2,soil} + N_2O_{soil} + GHG_{fert} + GHG_{diesel}}{E_{gross}} \qquad (3)$$

where

GHG_{Egross} :	GHG emissions in kg CO_2 eq. GJ^{-1} gross energy;
$CO_{2,soil}$	CO_2 emission or sequestration by the soil; kg CO_2 ha^{-1} yr^{-1}
N_2O_{soil}	N_2O emissions from the soil (kg CO_2 eq. ha^{-1} yr^{-1});
GHG_{fert}:	GHG emissions from production and transport of fertilisers (kg CO_2 eq. ha^{-1} yr^{-1})
GHG_{diesel}:	CO_2 from production and combustion of diesel (kg CO_2 eq. ha^{-1} yr^{-1})

$CO_{2,soil}$ was simulated by the FIELD model; N_2O_{soil} was estimated as 1% of the applied N fertiliser (IPCC, 2006). Agricultural operations, irrigation pumps, harvesting equipment and transportation of the feedstock to the mill are all assumed to be powered by diesel: the sum of all emissions from diesel use is GHG_{diesel}. GHG_{Egross} is calculated on a seasonal basis. Since gross energy yields and GHG emissions may display trends over the years, e.g. because of rapid SOC decomposition on recently cleared land, we calculate the average value over 25 years. Similar to the calculation of E_{net}, the above calculations are excluding GHG emissions from processing; for cassava, contrary to sugarcane and sweet sorghum, processing requires additional fossil energy hence emits additional GHGs. Nguyen *et al.* (2007) calculated emissions from converting cassava feedstock into bioethanol at 23.5 kg CO_2 eq. GJ^{-1} ethanol.

Soil erosion (Mg soil loss ha^{-1} yr^{-1}) was estimated by implementation of the Revised Universal Soil Loss Equation (Renard *et al.*, 1996; Table 3 A1). Roose (1977) indicated that crop factors for cassava vary between 0.2-0.8. We assumed this factor was proportional to biomass yield, hence canopy cover, where the seasonal crop factor was estimated at 0.8 for root yields of 25 tons and above and 0.2 for yields of 2 tons and less; in between these values it is interpolated linearly.

N leaching (kg N ha^{-1} yr^{-1}) is estimated as:

$$N_{leached} = F_{leached} \cdot N_{available} \qquad (4)$$

where

$N_{leached}$: the quantity of nitrogen lost through leaching (kg N ha^{-1})

F_{leach}: the fraction of mineral nitrogen lost by leaching; it is estimated from soil texture and rainfall by transfer functions derived by Smaling *et al.* (1993):

F_{leach} = $21{\cdot}10^{-5} \cdot P - 0.039$ for soils with clay contents ≤ 35%;
$14{\cdot}10^{-5} \cdot P - 0.0071$ for soils with 35% < clay content < 55%;
$71{\cdot}10^{-5} \cdot P - 0.0054$ for soils with clay content ≥ 55%
with P the annual precipitation (mm)

Water Productivity (GJ net energy m^{-3} of MJ: check) was calculated as:

$$P_{water} = \frac{E_{net}}{W_{available}} \qquad (5)$$

where

P_{water} : the water productivity of the biofuel (GJ net energy m^{-3})

$W_{available}$: the volume of water potentially available to the crop (m^3 y^{-1}), hence before e.g. conveyance losses and runoff occur. It includes both precipitation and supplied irrigation water.

The potential crop available water ($W_{available}$, mm) was estimated as:

$$W_{available} = P_{eff} + W_{irr} \qquad (6)$$

with

P_{eff} : the effective annual precipitation (mm)

W_{irr} : the supplied volume of irrigation water (mm ha^{-1})

First, irrigation water requirements were estimated as:

$$W_{irr,rq} = \frac{Y_{rainfed} - Y_{target}}{WUE_{irr}} \qquad (7)$$

where

$W_{irr,rq}$: irrigation water requirement for achieving the target yield (mm)

$Y_{rainfed}$: the water limited yield (kg ha^{-1})

Y_{target} the target yield (kg ha^{-1})

WUE_{irr}: the irrigation water use efficiency (kg DM biomass mm^{-1} ha^{-1})

$Y_{rainfed}$ is estimated as:

$$Y_{rainfed} = min(PREC_{eff} \cdot WUE_{prec}, Y_{potential}) \quad (8)$$

where

$Y_{rainfed}$: water limited yield (kg ha^{-1} of biomass DM);

$Y_{potential}$: the potential yield: it is calculated in FIELD according to a radiation use efficiency approach (Tittonell *et al.*, 2010); parameter values are given in Table 3 A1.

$PREC_{eff}$: the annual effective precipitation (mm); it is estimated according to the USDA SCS method (Dastane, 1978). Rainfall data were derived from Smith (1993).

WUE_{prec}: the water use efficiency with which the different crops makes use of precipitation (kg DM biomass mm^{-1} ha^{-1})

We now calculated the water productivity of biofuels (P_{water}, MJ of net energy m^{-3}) as:

$$P_{water} = \frac{E_{net}}{W_{available}} \quad (9)$$

where

P_{water} the water productivity of the biofuel (*GJ net energy m*$^{-3}$)

$W_{available}$ the volume of water potentially available to the crop (m^3 y^{-1})

Labour demand for agricultural operations and harvesting was estimated from the data in Table 3 A2. Labour requirements of harvesting were modelled proportional to yield, while those for all other agricultural operations were assumed constant per crop.

Table 3A 1 *Parameters and assumptions used in the calculation of the sustainability indicators*

Description	Symbol used in text	Value	Unit	Reference	Relating to calculation of
Radiation Use Efficiency	-	1.9	g DM biomass MJ^{-1} of PAR	Pellet and El-Sharkawy (1997)	Potential cassava yield
Fraction photosynthetically active solar radiation (PAR)	-	0.5	-		Potential cassava yield
Fraction photosynthetically active solar radiation (PAR) intercepted by the canopy	-	0.7	-	Van Dijk (2002)	Potential cassava yield
Conversion efficiency cassava roots to ethanol	-	137	l ethanol Mg^{-1} of fresh cassava root	Nguyen *et al.* (2007)	E_{gross}
Conversion efficiency sugarcane stems to ethanol	-	90	l ethanol Mg^{-1} of fresh sugarcane stems	Macedo *et al.* (2004)	E_{gross}
Conversion efficiency sweet sorghum stems to ethanol	-	60	l ethanol Mg^{-1} of fresh sorghum stems	Woods (2000)	E_{gross}
Lower heating value (LHV) of ethanol	-	21.2	MJ l^{-1}	Farrell *et al.* (2006)	E_{gross}
Energy efficiency of irrigation power unit	η_{PU}	25	%	Woods (2000)	E_{irr}
Energy efficiency of the lifting device (pump)	η_{field}	70	%	Woods (2000)	E_{irr}
Conveyance and distribution efficiency	η_{cnv}	95 (drip, pivot irr.); 70 (surface irr.)[£]	%	-	E_{irr}

[£] For drip and pivot irrigation, pipe conveyance systems were assumed; for surface irrigation lined field channels

Description	Symbol used in text	Value	Unit	Reference	Relating to calculation of
Field efficiency	η_{field} η_{app}	90 (drip); 80 (pivot); 60 (furrow)	%	Camp (1998); Magwenzi (2000); Nkomo *et al.* (2004)	E_{irr}
Total dynamic head	TDH §	18.6 (drip); 47.0 (pivot); 8.0 (furrow)	m	Woods (2000)	E_{irr}
Geometric mean particle diameter	D_g	0.1 (Gafaria); 0.4 (Nacuaca); 0.6 (Dombe)	mm	Shirazi and Boersma (1984)	RUSLE
Random surface roughness	R_u	0.545$	In	Renard *et al.* (1996)	RUSLE
Ratio of the area covered by a piece of residue to the mass of residue	A	0.00038 for cassava, maize and sorghum	acre lb^{-1}	Renard *et al.* (1996); Schiettecatte *et al.* (2008)	RUSLE
'b-parameter' in the calculation of the surface cover sub-factor	B	0.035	-	Renard *et al.* (1996)	RUSLE
Rainfall factor	R		-	Renard *et al.* (1996)	RUSLE
Crop factor	C	0.2-0.8 (cassava); 0.10 (sugarcane); 0.42 (sweet sorghum)	-	Roose (1977); Bengtson *et al.* (2007); Field and Solie (2007)	RUSLE
Water use efficiency (precipitation)	WUE_{prec}	19.5 (cassava); 28.6 (sugarcane); 23.0 (sweet sorghum)	kg DM biomass mm^{-1} effective rainfall	Manickasundaram *et al.* (2002); Bezuidenhout *et al.* (2006); Woods (2000)	

§ TDH includes the lift and head of friction loss in distribution lines

$ Calculated as the average of 0.7 directly after tillage, based on field observations and Renard (1996, Table 5-5) and 0.24, the equilibrium (minimum) surface roughness that is approached if cumulative rainfall increases over time

Description	Symbol used in text	Value	Unit	Reference	Relating to calculation of
Irrigation water use efficiency	WUE_{irr}	19.5 (cassava, surface irrigation); 31.3 (cassava, drip irr.); 12.0, (sugarcane furrow) 21.7, (sugarcane pivot) 24.5 (sugarcane; drip)	kg DM biomass mm^{-1} supplied water	Manickasundaram (2002)	$W_{available}$
Energy requirement for production and transport of fertilizers	E_{fert}	57.46; 16.11; 8.25	GJ kg^{-1} of N, P and K, resp.	West and Marland (2002)	E_{net}
Energy required for agricultural operations, except harvest	E_{mech}	0 (cassava, smallholder); 3.9 (cassava, plantation); 1.2 (sugarcane)[¶]; 1.34 (sweet sorghum)	GJ ha^{-1}	Nguyen *et al.* (2007); Macedo *et al.* (2004); Woods (2000)	E_{net}
GHG emissions from production and transport of fertilisers	GHG_{fert}	3138; 1385; 530	kg $CO_2 kg^{-1}$ of N, P and K, resp.	West and Marland (2002)	GHG_{Egross}
GHG emissions from production and combustion of diesel	GHG_{diesel}	80.3	kg CO_2 GJ^{-1}	West and Marland (2002)	GHG_{Egross}
Energy requirement mechanised sugarcane harvest	-	3.8[£]	GJ ha^{-1}	Macedo *et al.* (2004)	E_{harv}

¶ Sugarcane: the average for a 5 year crop cycle with one year plant cane (102.6 l ha^{-1} of diesel) and four years ratoon cane (9.1 l ha^{-1} of diesel), hence 27 l ha^{-1}

£ Assuming use of a harvester and a tractor hauler/transloader

Description	Symbol used in text	Value	Unit	Reference	Relating to calculation of
Energy requirement manual sugarcane harvest	-	1.0[¥]	GJ ha^{-1}	Macedo *et al.* (2004)	E_{harv}
Fuel consumption of trucks	-	1.7	MJ Mg^{-1} km^{-1}		E_{transp}
Distance field-processing facility (for trucks)	-	15	km	Woods (2000)	E_{transp}
Lignin content sugarcane, sweet sorghum residues	-	12	%	Singh *et al.* (2008)	SOC
N content sugarcane, sweet sorghum residues	-	0.8	%	Nijhoff (1987)	SOC
Lignin content cassava tops (leaves, stems, petioles)	-	12.9[€]	%	Reed *et al.* (1982); Fermont (2009)	SOC
N content cassava tops	-	1.9	%	Reed *et al.* (1982); Fermont (2009)	SOC

¥ Assuming use of a mechanical loader and a tractor hauler/transloader

€ Composition data from Reed, biomass partitioning data from Fermont

***Table 3A 2** Labour requirements of various activities in the assessed cropping systems*

Crop, activity	Value	Unit	Sources
Sugarcane			
Agricultural operations (mech.)[a]	14	Man hours ha^{-1}	Salassi and Deliberto (2010); average for 5 year ratoon cycle
Manual harvesting	1.6 [c]	Man hours Mg^{-1} of fresh stems (with burning)	Woods (2000)
Mechanised harvesting	2	Man hours ha^{-1}	Macedo *et al.* (2004); Salassi and Deliberto (2010)
Sweet sorghum			
Agricultural operations (mech./manual)[a, b]	100	Man hours ha^{-1}	Woods (2000)
Manual harvesting	2.7[c]	Man hours Mg^{-1} of fresh stems (with residue mulching)	Woods (2000)
Cassava			
Agricultural operations (manual)[a]	1226[c]	Man hours ha^{-1}	Enete *et al.* (2002)
Agricultural operations (mech.)[a]	600	Man hours ha^{-1}	Dai *et al.* (2006)
Manual harvesting[e]	35[d]	Man hours Mg^{-1} of fresh roots	Enete *et al.* (2002)

[a] agricultural operations comprise all agricultural activities except harvesting
[b] tillage is mechanically; due to poor accessibility of the field during the rainy season, weeding, bird scaring, and pesticide application are assumed to be done manually.
[c] for converting original data from man days to man hours, 8 hour working days were assumed
[d] calculated based on average African cassava yield 1998-2008 of 9.2 Mg ha-1 of fresh roots and 41 man days ha-1 for harvesting cassava (Enete et al., 2002)
[e] worldwide, cassava harvesting is still preferably performed by hand rather than machine (Nguyen et al., 2007)

chapter 4

Palm oil for biodiesel: the influence of previous land use and crop management on production-ecological sustainability

Expansion of palm oil production has become increasingly controversial due to the threat to tropical rainforest. Yet due to the increasing demand for vegetable oils that is projected, further expansion is anticipated. We developed and applied an oil palm agro-ecosystem model to assess sustainability aspects of several production modes, on land with different previous uses. We show that yield increase through introduction of best management practices in existing plantations and rehabilitation of degraded grasslands are much more sustainable ways of increasing palm oil production than through encroaching into tropical forest habitats. Rehabilitation of degraded grasslands offers great potential for carbon sequestration in soil and biomass and hence could be considered for eligibility as a carbon sink in the UN's REDD+ programme (Reducing Emissions from Deforestation and forest Degradation + Conservation of forest carbon stocks, Sustainable management of forests & Enhancement of forest carbon stocks).

This chapter is under review as:
De Vries SC, Van de Ven GWJ, Van Ittersum MK, Giller KE. Palm oil for biodiesel: the influence of previous land use and crop management on production-ecological sustainability. Journal of Cleaner production

4.1 Introduction

Oil palm (*Elaeis guineensis* Jacq.) supplies 30% of the world's vegetable oil (Carter et al., 2007), but its use has become increasingly controversial due to the negative environmental effects of the land use change associated with its cultivation (Casson, 2003; Greenpeace, 2007). The demand for vegetable oil and particularly palm oil is expected to increase strongly over the next 40 years (Corley, 2009) and the production of biodiesel may further boost demand. Biodiesel from palm oil is a relatively resource use efficient and sustainable biofuel from a biophysical perspective (Chapter 2). However, it may take more than 86 years before use of biodiesel compensates for the greenhouse gas emissions from land use change, if planted on tropical rainforest (Fargione et al., 2008).

Proposed solutions to reduce pressure from oil palm area expansion on the world's remaining forest reserves are yield intensification through best practice management (BMP, Donough et al., 2009) and area expansion on degraded anthropogenic grassland (Fairhurst and McLaughlin, 2009). Degraded anthropogenic grasslands cover 21 Mha in Southeast Asia and 7.5 Mha in Indonesia alone, and are often dominated by *alang-alang* grass (Imperata cylindrica (L.) Beauv.; Garrity et al., 1996).

The aim of this chapter is to assess and compare the production-ecological sustainability of oil palm production systems on three different previous land uses, i.e. secondary forest, oil palm (replanting) and anthropogenic savannah. We considered secondary forest rather than primary forest, since it is much more common in the case study area (Van Noordwijk et al., 1997). We also assess best management practice (BMP), which could be applied by smallholders and plantations, and compare it with average plantation management and smallholder management. Thus far, most studies on sustainability of palm oil and palm oil biodiesel have assessed average crop management rather than the effect of specific management strategies, while in studies on carbon payback time, management has not been taken into account, generally. The sustainability indicators that we use focus on resource use efficiency, soil quality, net energy production and greenhouse gas emissions (Chapter 2).

4.2 Methods

4.2.1 Background

The study was carried out for Bah Lias (3°11'N, 99°20'E), located in the coastal plains east of Medan in North Sumatra, Indonesia. This country is currently the largest producer of palm oil (Carter et al., 2007) and North Sumatra is its major production area (USDA, 2009). Palm oil production has long been important in the case study area (Deasy, 1942). Daily weather data were available for Bah Lias; 10-year average rainfall is 1663 mm. Soils are red-yellow podzolic (Ultisols) with a sandy clay-loam texture (Gerritsma and Soebagyo, 1999), assumed bulk density 1.25 Mg m^{-3}. Although generally of low inherent fertility (Mutert, 1999), most of the world's oil palm is grown on Ultisols (Uexküll and Mutert, 1995); they are also very common in Sumatra (Van Noordwijk et al., 1997). We assumed soil depth greater than 1.5 m; physical properties such as depth, texture and structure of the soil are major criteria for assessing suitability for large scale oil palm planting (Mutert, 1999). Assumed planting density is 136 palms ha^{-1} (cf. Henson and Chang, 2007; Khalid et al., 2000a; Wood and Corley, 1991).

Oil palm in Indonesia is grown by estates (privately owned as well as government owned) and smallholders, who cultivate 44% of the 7.32 million hectare palm area (USDA, 2009). The importance of smallholders has increased rapidly over the past decades (USDA, 2009) since the Indonesian government has used oil palm as a tool of rural socioeconomic improvement (Zen et al., 2005). Since 1979, NES schemes (Nucleus Estate and Smallholder Scheme) have been established to support smallholders. In these schemes, private developers (the 'Nucleus Estate' or plantation) prepare small plots of lands for the smallholders. The smallholders (Plasma) then further develop these plantations under the supervision of the private developers, who buy the fresh fruit bunches (FFB) from the smallholders (Degn and Bertule, 2009). We assume that these so-called 'supported smallholders' (Vermeulen and Goad, 2006) manage their plots in much the same way as the nucleus estate that they are related to. Supported smallholders constitute ca. 50% of the smallholders (Zen et al., 2005). However, the remaining 50% consists of independent smallholders, i.e. growers who cultivate oil palm without direct assistance from government or private companies. They sell their crop to local mills either directly or through traders (Vermeulen and Goad, 2006). Independent smallholders are often less productive; studies have identified inefficiencies that relate to maintaining old oil palms too long, using smallholders' own low-quality seedlings, applying insufficient amounts of fertilizer and harvesting unripe fruit bunches (Rahman et al., 2008). In this paper, the sustainability of production by independent smallholders is assessed and compared with that of average plantation management and best management practice (BMP). For carrying out the assessment, we developed a simple dynamic model, consisting of three interconnected components, simulating: growth and productivity of oil palms and legume cover crops (i); soil organic matter dynamics and GHG emissions (ii) other sustainability indicators, comprising net energy yield, soil erosion, N leaching, nitrogen use efficiency and water productivity (iii). Simulating a daily water balance was part of the simulation of N leaching and water productivity.

4.2.2 Crop management

Differences between smallholder management, average plantation management and BMP that we used as input in our assessment are summarized in Table 4.1. We assumed crop management and crop growth to be independent from the previous vegetation. Fairhurst (2009) shows that inputs required for planting and other operations are rather similar for anthropogenic savannahs and secondary forest on flat land and that topography, especially slope, is more important. Land clearing is much more costly on secondary forest than on anthropogenic savannah, mainly due to the requirement of bulldozers (Fairhurst and McLaughlin, 2009), but is not taken into account here. Fertilizer applications (Table 4.1) required for achieving the biomass production in the different scenarios were estimated according to a target oriented approach (Van Ittersum and Rabbinge, 1997), assuming:

Nutrient requirement (kg ha^{-1} yr^{-1}) = nutrients removed in fresh fruit bunches + nutrients stored in trunk and roots + potential nutrient losses - nutrients returned in empty fruit bunches – N fixed by legume cover crop. (4.1)

Table 4.1 *Overview of crop yield and management practices for smallholders, plantations and best management practice*

	Smallholder management (SMH)	**Average plantation management (AVG)**	**Best management practice (BMP)**
FFB yield	15.8 Mg ha^{-1} §	22.5 Mg ha^{-1} §	30 Mg ha^{-1} §
Fertiliser (depending on yield)	145:12:125 kg of N:P:K ha^{-1}y^{-1} §	168:15:156 kg of N:P:K ha^{-1}y^{-1} §	176:16:133 kg of N:P:K ha^{-1}y^{-1} §
Pruned fronds: placement and quantity	Stacked on 20% of the area; 5.3 Mg ha^{-1} y^{-1} §	Stacked on 20% of the area; 7.5 Mg ha^{-1} y^{-1} §	Spread over 70% of the area; 10 Mg ha^{-1} y^{-1} §
Legume cover crop	No	Yes	Yes
Empty fruit bunches (EFB)	Not returned from mill	Ashes returned to soil	EFB returned to soil; 2.3 Mg DM ha^{-1}y^{-1} §
Trunks	Burnt	Shredded & spread	Shredded & spread
Palm oil mill effluent (POME)	Methane released from ponds	Methane released from ponds	Methane captured

§ for mature palms, i.e. during plateau yield phase (Figure 4.1)

Nutrient content data of exported oil palm products and residues and assumptions regarding nutrient losses used in Equation 4.1 were taken from Tarmizi and Mohd Tayeb (2006).

Pruned fronds are normally stacked in piles, occupying about 20% of the plantation area (Haron et al., 1998). However, under BMP, it is recommended to spread pruned fronds widely in the inter-rows and between palms within the rows (Donough et al., 2010; Weng, 2005) to achieve better erosion control among others; we assumed that under BMP fronds are spread over 70% of the area.

In the avenues of oil palm plantations, legume cover crops are normally grown (Basiron, 2007). The main cover crop species used are *Calopogonium mucunoides* Desv., *Centrosema pubescens* Benth. and *Pueraria phaseoloides* (Roxb.) Benth., often grown in mixtures of 2 or 3 species (Giller and Fairhurst, 2003). We assumed that independent smallholders do not plant legume cover crops; instead they may interplant some food crops during the establishment phase of the plantation (cf. Godoy, 1992; Vermeulen and Goad, 2006).

Smallholders normally sell fresh fruit bunches, and no attempt is made to return empty fruit bunches (EFB) to smallholdings. In effect, therefore, the smallholder subsidises the fertiliser bill of the company buying his fruit; he/she exports nutrients, which are then recycled into the company's plantations (Corley, 2004). In Indonesia, EFB is usually burned in incinerators at the palm oil mills with no heat recovery or just burned on the farms (Santosa, 2008); the ash may be beneficial as fertilizer to the palm fields, but burning EFB also generates air pollution (Santosa, 2008). We assumed that with average plantation management, the ash is returned to the soil; P and K are then recycled. Alternatively, EFB is returned to the farms to improve soil organic matter and soil fertility, which is recommended as BMP (Donough et al., 2009; Weng, 2005); N, P and K are then recycled. The quantity returned EFB per hectare was taken equal to that remaining from processing one hectare's yield of FFB.

When replanting, trunks were assumed to be burnt by smallholders, in order to control pests and save labour. For average plantation management and BMP, we assumed that replanting is done using zero-burning techniques (Noor, 2003); it is recommended that stems are chipped and placed in the windrows (cf. Basiron and Weng, 2004).

Palm oil mill effluent (POME), the wastewater produced during the milling process, is being used as a nutrient source in plantations after treatment (Basiron and Weng, 2004), but also discharged to landfills (Santosa, 2008) and incidentally released into surface water (Wakker, 2005). When untreated, it is highly polluting (Henson, 1994). The most common POME treatment system consists of a pond or lagoon treatment system, in which anaerobic decomposition results in the production of biogas (methane). Methane normally dissolves from the ponds into the atmosphere (Brinkmann Consultancy, 2009) and is a GHG 23 times more active than CO_2 (Dentener et al., 2001). However, under BMP, we assumed that it is captured (Weng, 2005) hence reducing emissions. After treatment, the digestate can be used as a source of nutrients. However, there is only sufficient digestate for treating 3% of the planted area, and areas adjacent to mills are likely to be preferred to minimize transport costs (Henson, 1994). Therefore, we did not take into account its value as a fertiliser.

4.2.3 Model description

Oil palm growth and productivity

Relevant aspects of the growth of oil palm are described by simple functions based on data from the literature. Oil palm LAI (Leaf Area Index, defined as the area of leaves per area of underlying ground surface averaged over a large area, $m^2\ m^{-2}$) is set to increase linearly with time, reaching a plateau value of 6.5 after 6 - 10 years (Breure, 1985; Corley and Gray, 1976; Gerritsma and Soebagyo, 1999; Van Kraalingen et al., 1989). We assumed the faster increase applies to BMP and the slower increase applies to smallholder and average plantation management. High early yields depend on a high LAI as soon as possible after field planting. This can be achieved by palm varieties with a more rapid crown expansion, by higher density planting (Breure, 1985), but also by good (BMP) fertiliser management (Von Uexküll, 1992).

The production of fresh fruit bunches over the years was set to follow different ‘yield profiles’ for smallholder management, average plantation management and BMP (Figure 4.1), based on Henson (1998), Goh et al. (1999) and Jelsma et al. (2009). Plantations become productive in the third year after planting; highest yields are reached at 6 (BMP) or 9 year after planting (smallholder and average plantation management); the difference may be attributed to better management and earlier canopy closure under BMP. After a ‘plateau yield’ phase during which yields are constant, a phase of decline sets in (Figure 4.1), starting at 23 year after planting for BMP and 19 year after planting for smallholder and average plantation management. Average yields over a 25 year plantation cycle, hence taking into account the unproductive years, were 11.2 Mg $ha^{-1}\ y^{-1}$ and 16 Mg $ha^{-1}y^{-1}$ for smallholder and average plantation management, hence equal to the yields reported by Suharto (2009). For BMP plantations in North Sumatra we set the ceiling yield at 30 Mg FFB $ha^{-1}\ y^{-1}$, resulting in an average yield over a plantation cycle (including the initial unproductive years) of 24.6 Mg $ha^{-1}y^{-1}$. Donough (2010) lists average FFB yields under BMP of 29.3

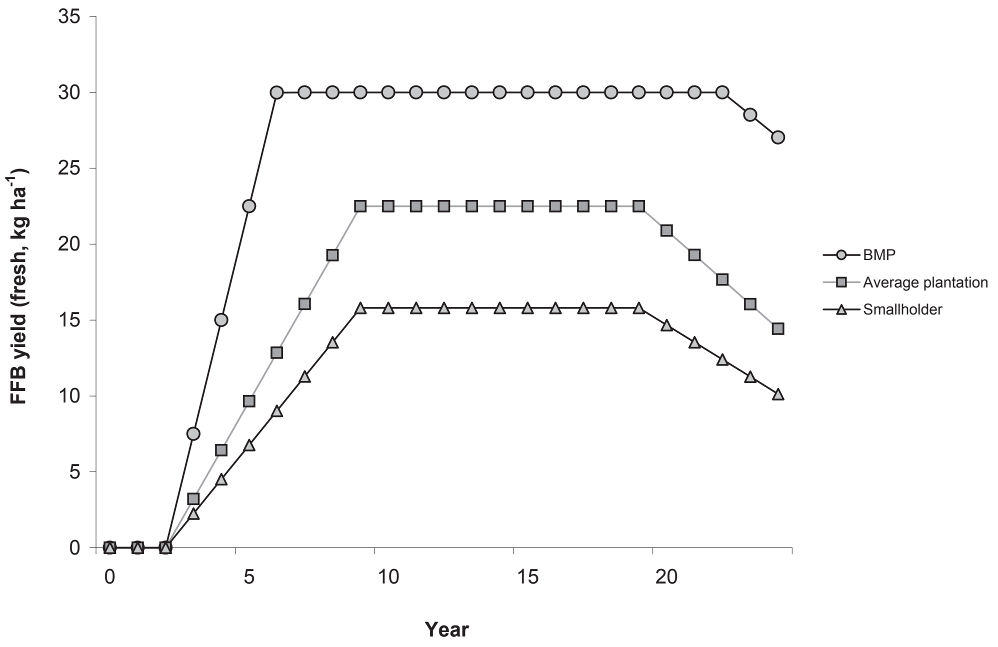


Figure 4.1 *Yield of oil palm Fresh Fruit Bunches (FFB) over a 25-year plantation cycle for BMP, average plantation management and smallholders.*

Mg ha^{-1} over 3-4 years and two sites in North Sumatra, together comprising over 400 ha. Highest recorded BMP yields of a single 36 ha block in these locations were 37.9 and 34.8 Mg ha^{-1}.

After extracting the oil from the FFB (oil extraction rate 23% including palm kernel oil, i.e. 230 kg palm oil Mg^{-1} of FFB ; Santosa, 2008), EFB remain, among others. The availability of this residue was estimated as 22% of the FFB production, containing 35% dry matter (Corley, 2004).

Availability of pruned fronds was assumed proportional to FFB production; pruning is necessary to facilitate access to the bunches for harvesting. The availability of pruned fronds therefore follows a profile similar to the FFB yield profiles described above, with a plateau production of pruned fronds of 10 Mg DM ha^{-1} yr^{-1} for BMP (Quencez, 1986). For the lower FFB yields of smallholder and average plantation management (Figure 4.1), we reduced the input of pruned fronds proportionally.

Annually, a mature oil palm grows 60 to 90 cm in height (Tarmizi and Mohd Tayeb, 2006); over the 25-year plantation cycle, we assumed an average increase of 0.6 m/year.

The initial height at planting (when coming from the nursery) was set at 0.75 m. The initial rooting depth of oil palm is set at 20 cm, extending downward at constant pace until a final depth of 150 cm is reached after one year (Jourdan and Rey, 1997a). Growth of oil palm standing biomass was not simulated; a fixed average standing biomass was assumed.

Growth and development of leguminous cover crops

Similar to oil palm, we described growth of leguminous cover crops by simple linear functions, based on Quencez (1986) and Henson and Chang (2007). The cover crop canopy was modelled to provide full ground cover three months after planting. Due to increasing shade under the developing oil palm canopy, the cover crop canopy starts to die back at the beginning of year 3; in year 6 it has completely vanished. We assumed LAI = 3 at full cover (e.g. Haverkort et al., 1991) and an annual nitrogen return to the soil proportional to legume canopy cover, with a maximum of 150 kg N ha^{-1} y^{-1} (Giller, 2001). Maximum rooting depth of cover crops was assumed 60 cm, hence oil palm remained the deepest rooting crop, determining the depth and water holding capacity of the root zone.

Soil organic carbon

Soil organic carbon (SOC) dynamics are simulated by a simple 3-pool SOC model with an annual time step (Tittonell et al., 2010). SOC changes are the net effect of addition of carbon in crop residues and the on-going decomposition of crop residues and SOC. The model distinguishes active, slow and passive soil organic carbon pools, in order of increasing turnover time. Furthermore, different residue carbon pools are distinguished, i.e. C inputs from rachis, pinnae, roots, empty fruit bunches and shredded trunks (from previous plantation cycles). C from residue turnover first enters the active C pool; consequently, turnover of this active C pool is partly converted into CO_2 and partly 'humified' into stabile C. Of the turnover of residues containing relatively high fractions of lignin (the roots, Jourdan and Rey, 1997a), the lignin C flows directly into the stabile C pool (Parton et al., 1987). The relative annual decomposition rates of fronds (pinnae and rachises) and trunks were converted from daily rates measured by Khalid et al. (2000b) and are 0.54 (pinnae), 0.45 (rachis, trunk), 0.38 (roots). For EFB, we used a relative annual decomposition rate of 0.99, converted from the monthly value found by Lim and Zaharah (2000). The carbon content (CC) of all residues was set at 40% (Syahrinudin, 2005).

The model was modified to separately simulate SOC content under the frond stacks and the remaining area, which we will refer to as 'avenues'. Actually the remaining area may be subdivided into the weeded circle and the avenues, however, in both zones virtually all C input comes from turnover of palm roots. We simply assumed that roots are distributed uniformly over the plantation (Haron et al., 1998). Under the frond stacks, a large additional C input is coming from pruned fronds. In the avenues, legume cover crops are normally grown (Basiron, 2007). However, Haron et al. (1998) found no measurable influence of this organic resource on SOC; in quantity and quality, it may be considered negligible compared to the palm residues, especially if it dies back in the course of time due to increasing shade under the developing palms (Henson and Chang, 2007; Quencez, 1986).

We ran the model for three consecutive plantation cycles of 25 years, to investigate the duration of the effect of previous land use (anthropogenic savannah, secondary forest and replanted oil palm). The model was parameterized with data from the literature. The annual decomposition rate of organic carbon in the slow pool was set at 8%, based on data from Ultisols in similar climates in Sumatra and Brazil by Sitompul (2000) and Bernoux et al. (1998), respectively. The decomposition rate of the active pool was set at 0.69, based on earlier work with the model. Decomposition of the fraction of SOC that is physically protected or chemically resistant (the 'passive pool') was set to zero, similar to e.g. de Moraes et al. (1996).

Calibration for oil palm plantations was done using data from Haron et al. (1998) who measured SOC dynamics in weeded circles under the palms, avenues in between the palms and the frond stacks in oil palm plantations on Ultisols in peninsular Malaysia. Initially, these zones had equal SOC contents of 0.8%; this may constitute the baseline for soil organic matter derived from the previous forest cover in this case (Haron et al., 1998). However, they received different organic carbon inputs and therefore approached different equilibrium contents of soil organic carbon over time. We calibrated our model to replicate these SOC dynamics and set the initial SOC content under frond stacks and in avenues at 0.8 %. In the avenues, where the only C input comes from turnover of palm roots, we found that model output approached the measurements at 10 and 20 years after planting[$] if root turnover was set at 3.3 Mg C ha^{-1} y^{-1}. For the frond stacks, we assumed input of 10 Mg DM y^{-1}, of pruned fronds hence 4 Mg C y^{-1} during the plateau yield phase (BMP management, Table 4.1), on top of the 3.3 Mg C ha^{-1} y^{-1} from root turnover; changes in frond prunes supply over the years followed the shape of the BMP curve in Figure 4.1. A good fit with the measured data[1] was obtained after reducing this input of pruned fronds with a factor 0.62; this may account for the fact that a significant portion of the C input from pruned fronds could be lost, since most of the fronds are hardly in contact with the soil if concentrated on a small area. Following this reasoning, for BMP the conversion efficiency of fronds into SOC should be higher since they are spread over 70% of the

[$] Avenues 1.53% in year 10; 2.00% in year 20. Frond stacks 2.47% in year 10 and 3.09% in year 20 (Haron et al., 1998).

soil surface hence have much better contact with the soil. However, we did not make such an adjustment, due to lack of data.

Soil water balance
Our indicator for N leaching is based on the assumption that N leaching is correlated with the amount of water draining from the oil palm root zone to the subsoil. Similar to Chang and Chow (1985), we implemented a simple daily water balance model for estimating this amount. In addition to their approach, we included estimation of runoff. We simulated the water balance over three full oil palm plantation cycles of 25 years, taking into account the effects of palm and cover crop development on evapotranspiration, runoff and rooting depth. Also, we use daily weather data as input for our calculations. Since daily data were only available for three consecutive years (1989-1991), we randomly allocated one of these years to each year of the 75-year simulation period. Climate change was ignored. Rainfall for 1990 (1671 mm) was close to the average of 1663 mm, while 1989 and 1991 were relatively wet (1823 mm) and dry (1401 mm), respectively. We used the average annual drainage over 3 consecutive plantation cycles as indicator value; further details on our simulation of the soil water balance are provided in the Appendix.

Sustainability indicators - Net energy yield per hectare
The gross energy yield, i.e. the energy in the produced palm oil biodiesel was calculated as:

$$E_{gross} = Y_{FFB} \cdot \eta_{oil\ extraction} \cdot LHV_{palm\ biodiesel} \tag{4.2}$$

with E_{gross} the gross energy yield (GJ ha^{-1} y^{-1}), Y_{FFB} the fresh fruit bunch yield (Mg fresh matter ha^{-1} y^{-1}) , $\eta_{oil\ extraction}$ the oil extraction ratio (230 kg oil Mg^{-1} of FFB, Santosa, 2008) and LHV the lower heating value of palm oil biodiesel (37 GJ Mg^{-1}, Benjumea et al., 2008)

The net energy yield is calculated by subtracting the energy requirements for fertilisers (Table 4.1; West and Marland, 2002), agricultural operations and transporting feedstock to the mill, transport of palm oil to the biodiesel plant and transesterification from the gross energy yield. Energy requirements for extracting the oil at the mill are not taken into account since they are usually covered by combusting oil palm fibres and shells (De Vries, 2008; Sumiani, 2006). Energy requirements and emissions from pesticides were considered negligible (Brinkmann Consultancy, 2009; Wicke et al., 2007). It was assumed that during the agricultural phase, smallholders use no diesel; however for average plantation management and BMP we assumed a consumption of 2 l diesel Mg^{-1} FFB for mini-tractors collecting the bunches (Wood and Corley, 1991). Mechanised FFB collection may ensure quick transport to the mill which increases productivity and oil quality (Weng, 2005). For transporting FFB to the mill, we assumed a distance of 17 km (Wood and Corley, 1991), fuel consumption of small trucks of 1.8 MJ Mg^{-1} FFB km^{-1} and 65% of that requirement for the empty return trip (Damen and Faaij, 2006). For transporting the extracted palm oil to a biodiesel plant in the harbour of Medan, we assumed similar fuel consumption but a distance of 100 km. Energy requirement for transesterification was estimated as 6.5 GJ Mg^{-1} of biodiesel, including production of methanol from natural gas (Kaltschmitt et al., 1997). We used the average net energy over a 25-year plantation cycle as indicator value.

Sustainability indicators - GHG emissions

The greenhouse gas (GHG) emissions indicator was calculated on a gross energy basis (kg CO_2 eq. GJ^{-1} gross energy) similar to e.g. Farrell et al. (2006). We took into account emissions from changes in standing biomass and SOC, from the energy consuming processes listed in the previous section, N_2O emissions from the soil, and methane emissions from treatment of POME. Emissions arising from the change in carbon in the standing biomass, aboveground and belowground ($CO_{2,\Delta\,standing\,biomass}$, Mg CO_2 ha^{-1}) were calculated from average data from the literature (Table 4.2) according to:

$$CO_{2,\Delta\,standing\,biomass} = (C_{previous\,land\,use,\,ABG} + C_{previous\,land\,use,\,BLG} - C_{oil\,palm,\,ABG} - C_{oil\,palm,BLG}) \cdot F_{conv} \qquad (4.3)$$

with:

$CO_{2,\Delta\,standing\,biomass}$	CO_2 emissions resulting from changes in standing biomass;
$C_{previous\,land\,use,\,ABG}$;	the average aboveground (*ABG*) or belowground (*BLG*)
$C_{previous\,land\,use,\,BLG}$;	biomass of the previous landuse (Table 4.2, Mg C ha^{-1});
$C_{oil\,palm,\,ABG}$;	the average aboveground (*ABG*) or belowground (*BLG*);
$C_{oil\,palm,\,BLG}$;	standing biomass of oil palm (Table 4.2), Mg C ha^{-1};
F_{conv}	the conversion factor from C to CO_2 (3.66 kg CO_2 kg^{-1} C)

We did not simulate the gradual increase in oil palm standing biomass over a plantation cycle, but instead used the average standing biomass over a plantation cycle from Table 4.2 for each management scenario, ignoring a possible relationship between FFB yield and biomass. Therefore, $\Delta C_{standing\,biomass}$ is calculated as a one-time addition

***Table 4.2** Quantity of carbon stored in standing biomass and SOC for different land use types on Ultisols.*

Land use type	**C in aboveground biomass (Mg ha^{-1})** / **C in belowground biomass (Mg ha^{-1})**	**Sources**	**SOC upper 20 cm (%)**	**Sources**
Oil palm	50 / 20	Henson, 1998; Khalid et al., 2000a; Syahrinudin, 2005	Simulated	Syahrinudin, 2005
Secondary forest	132 / 33	Agus et al., 2009)	2.4%	Sitompul et al., 2000; Van Noordwijk et al., 1997
Anthropo-genic savannah	3.0 / 2.9	Syahrinudin, 2005	1.08%	Syahrinudin, 2005

to the simulated GHG emissions. GHG emissions from fertiliser production were estimated according to West and Marland (2002). N_2O emissions were estimated as 1% of the applied N fertiliser (IPCC, 2006). Methane emissions from POME were estimated as 9 kg CH_4 Mg^{-1} of FFB (Brinkmann Consultancy, 2009). Diesel emissions were 87.4 g CO_2 eq. MJ^{-1} (Punter et al., 2004). Emissions for transesterification were 439 kg CO_2 eq. Mg^{-1} of palm oil biodiesel (Kaltschmitt et al., 1997). We used the cumulative GHG emissions and cumulative gross energy over three consecutive plantation cycles for calculating our indicator value.

Sustainability indicators - Changes in soil organic carbon

This indicator was simulated by the SOC model; we used the difference between total SOC (frond stacks + avenues) at the end and the beginning of the simulation over three consecutive plantation cycles as an indicator.

Sustainability indicators - N leaching hazard / drainage

We assumed N leaching to be correlated with the amount of drainage water, simulated by the water balance sub-model. Since we did not mechanistically model the N concentration in the drained water, we simply used minimum and maximum N concentration found in literature for calculating estimates of minimum and maximum N leaching from our systems. We also compared results with those from Chang (1985), who conducted a very similar simulation experiment in oil palm plantations in Malaysia.

Sustainability indicators - Soil erosion

We used the soil-loss ratio (SLR) from the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1996) as an indicator for the erosion hazard. The SLR is an estimate of the ratio of soil loss under actual conditions to losses experienced under the reference conditions defined by Wischmeier (1978).

The soil loss over a hectare of plantation was calculated as the weighted average of soil loss in the frond stacks and under the trees; lateral interactions were ignored. Under the trees, additional cover by pruned fronds or legume cover crop was taken into account where relevant. We used the average annual soil loss over one plantation cycle as indicator value.

Sustainability indicators - Nitrogen Use Efficiency (NUE)

Similar to Chapter 2, we define the Nitrogen Use Efficiency (NUE, GJ net energy kg^{-1} N) as the efficiency with which applied fertiliser N is used for producing net energy. It is calculated as:

$$NUE = E_{net} / N_{fert} \tag{4.4}$$

with E_{net} the net energy yield (GJ ha^{-1} y^{-1}) and N_{fert} the N applied in fertilisers (kg N ha^{-1} y^{-1}). We used the average NUE over one plantation cycle as indicator value.

Water Productivity (WP)

Water productivity of the biodiesel production system (WP, GJ net energy m^{-3} evapotranspiration) was calculated as:

$$WP = E_{net} / (ET_{tot} \cdot 10) \tag{4.5}$$

with *WP* the water productivity of palm oil biodiesel (GJ net energy m^{-3} of evapotranspiration) and ET_{tot} the total evapotranspiration (mm). We used the average WP over one plantation cycle as indicator value.

4.3 Results

4.3.1 Net energy yield

Simulated net energy yields over a full plantation cycle are 149, 96 and 66 GJ ha^{-1} y^{-1} for BMP, average management and smallholders, respectively (Figure 4.2). Energy required for transesterification is proportional to oil or FFB yield. With higher yields, energy requirements for fertilisation also increase. However, this is partly compensated for by the use of legume cover crops and EFB (BMP) or ash (average plantation management). The effect of EFB ash is small (not shown), since we assumed N is lost with burning EFB.

4.3.2 Soil organic carbon

Simulated SOC for an average hectare of plantation (consisting of frond stacks and avenues in the proportions listed in Table 4.1) increases over time for plantings on anthropogenic savannah and secondary forest (Figure 4.3). The simulated increase was greater for plantings on anthropogenic savannahs (from 27 to 72-82 Mg ha^{-1} after 75 years, depending on management) than for plantings on former secondary forest (from 60 to 72-82 Mg ha^{-1} after 75 years, depending on management), due to the smaller initial SOC content (Table 4.2). The greatest quantity of soil C is sequestered during the first plantation cycle; at the beginning of the third plantation cycle, systems on previous anthropogenic savannahs and secondary forest with similar management have reached similar SOC content. Apparently, the final equilibrium SOC content is independent from previous land use.

Management has limited influence through frond pruning: SOC increases in the order smallholder (72.4 Mg ha^{-1} or 2.9%) < average plantation management (76.4 Mg ha^{-1} or 3.1%) < BMP (81.7 Mg ha^{-1} or 3.3%). Apparently, most of the sequestered SOC is from root turnover which was modelled to be independent from crop management. The peaks in SOC for BMP and average plantation management after 25 and 50 years are due to the C input from shredded palm biomass from the previous plantation cycle. Most of this biomass is decomposed again after a few years.

For plantations on secondary forest, an initial drop in SOC is simulated; this is partly due to low or absent biomass input during the establishment phase of the plantation, partly due to larger SOC turnover due to higher initial SOC content compared to anthropogenic savannahs, and partly caused by initialisation of the different residue pools in the model.

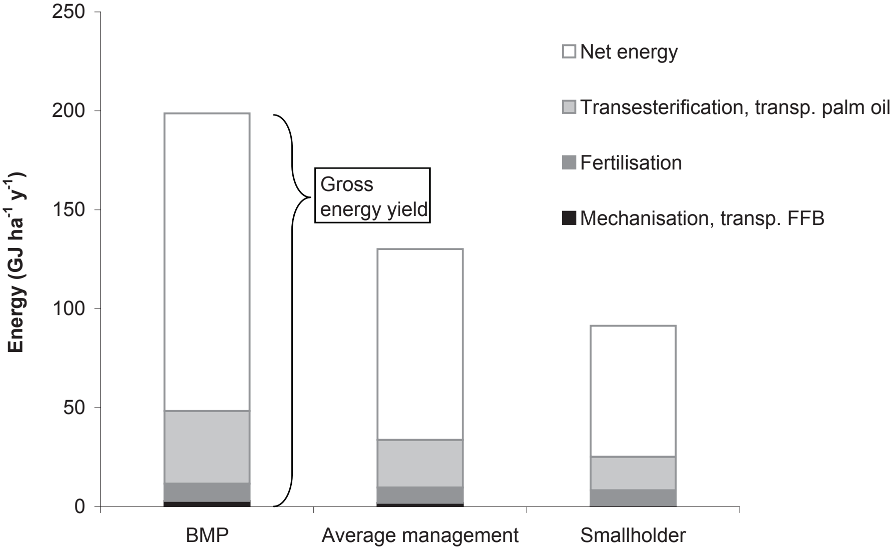


Figure 4.2 *Average annual net energy over a plantation cycle for BMP, average plantation management and smallholders*

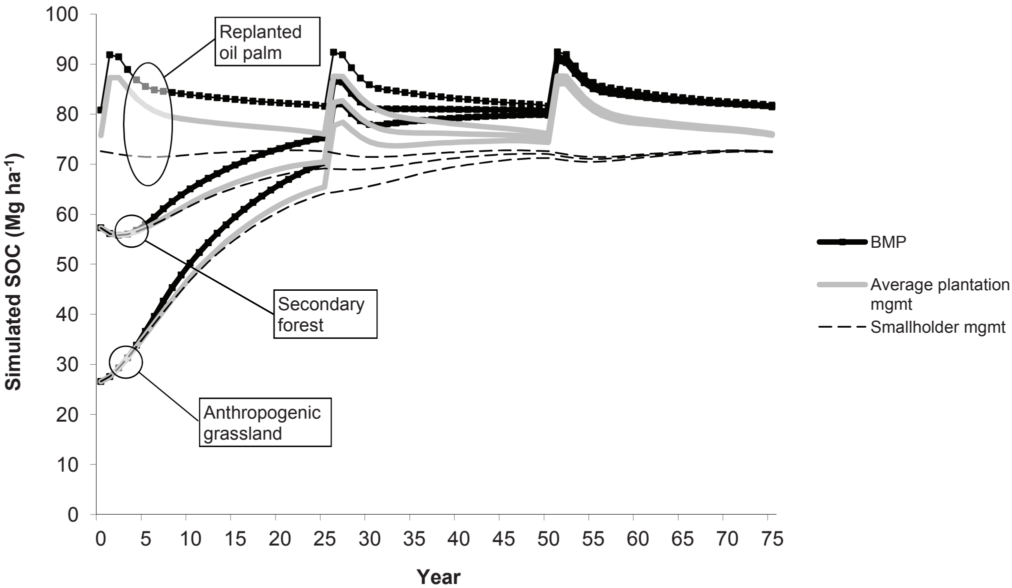


Figure 4.3 *Simulated total SOC (Mg ha^{-1}) for all assessed systems*

4.3.3 Greenhouse gas emissions

For plantations with average management planted on secondary forest, the one-time reduction in average standing biomass compared to forest (Table 4.2) is the greatest source of GHG emissions (348 Mg ha^{-1}, Figure 4.4). Next in importance are methane emissions from POME treatment, transesterification (methanol production and fossil energy use) and sequestration by the soil, respectively. Contributions from agricultural management, comprising fertilizer use, N_2O and diesel are relatively minor. It takes long before biodiesel from this system starts meeting its goal of reducing GHG emissions: the emissions avoided by using oil palm biodiesel instead of fossil diesel are exceeding emissions from the oil palm system temporarily after 24 years and definitively after 43 years (the 'carbon payback time', Figure 4.4), hence during the second plantation cycle. The temporary dips in the curve, caused by SOC sequestration correspond with the peaks in SOC in Figure 4.3, caused by C input from shredded biomass from old palms. Most of this sequestered C is decomposed again after a few years, however.

For plantings on degraded anthropogenic savannah and replanted oil palm, emissions resulting from changes in standing biomass are absent; average standing biomass in oil palm plantations is greater than that of anthropogenic savannahs (Table 4.2), hence net sequestration occurs, and when oil palm replaces oil palm, average standing biomass remains similar. For all systems, we calculated GHG emissions on a gross energy basis (Figure 4.5). Biodiesel production and use reduces GHG emissions if emissions are lower than those from fossil diesel of 87.4 g CO_2 eq. MJ^{-1} (Figure 4.5, Punter et al., 2004). This is achieved after 19 (BMP), 42 (average plantation management) and 68 years (smallholder management) for systems after secondary forest (Figure 4.5). Only systems on secondary forest create a carbon debt (Figure 4.5), due to large emissions from the change in standing biomass. For plantations on former anthropogenic savannahs, the sequestration of C in standing biomass and soil organic carbon is far greater than emissions from agriculture and processing hence emissions are negative (sequestration). With replanted oil palm there is no net change in SOC, in fact, C has already been sequestered or emitted during previous plantation cycles. Therefore, emissions are entirely determined by management aspects. The large difference between BMP and other management is due to the capturing of methane escaping from POME under BMP; these emissions increase carbon payback time by 10-20 years (data not shown) for smallholder and average plantation management. Emissions from systems after secondary forest and anthropogenic savannahs will in the longer run converge to those of replanted oil palm.

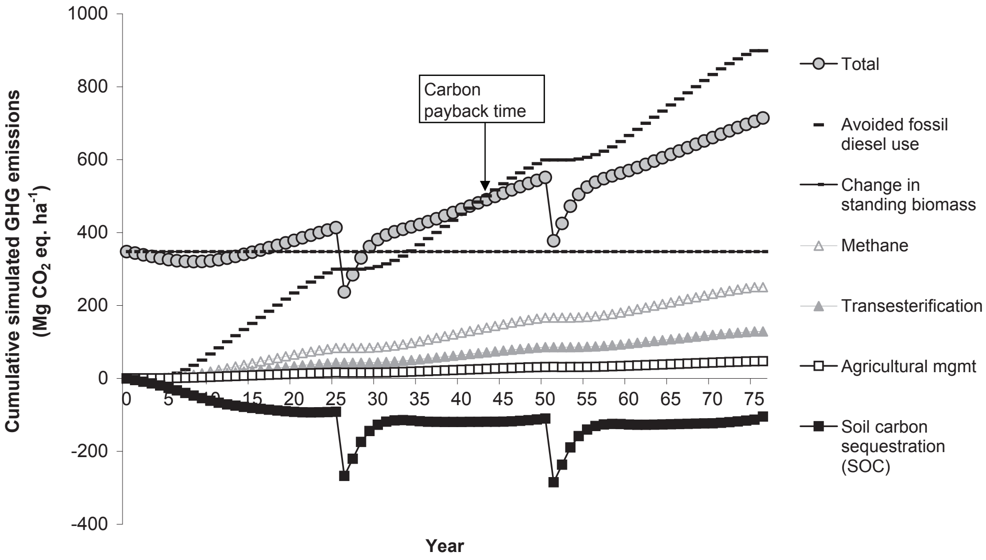


Figure 4.4 *Simulated cumulative GHG emissions (Mg CO_2 eq. ha^{-1}) for average plantation management planted on secondary forest. Carbon payback (indicated with arrow) is achieved where the avoided emissions from using fossil diesel start to exceed the total emissions from biodiesel production.*

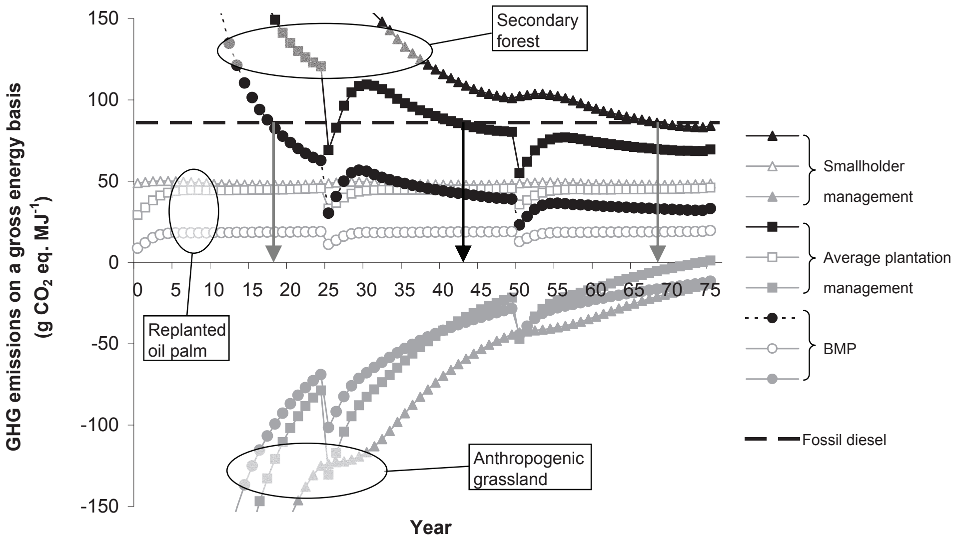


Figure 4.5 *Simulated GHG emissions for all assessed systems on a gross energy basis (g CO_2 eq. MJ^{-1}). Arrows indicate carbon payback times; the black arrow corresponds with the carbon payback time in Figure 4.4.*

4.3.4 Nitrogen leaching hazard / drainage

For smallholders, simulated annual drainage was negligible, except after replanting (years 26 and 51, Figure 4.6), when rooting of young palms is shallow. Simulated drainage under BMP (annual average 114 mm) was greater than under average plantation management (annual average 47 mm). With N concentrations in drainage water ranging from 0.79 – 2.31 ppm (Henson and Chang, 2007), average N leaching in our study of 0.9 – 2.6 kg N ha^{-1} y^{-1} is negligible. Drainage was inversely related to runoff, which was smallest for BMP (286 mm y^{-1}, on average), while for average plantation management and smallholders it was 447 and 669 mm y^{-1}, respectively.

4.3.5 Soil erosion

Simulated soil loss for average plantation management varies within the plantation between zones with different soil cover (Figure 4.7). If palm trees are the only soil cover (‘trees only’ treatment), soil loss decreases initially because of increasing LAI. However, once full canopy cover is reached after 5 years, the trend is reversed since the gradually increasing palm height increases drop impact and takes the overhand. If trees are underplanted with a quickly growing legume cover crop (‘trees and legumes’ treatment, Figure 4.7), the initial soil loss is controlled better, however, after 6 years, the cover crop has vanished and soil loss returns to the same rate as with palm trees only. In the frond stacks, which we assumed to be situated underneath the palm canopies, erosion is strongly reduced from year 4 on, when the palms become productive. Although their quantity is still limited at that time, the fronds are concentrated on 20% of the area (average plantation management, Table 4.1), hence directly providing strong protective effect in this case.

Average soil loss over a full plantation cycle for one hectare of plantation was 3.1, 6.6 and 7.4 Mg ha^{-1} y^{-1} for BMP, average plantations and smallholders, respectively. The lower value of BMP is caused by spreading fronds over a larger share of the plantation area; the difference between average plantation management and smallholder management is due to the difference in frond productivity (Table 4.2).

4.3.6 Nitrogen use efficiency (NUE) and water productivity (WP)

NUE for BMP was best, followed by average plantation and smallholder management, respectively (Figure 4.8). Nitrogen from cover crop litter contributed to the improved NUE for BMP and average plantation management (Figure 4.8). For BMP, the effect of EFB was of similar magnitude as that of legume cover crops. Water Productivity for BMP was best (10 MJ net energy m^{-3} actual ET) followed by average plantation and smallholder management with 7 and 6 MJ net energy m^{-3} actual ET, respectively.

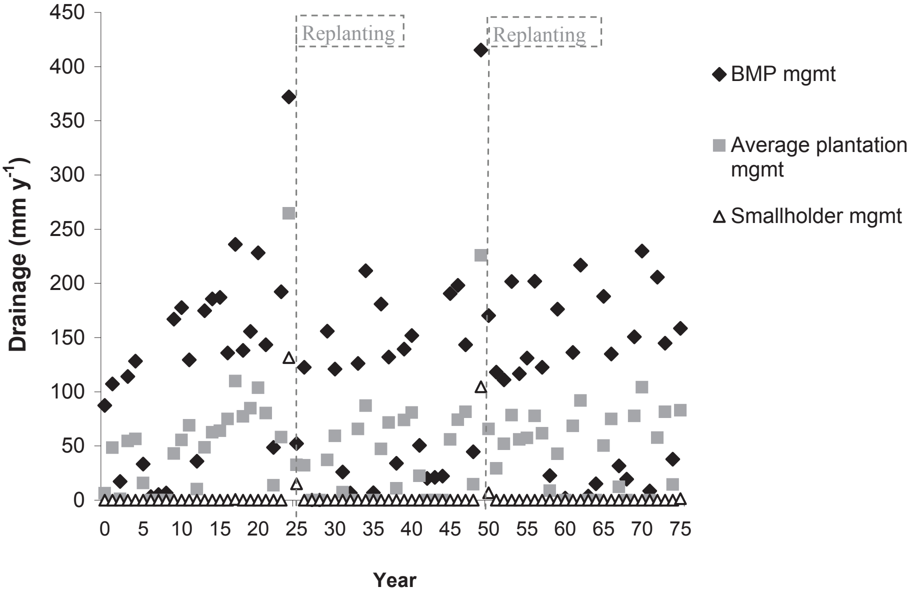


***Figure 4.6** Simulated annual drainage over three plantation cycles for BMP, average plantation management and smallholders management.*

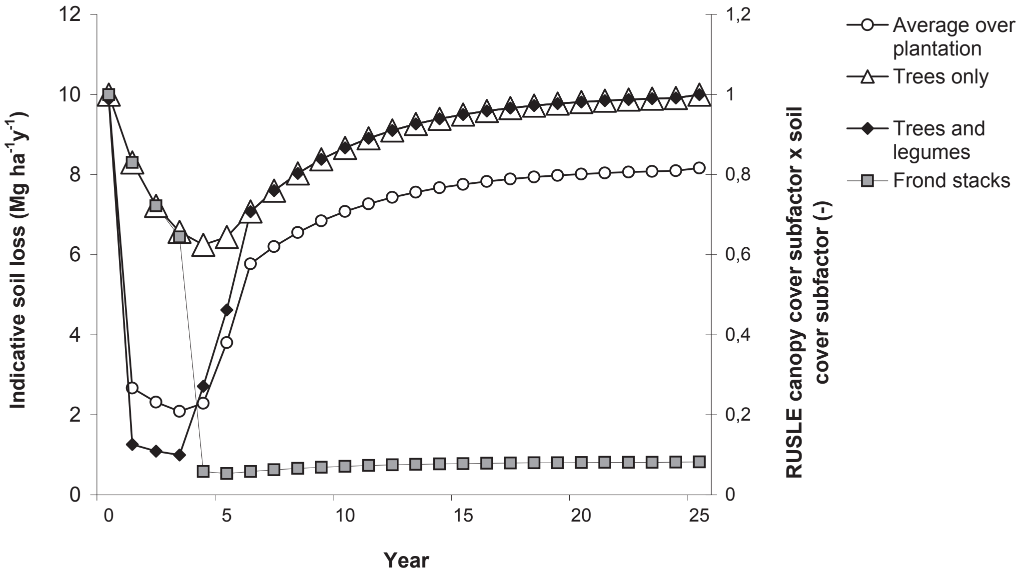


***Figure 4.7** Simulated indicative soil loss over one plantation cycle for different types of soil cover in a plantation with average management, and the soil loss of an average hectare of plantation, calculated as a weighted average of the soil loss in areas with tree and legume cover and the frond stacks. The latter averaged 3.1 Mg ha^{-1} y^{-1} over one plantation cycle.*

4.3.7 Synthesis of results

In order to facilitate comparing production ecological sustainability of the analysed systems, we expressed all indicator values as percentages of the best value that we found across all nine systems. For the GHG indicator, we displayed the percentage emission reduction compared to the replaced fossil diesel. Where reductions greater than 100% occurred (i.e. 'carbon negative' biodiesel; all systems planted on anthropogenic savannah, Figure 4.5) a reduction of 100% is displayed. SOC dynamics were captured in a single figure by taking the difference between soil C stocks at the end and the beginning of the simulation (75 years); this number was then again indexed as a percentage. Results for selected systems are displayed in Figure 4.9 a) – e).

Since BMP planted on anthropogenic savannahs performed best for all indicators and had negative GHG emissions, its relative score is 100% for all indicators (Figure 4.9c). Performance of BMP on secondary forest (Figure 4.9a) or with replanting (Figure 4.9b) only differed for the (interrelated) SOC and GHG indicators, due to different initial SOC contents and changes in standing biomass for secondary forest.

Over time, the effects of previous land use disappear and systems in Figures 4.9a and 4.9c converge towards those in Figure 4.9b: replanted oil palm under BMP. The same applies to smallholder and average plantation management: for these management types we only displayed replanted systems (Figure 4.9 d,e). Differences between figures 4.9 b, d and e are exclusively caused by management. Since these systems are at equilibrium, SOC build up is nihil. Further carbon sequestration for smallholder and average plantation management may however be achieved by adopting BMP.

4.4 Discussion

4.4.1 Assumptions made and their impact on the model outcomes

In this study, a number of generalisations and assumptions were made, some of which may have a substantial influence on the results, namely: (i) independence of crop management and crop growth from the previous vegetation; (ii) C input from pruned fronds proportional to FFB yield and introduction of a 'frond efficiency'; (iii) absence of a relationship between palm biomass production and yield; (iv) the initial SOC content of soil under forest and anthropogenic savannah. Instead of making these assumptions, actual data on crop management and crop growth could have been used. However, commercial plantations are generally hesitant to disclose management data, while independent smallholders are difficult to reach for obtaining such information. In this section, we discuss the validity of the assumptions that we made and the extent to which they influence our results.

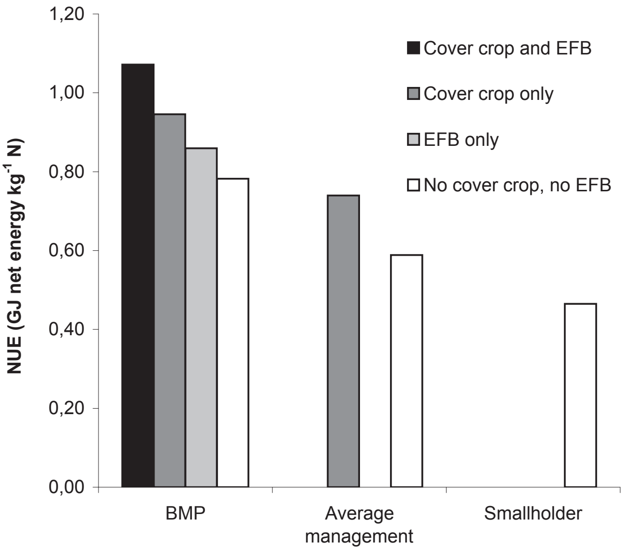
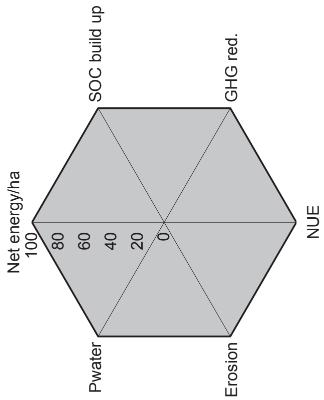


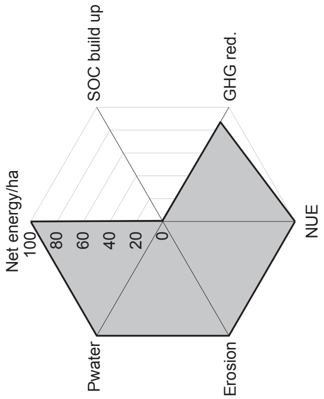
Figure 4.8 *Simulated NUE of BMP and average management with and without the effects of EFB and legume cover crop, and of smallholders*

(i) Our only data source showing relative independence of crop management from previous vegetation is Fairhurst (2009). Since most anthropogenic savannahs have replaced forest, soil physical properties should have remained be the same, generally. However, SOC content (cf. Table 4.2) and soil fertility under anthropogenic savannahs are reduced compared to soil under forest. When planting oil palm, this is generally addressed by a one-time application of 1 Mg ha^{-1} of rock phosphate (Fairhurst and McLaughlin, 2009), which in our analysis would be negligible in terms of energy and GHG emissions. With lower SOC content, N availability is normally also reduced. However, SOC levels after forest and anthropogenic savannah approach each other over the first plantation cycle and where the difference is largest, N requirements are smallest due to immature palms. No management data are available, but the potential effect of extra fertilisation in anthropogenic savannahs on our results is limited, considering the limited share of fertilisation energy in energy expenses (Fig. 2) and GHG emissions (cf. Figure 4.4). Land clearing is much more costly on secondary forest than on anthropogenic savannah (Fairhurst and McLaughlin, 2009) and therefore taking it into account would emphasize the results found in this study: higher GHG emissions for plantations on secondary forest.

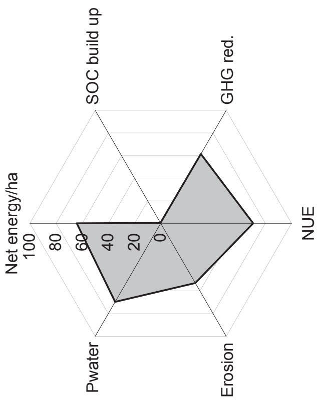
(ii) Our assumptions regarding the availability of pruned fronds exert only a minor influence on results: we found that root turnover was a much more significant contributor to SOC. Soil erosion is also relatively insensitive to variations in frond



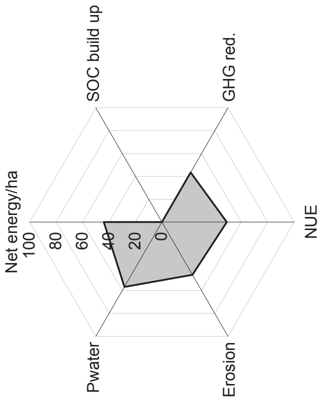
c. BMP after anthropogenic savannah



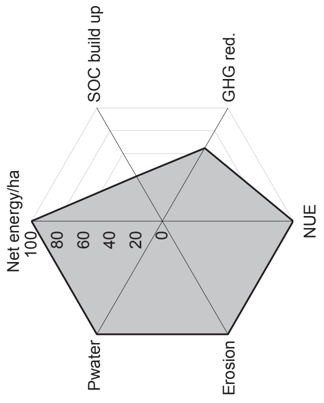
b. BMP, replanting



d. Avg mgmt., replanted oil palm



e. Smallholder, replanted oil palm



a. BMP after secondary forest

***Figure 4.9** Relative sustainability of selected systems. Indicator values (except GHG reduction) are indexed in percentages relative to the best indicator value found across all systems; BMP after anthropogenic savannah performed best for all indicators. GHG reduction is expressed relative to fossil diesel* pruning; even under smallholder management, more than enough fronds are pruned to cover the soil between the trees. It would however be more important to verify whether smallholders actually stack their fronds or have alternative uses for them.

(iii) Although we assumed palm biomass production (above and belowground) and yield to be unrelated, Henson (1998) found a fairly constant ratio between aboveground vegetative dry matter production and fruit bunch dry matter production, for palms aging 8-10 years in two different locations. Hence, higher yields would generally go hand in hand with greater standing biomass. In this case, GHG emissions from changes in standing biomass would be reduced for higher yielding systems (BMP), making the differences that we found between different management systems more pronounced. However, because of the limited data available and the fact that other factors may have a stronger effect on yield (e.g. the ratio between male and female flowers, the sex ratio), we did not include this effect in our model.

Regarding a possible relationship between belowground biomass production and FFB yield, a complicating factor are highly variable root-shoot ratios and a relative lack of research in this area (Henson and Chai, 1997). The constant turnover of root C of 3.3 Mg ha^{-1} y^{-1} that we obtained by calibration and applied across all management types implies a biomass turnover of about 3.3/CC = 8.25 Mg DM ha^{-1} y^{-1} in oil palm. Measured standing root biomass in oil palm varies from 7 to 59 Mg ha^{-1} (Henson and Chai, 1997; Jourdan and Rey, 1997b; Khalid et al., 2000c). Our calibration result seems to fit best with the results from (Jourdan and Rey, 1997a).

(iv) Our value of 2.4% SOC under secondary forest is within the IPCC values of 120 ± 60 Mg ha^{-1} of C for the 0-30 cm soil layer. It also reasonably in proportion with the SOC content that we used for anthropogenic savannahs of 1.1%, if one assumes soil carbon of these savannahs to be approximately half that of the forest type from which they were formed (Palm et al., 1986).

4.4.2 The influence of previous land use

Differences in indicators between different types of previous vegetation exclusively concerned the interrelated SOC and GHG indicators (Figure 4.9). The greatest increase in SOC is achieved on rehabilitated anthropogenic savannahs due to their initially small SOC content. We simulated a stronger increase in SOC than Syahrinudin (2005) measured in oil palm plantations after anthropogenic savannah on Ultisols in Sumatra. He found SOC content in the upper soil layers doubled after 30 years while in our simulations SOC increases with a factor 2.8 – 2.5, for BMP and smallholders respectively. In absolute terms, this represents sequestration of 48 - 55 Mg C ha^{-1} for smallholder management and BMP respectively (Figure 4.3). The increase in standing biomass from the *Imperata cylindrica*-dominated vegetation to oil palm represents sequestration of another 67 Mg C ha^{-1} (Table 4.2). Due to this great potential for carbon sequestration, planting on anthropogenic savannah could be considered eligible as a carbon sink in the UN's scheme for reducing emissions from deforestation and forest degradation (UN-REDD programme, 2010). This was also suggested by Anderson (2008), under the condition that no replanting was carried out. However, our findings show that replanting has negligible effect on soil C sequestration, eliminating the need for this restriction.

Compared with findings by Gibbs et al. (2009), Danielsen et al. (2008), Agus et al. (2009) and Aweto (1995), it may seem remarkable that we found an increase in SOC when secondary forest is replaced by oil palm. However, Lugo and Brown (1993) already pledged for a shift from the paradigm in which land conversion usually entails reductions in SOC in managed systems (agriculture and tree plantations) relative to mature tropical forests. They mention that after clearing forest, some plantation forests may lose SOC after conversion while others show fast rates of accumulation. Management objectives and intensity, site conditions, and species selection determine where in the response envelope a particular plantation may be. Oil palm plantations apparently are a favourable example.

This conclusion is supported by comparing residue inputs from forest and oil palm. Aboveground litter input of humid tropical forests may range from 8.8 – 10 Mg DM ha^{-1} y^{-1}, depending on soil fertility (Palm et al., 1996); this is similar to the input of pruned fronds in oil palm plantations. Data on belowground C input are more scarce; however, Palm et al. (1996) also mention that approximately 5.8 Mg DM ha^{-1} y^{-1} of below-ground inputs would be required to maintain soil organic matter levels similar to those of humid tropical forests. Based on calibration, we found a belowground input of 8.25 Mg DM ha^{-1} y^{-1} in oil palm.

That we found an increase in SOC instead of a decrease also depends on the specified SOC content of secondary forest; 2.4% is an average value for Sumatra. In reality, SOC content may vary with the age of the secondary forest and its previous land use history; decreases in SOC are also likely to be found in situations with a higher SOC content.

The best way of avoiding large GHG emissions and long carbon payback times is avoiding the large change in standing biomass C from deforestation. Oil palm after secondary forest pays back its carbon debt in 17, 43 or 68 years for BMP, average plantation and smallholder management, respectively (Figure 4.5). This is somewhat quicker than the 86 years found by Fargione et al. (2008). However, they assumed a carbon stock of standing forest biomass of 276 Mg C ha^{-1} for undisturbed forest, while we used a figure of 165 Mg C ha^{-1} for secondary forest, entailing a smaller carbon debt. The palm oil yield level considered by Fargione et al. (2008) is in between that of smallholder and average plantation management in our study. GHG emissions over the first plantation cycle of average plantation management after secondary forest are within the range calculated by Reijnders (2007); they assumed conversion of primary forest, entailing greater reduction in standing biomass hence higher GHG emissions, a slightly lower FFB yield and use of fossil fuels in the oil mill.

Planting new palms on anthropogenic savannahs results in negative emissions directly from the start hence has no carbon debt. However, further reduction of tropical rainforest should not only be stopped to avoid GHG emissions. Perhaps first and foremost it should be stopped because of biodiversity reasons. Expanding palm oil production by introducing BMP or rehabilitating anthropogenic savannahs should cause little harm to biodiversity.

4.4.3 The influence of management

Net energy yields

Net energy is strongly related to gross energy yield. The estimate of 149 GJ ha^{-1} y^{-1} for BMP is similar to the figure used in Chapter 2. The fraction of gross energy consumed by fertilisation is small and increases in the order BMP < average plantation management < smallholder management; this is due to the beneficial effects of legume cover crops and recycling of nutrients in EFB.

SOC content

Plantation management only causes variations in the eventual (equilibrium) SOC content of ca. 10% (Figure 4.3). Apparently root turnover, which was set equal for all treatments, remains a much more important determinant of SOC content than aboveground C input. A low degree of coupling between above ground inputs of frond material and the dynamics of soil organic carbon in Ultisols was confirmed by Law et al. (2009b) and Law et al. (2009a). In plantations on finer textured volcanic Andosols in West Sumatra, Fairhurst (2003) also found a minor difference between SOC content under frond stacks and weeded circle after 18 years. Possible factors underlying the more efficient conversion of C from root turnover into SOC could be the more intimate mixing of belowground inputs with the mineral phase of the soil, causing have lower decomposition rates (Van Noordwijk et al., 1997). The higher lignin content of oil palm roots (Jourdan and Rey, 1997a) also plays a role.

GHG emissions

With replanted oil palm, the main contributor to GHG emissions is methane from POME for average plantation management and smallholder management; for BMP it was captured. The large difference leads to the conclusion that capturing POME is an efficient way of reducing GHG emissions of oil palm biodiesel. Next in importance are emissions from transesterification. These could be reduced by using methanol from biomass origin, instead of producing it from natural gas.

N leaching and soil erosion

Our simulations indicate a trade-off between soil erosion and N leaching hazard. Improved soil cover, e.g. from spreading fronds over a large fraction of the area (BMP), may reduce runoff (and erosion) but improve infiltration and thereby increase the water available for drainage. Simulated average drainage of 114 mm y^{-1} for BMP is low compared to 858 mm y^{-1} simulated by Chang and Chow (1985) however. They did not take runoff into account, hence infiltration was 100%, and average rainfall in their case was also much higher at 2356 mm y^{-1}. Nevertheless they concluded that even in their case, leaching losses of nutrients are likely to be small. It seems that oil palm plantations, once established, are inherently fairly leaching proof due to their deep rooting zone and constant evapotranspiration, except perhaps after replanting (Figure 4.5). Estimated N leaching in our study of 0.9 – 2.6 kg N ha^{-1} y^{-1} is negligible compared to potential volatilization losses from urea fertilisers of more than 30 - 50% (Goh et al., 1999). N losses in runoff and eroded sediments may also be 5 - 8% of the applied N (Kee and Chew, 1996).

Though simulated independently, simulated runoff appeared in proportion with erosion results: from our results, we calculated an average sediment load in runoff water of 1.3 g l^{-1}. Results by Kee et al. (1996) indicate 0.3 – 1.1 g l^{-1} and Maene et al. (1997) measured 3.1 – 4.0 g l^{-1}.

Our results further indicate that with BMP, sufficient pruned fronds are present for covering 70% (or even a larger fraction) of the plantation soon after the plantation becomes productive hence providing excellent erosion control. Although not quantitatively assessed, we expect this also to apply for smallholder and average plantation management. Net soil losses may be lower than our results, due to sedimentation in the plantation of soil eroded from areas further up the slopes.

Nitrogen use efficiency (NUE), water productivity (WP)

Our NUE estimates are lower than the 1.2 GJ kg^{-1} of N calculated in Chapter 2; however, the fertiliser application in that paper is substantially lower at 88 kg N ha^{-1} y^{-1}. It may apply to different circumstances; optimum N fertilisation levels vary strongly with environment. The present work further demonstrates that applying EFB and planting of cover crops substantially contribute to improving NUE.

Simulated WP of BMP (10 MJ m^{-3}) is somewhat lower than the 12 MJ m^{-3} found in Chapter 2. For smallholder and average plantation management WP is poorer. Apparently, lower net energy yields compared to BMP outweigh the effect of lower evapotranspiration due to higher runoff. In the current modelling approach, yields are predefined and therefore do not change with evapotranspiration. It would take more research, e.g. with mechanistic oil palm growth models, to find out whether the chosen yield levels match well with the simulated levels of water stress.

4.5 Conclusions

Based on an assessment of a limited number of production-ecological sustainability indicators, new oil palm plantations planted on anthropogenic savannahs score much better for production-ecological sustainability than those on secondary forest, due to better SOC and GHG indicators. This is due to the great potential for carbon sequestration on these degraded lands. Hence, rehabilitating anthropogenic savannah by planting oil palm should be considered for eligibility as a carbon sink in the UN's scheme for reducing emissions from deforestation and forest degradation (UN-REDD programme, 2010). After one plantation cycle of 25 years, most of the sequestration potential has been realised however and systems progress towards a new steady state with constant SOC. Differences between systems at steady state are exclusively caused by differences in crop management. BMP scores much better than average plantation management and smallholder management; the difference between the latter two systems is relatively small. Capturing methane escaping from POME significantly reduces GHG emissions of BMP. Another key aspect of BMP contributing to its favourable performance is frond mulching over a relatively large fraction of the surface. This reduces soil erosion and runoff and increases infiltration. More water is available for the crop therefore, while leaching hazard remains negligible. Legume cover crops and mulching of EFB contribute to favourable nitrogen use efficiency of BMP. We conclude that both proposed solutions to reduce pressure on the world's remaining forest reserves that we assessed, yield intensification through best practice management, and area expansion on degraded anthropogenic grassland, perform well in terms of production ecological sustainability compared to the other options for producing palm oil.

Appendix I: additional model description

Simulation of the soil water balance

The water balance in oil palm plantation was calculated according to:

$$SWC = (P - Q) - E - T - D \tag{1}$$

where:

SWC is the soil water content of the root zone (mm)
P is the precipitation (mm)
Q is the amount of rain that directly disappears through runoff (mm)
E is the soil evaporation (mm)
T is the transpiration by oil palm and cover crop (mm)
D is the drainage of water from the rootzone to the subsoil (mm)

Drainage occurs whenever simulated soil moisture content (SWC) of the root zone exceeds the water content at field capacity (0.25 m^3m^{-3}); in such case, the excess water is assumed to drain to the subsoil. Water holding capacity of the root zone increases linearly with rooting depth, hence the risk of leaching is greatest with immature palms; assumptions regarding root growth of oil palms and cover crop were explained above. Q is calculated according to the US Soil Conservation Service (SCS) 'Curve Number' method (Mockus, 1972 ; USDA, 1986):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2}$$

where
Q is the runoff (mm)
P is the precipitation (mm)
S is the potential maximum water retention once runoff begins (mm). It is related to soil and cover conditions through the curve number (CN) by:

$$S = \frac{1000}{CN} - 10 \tag{3}$$

We used CN values for orchards or tree farms of 57, 43 and 32 for poor ground cover (smallholder), average ground cover (average plantation management) and good ground cover (BMP), (USDA, 1986).

E and T of oil palm and leguminous cover crops are calculated according to the 'FAO56' method (Allen et al., 1998), where a reference crop (grass) evapotranspiration is multiplied with appropriate crop coefficients (K_c) to obtain oil palm and cover crop evapotranspiration. We used the 'dual crop coefficient approach' where K_c is split into two separate coefficients, one for crop transpiration (i.e., the basal crop coefficient K_{cb}) and one for soil evaporation (K_e), enabling separate calculation of these terms. Evaporation is assumed to draw water from the upper 10 cm of soil only (Allen et al., 1998); when water content falls below the readily evaporable water content (REWC, values for different soil textures given by (Allen et al., 1998)), evaporation is no longer only energy limited and enters the 'falling rate stage' until it completely ceases when all evaporable water (TEWC) has gone (Allen et al., 1998). TEWC may be calculated as:

$$TEWC = 1000 \cdot (\theta_{FC} - 0.5\theta_{WP}) \cdot Z_e \qquad (4)$$

with

TEWC	the total evaporable water content (mm)
θ_{FC}	the soil water content at field capacity (m^3 m^{-3})
θ_{WP}	the soil water content at wilting point (m^3 m^{-3})
z_e	the depth of the surface soil layer that is subject to drying by way of evaporation (0.10 m)

Similarly, when the crops have transpired water readily available for transpiration (RTWC), transpiration is reduced; it completely stops when all crop available water (TTWC) has been exhausted. TTWC may be calculated as:

$$TTWC = 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot Z_r \qquad (5)$$

with

TTWC	the total evaporable water content (mm)
θ_{FC}	the soil water content at field capacity (m^3 m^{-3})
θ_{WP}	the soil water content at wilting point (m^3 m^{-3})
z_r	the rooting depth

RTWC may be calculated as

$$RTWC = p \cdot TTWC \qquad (6)$$

with

RTWC	the readily available water content (mm)
p	the average fraction of TTWC that can be depleted from the root zone before moisture stress occurs (-). For oil palm, we used a value of 0.65 (Allen et al., 1998)

K_{cb} was calculated according to FAO-56 methodology, taking into account LAI and height of palms and cover crop (where present).

Calculation of the soil cover (SC) and canopy cover (CC) subfactors of the Revised Universal Soil Loss Equation (RUSLE)

We used the soil-loss ratio (SLR) from the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1996) as an indicator for the erosion hazard. The SLR is an estimate of the ratio of soil loss under actual conditions to losses experienced under the reference conditions defined by (Renard et al., 1996). The SLR may be calculated as the product of a number of sub factors (Renard et al., 1996):

$$C = PLU \cdot CC \cdot SC \cdot SR \cdot SM \tag{7}$$

where

PLU	is the prior-land-use subfactor (-),
CC	is the canopy-cover subfactor (-),
SC	is the surface-cover subfactor (-),
SR	is the surface-roughness subfactor (-),
SM	is the soil-moisture sub factor (-)

Since we focused on the effects of plantation management on erosion we only considered the product CC · SC which may range from 0 (maximum erosion protection from crop canopy and residue cover) to 1 (no erosion protection from crop canopy and residue cover). Although previous land use (PLU) differs between treatments, we did not have enough data for calculating this effect. Further, SR describes the effects of tillage, which is less relevant in oil palm plantations, while variations in SM may be disregarded if erosion risk is calculated on an annual basis.The canopy-cover sub factor may be calculated as:

$$CC = 1 - F_c \cdot e^{(-0.328h)} \tag{8}$$

where

CC	is the canopy-cover subfactor ranging from 0 to 1;
F_c	is fraction of land surface covered by canopy; the development of crop cover by palms and legume cover crops over time was described above;
h	is the distance that raindrops fall after striking the canopy (m); we set it equal to palm height.

For estimating the effect of mulching pruned fronds, we calculated the SC factor:

$$SC = e^{\left[-b \cdot S_p \cdot \left(\frac{0.61}{R_u}\right)^{0.8}\right]} \tag{9}$$

where:

b is an empirical coefficient; it was set at 0.025 for fields dominated by interrill erosion (Renard et al., 1996)

S_p is the percentage of land area covered by surface cover (pruned fronds);

R_u the is surface roughness (cm); it was set at 0.61 cm, the value for unit plot conditions of clean cultivation smoothed by extended exposure to rainfall of moderate intensity.

S_p may be calculated as:

$$100 \cdot [1 - e^{-\alpha \cdot B_s}] \qquad (10)$$

where

α is the ratio of the area covered by a piece of residue to the mass of that residue (ha kg^{-1}); Ozara (1992) gives a value of 0.0002 ha/kg;

B_s is the dry weight of crop residue on the surface (kg ha^{-1}); in our study it concerns the decomposing pool of pruned fronds

For obtaining indicative estimates of annual soil loss, we multiplied CC · SC with a combined estimate of the remaining factors of the RUSLE of 10 Mg ha^{-1} y^{-1}. Simulated soil losses in avenues and under frond stacks for average plantation management then correspond roughly with measured data by Maene et al. (1997) for a 'standard slope' (Wischmeier and Smith, 1978) in an oil palm plantation with climate and soil similar to our case.

chapter 5

First and second generation biofuel cropping systems in Brandenburg, Germany: a comparison of their production-ecological sustainability

We assessed and compared the production-ecological sustainability of first and second generation biofuel production systems in the state of Brandenburg, Germany. Production ecological sustainability was defined by a set of sustainability indicators including net energy yield per hectare, GHG emissions, N leaching, soil organic and soil erosion, and several resource use efficiencies. The assessed first generation fuels are biodiesel and bioethanol produced from rapeseed (*Brassica napus* L.) and sugarbeet (*Beta vulgaris* L.) feedstock, respectively. Assessed second generation systems are based on feedstock from Miscanthus (*Miscanthus x giganteus* Greef et. Deu. ex Hodkinson et Renvoize) and black locust (*Robinia pseudoacacia* L.); for both crops conversion into cellulosic ethanol and Fischer Tropsch Diesel was assessed. Second generation biofuel production systems based on Miscanthus and black locust perform substantially better than first generation systems based on rapeseed and sugarbeet. They contribute much more to GHG emission reduction, had much higher net energy yields and better resource use efficiencies; soil erosion and N leaching were also lower. Miscanthus performed better than black locust, except for its N use efficiency; it is the most water-efficient species, which is important in a region with declining groundwater tables. However, in Brandenburg, low temperatures during winter and early spring are often threatening to survival of first-year Miscantus plantings; there have been disastrous experiences in the past. The drawback of black locust is that it has invasive characteristics. Of the first generation systems, rapeseed has low net energy yields and large N requirements per unit of energy produced; it also performed poorly for N leaching. Erosion hazard in rapeseed is especially present after the seedbed has been prepared in the end of summer. Greatest erosion risk was calculated for sugarbeet however, due to its late canopy closure.

This chapter is submitted as:
De Vries SC, Van de Ven GWJ, Van Ittersum MK. First and second generation biofuel cropping systems in Brandenburg, Germany: a comparison of their production-ecological sustainability
European Journal of Agronomy

5.1 Introduction

From a production-ecological perspective and assuming no cost at the expense of ecosystems, first-generation biofuels produced from tropical crops such as sugarcane (*Saccharum officinarum* L.) and oil palm (*Elaeis guineensis* Jacq.) are more sustainable than from temperate crops such as sugarbeet (*Beta vulgaris* L.) and rapeseed (*Brassica napus* L.) (Chapter 2). This is due to their favourable harvest indices, C4 photosynthesis and perennial nature. However, energy crops exist that possess similar features and yet can be grown in temperate areas; examples are *Miscanthus* (*Miscanthus x giganteus* Greef et. Deu. ex Hodkinson et Renvoize), willow (*Salix* spp.), poplar (*Populus* spp.) and black locust (*Robinia pseudoacacia* L.). Unlike first-generation crops, these species contain no plant oil, sugar or starch that can easily be converted into biodiesel or bioethanol. They largely consist of ligno-cellulosic compounds and hence require more advanced (second generation) processing methods. Cellulose may be converted into ethanol along biological pathways, using modified yeasts (Ragauskas et al., 2006), while biodiesel from ligno-cellulosic biomass is mostly obtained by gasification and consecutive Fischer Tropsch synthesis ('Biomass to Liquid', BtL; cf. van Vliet et al., 2009). At present, the production of such fuels is not cost-effective because there are a number of technical barriers that need to be overcome before their potential can be realized (Naik et al., 2010). Virtually all biofuels are therefore produced with first-generation technology (OECD and FAO, 2011). In Germany for instance, the country with the largest biodiesel production volume in the world (US-EIA, 2011), biodiesel is almost exclusively produced from rapeseed (FNR and BMELV, 2011a), while bio-ethanol is produced from wheat (*Triticum aestivum* L.), rye (*Secale cereale* L.) and sugarbeet (FNR and BMELV, 2011b). Rapeseed, wheat and sugarbeet require good quality agricultural land (LVLF, 2010). Replacing these feedstocks with ligno-cellulosic crops that can be grown on lower quality land and have higher net energy yields could substantially reduce indirect land use change by releasing sugarbeet and rapeseed production for food purposes. It could also be more favourable for soil carbon sequestration.

Miscanthus is such a ligno-cellulosic crop and has enjoyed considerable attention from researchers in Germany over the years (cf. Jones and Walsh, 2001). Of more recent origin is the interest in black locust for biomass (Grünewald et al., 2009). This legume species has habitat-forming characteristics and is often planted in poor and loose sandy soils to fix and enrich them (Rahmonov, 2009). Fast growth, good resprouting ability after cutting and high wood density proved to be particularly useful for the production of woody biomass for bioenergy in areas with marginal soils (Böhm et al., 2011). Marginal soils can be defined as soils on which cost-effective production is not or hardly possible; it is an economic term (Schroers, 2006). Black locust is mentioned as a feedstock for BtL (CHOREN, 2011a). It is native in North America. Since the early 1600s, when black locust seeds were first sent to France, it has been extensively planted throughout Europe, U.S.S.R., Korea and China. There are now over one million hectares of black locust plantations, making it second among broad-leaved species only to Eucalyptus spp. on the basis of world-wide planted area (Boring and Swank, 1984).

In this chapter, we assess and compare the production-ecological sustainability of biofuel production chains based on *Miscanthus* and black locust ('second generation') with production chains based on sugarbeet and rapeseed ('first generation') in the state of Brandenburg. Brandenburg was selected because of its relatively low population density, large-scale agriculture and general interest in renewable energy. Rapeseed, sugarbeet and *Miscanthus* were assumed to be grown on agricultural land; black locust production was assessed on reclaimed mine soils. Ca. 77,000 ha land in the southeast of Brandenburg (*Lausitz*/Lusatia) are affected by large-scale open-cast lignite mining operations (Grünewald et al., 2009). After removal of the overburden sediments up to 120 m depth and consecutive extraction of the lignite, it is required by law (Bundestag, 2004a) to 'recultivate' the land: 'to achieve a natural, pre-industrial landscape' (Vattenfall, 2009; Vattenfall, 2011). One of the most important issues for restoration of ecosystems in post-mining landscapes is soil formation through accumulation of organic C in the surface layers of the spoil material (Keskin and Makineci, 2009). To supply this organic C, over the years planting of different tree species has been carried out. Under deciduous trees, organic matter with higher bioactivity and better water and nutrient balance is found than under pine and larch (Katzur and Haubold-Rosar, 1996). As part of a 170-ha project, the mining company Vattenfall Europe Mining started with the establishment of *R. pseudoacacia* on mining substrates in 2005 (Grünewald et al., 2009).

Brandenburg may be considered representative of the agro-ecological conditions prevalent in large parts of Poland, Hungary, Rumania, Bulgaria, Slovakia and the Czech republic, with precipitation below 600 mm y^{-1} (Nellesteijn and Dekker, 1998) and mostly sandy soils with low base saturation (dystric cambisols; FAO/UNESCO, 2007). In a climatic stratification of the environment of Europe (Metzger et al., 2005), these areas are grouped under the continental zone. In our assessment, we used the same sustainability criteria as in Chapter 2. Some of these are of legal importance in the case study area: soil erosion and soil organic matter content are part of the German Ordinance on Direct Payments (Bundestag, 2004b) while GHG emission reduction is part of the Sustainability Decree for Biofuels (Bundestag, 2009).

5.2 Methods

5.2.1 Soils

Soils in Brandenburg are predominantly sand and loamy sand; less than 20% of the arable land consists of better quality sandy loam and sandy loess soils (Holsten et al., 2009; Wechsung et al., 2000) whilst loam and clay soils constitute only 3% of the area (LVLF, 2010). We assessed sugarbeet production on loam (data from SEAMLESS project; Hazeu et al., 2010: Table 5.1) since in Northern Europe, sugarbeet is often grown on heavier soils (Elzebroek and Wind, 2008). Production of rapeseed and *Miscanthus* is assessed for the predominant loamy sand (Table 5.1). They can both be grown on a wide range of soils, as long as they are well-drained (Elzebroek and Wind, 2008; Lewandowski et al., 2003). Black locust cultivation was assessed on reclaimed mine soils; these have loamy sand and sandy loam textures (Grünewald et al., 2007), similar to the agricultural soils; in the assessment we used loamy sand (Table 5.2). SOC content of ~0.5% is also similar to that of the agricultural soils (Bungart and Hüttl, 2004). The main differences between agricultural soils and reclaimed mine soils are soil chemical properties such as acidity and nutrient availability and the absence of soil aggregates. Further, part of the total C in these soils can be assigned to lignite (Rumpel et al., 1998). These issues are not explicitly taken into account by our models, but are accounted for by using actual yield data from production systems on reclaimed mine soils.

Table 5.1 *Properties of the soils used in the assessment (Hazeu et al., 2010)*

Soil type	Crops assessed	Sand (%)	Silt (%)	Clay (%)	SOC (%)	Bulk density (Mg m^{-3})	Relative volumetric water content at wilting point	Relative volumetric water content at field capacity
Loam	Sugarbeet	45	35	20	1.5	1.3	0.150	0.347
Loamy sand	Rapeseed, *Miscanthus*, Black locust	80	10	10	0.5	1.6	0.059	0.243

5.2.2 Crop production

For rapeseed and sugarbeet, input usage and crop and crop residue yields from agricultural practice in Brandenburg were used (LVLF, 2010). Since *Miscanthus* and black locust cultivation in Brandenburg are still in the experimental phase, for these crops we used data from experiments. Furthermore, for all of the assessed crops, we used dynamic crop growth models for obtaining daily values of leaf area index (LAI, m^2m^{-2}) and evapotranspiration (mm d^{-1}) during the season as these were required for calculating soil erosion and water productivity. We ran the models for water-limited production, assuming that all systems are entirely rainfed and that no limitation from nutrient shortages occurs. However, for black locust on reclaimed mine soils, we calibrated a crop growth model so that simulated yields matched with actual biomass yields in trials (Grünewald et al., 2009); in these soils, nutrient limitations are likely to occur. Daily weather data from the SEAMLESS project (Hazeu et al., 2010) for Brandenburg were available for 25 years (1982-2006) and used as model input; soil data were derived from the same source. For calculating soil erosion and water productivity, we used averaged daily model results of LAI and evapotranspiration over the 25 years of simulation. A summary of the cultivation systems and of the crop growth models used is given below for each of the four feedstock crops.

Miscanthus stands are established through vegetative propagation by rhizome pieces or by plants grown from callus culture. We considered planting from rhizomes since this is more favourable than using micro-propagated plants in terms of growth and winter survival in the first year (Christian and Haase, 2001) and in terms of energy use; energy cost of the propagation material is considered negligible (Ercoli et al., 1999). Planting can be done from the middle of May to the beginning of June when the soil temperature reaches 10°C (Lewandowski et al., 1995). Every year in spring shoots emerge from the rhizomes. Shoots may reach a height of 3 m. Growth stops in autumn, but usually the senescent crop is left in the field until harvest at the end of winter. By then, most of the leaves have fallen, and the harvested biomass is mainly stem material. The estimated productive lifetime of a *Miscanthus* crop is 10-15 years (Vleeshouwers, 2001); we used 15 years in our calculations. In the year of planting, usually no yield is obtained; in the second and third year after planting, 50% and 90% of full productivity are attained, while full productivity is reached in the fourth year after planting. (Vleeshouwers, 2001). In Germany, an extensive network of Miscanthus field trials was established in 1990-1992; at maturity, yields of on average 19 Mg DM ha^{-1} were measured (Clifton-Brown et al., 2001). We assumed 60% of this dry matter can be harvested in spring (Table 5.2; Kahle et al., 2001); the remaining 40% remains in the field as litter and stubble and is used as C input in our SOC simulation. Fertiliser applications and diesel use in *Miscanthus* are based on Lewandowski et al. (1995). Weed control is essential during the establishment phase of the crop because the slow initial growth of *Miscanthus* restricts its ability to compete. Although herbicides can be used, weed control is mostly reported to be done mechanically (cf. Ercoli et al., 1999; Lewandowski et al., 1995). In subsequent years, weeds are effectively suppressed by leaf litter on the soil surface and canopy closure (Christian and Haase, 2001). There are no reports of plant diseases significantly reducing the productivity

Table 5.2 Characteristics of the assessed crops and cropping systems

	Miscanthus	Black locust	Winter oilseed rape	Sugarbeet
Sowing/planting	May/June, once per 15 years	Spring, once per 27 years	1 September	1 April
Harvest	Winter, annually	Winter, every 3 years	1 July	10 October
Source of yield and residue data	Experiments (Clifton-Brown et al., 2001; Kahle et al., 2001)	Experiments (Grünewald et al., 2007; Grünewald et al., 2009)	Brandenburg statistics (LVLF, 2010)	Brandenburg statistics (LVLF, 2010)
Feedstock yield (fresh; dry; Mg $ha^{-1}y^{-1}$)	13.4[a]; 10.2[a]	10.0[a]; 6.5[a]	3.6; 3.2 (seeds)	55.0; 13.8 (beet)
Residues (fresh; dry; Mg ha^{-1})	9.4; 7.1	6.2; 4.0	6.1[b]; 5.2	38.5[b]; 6.2
Residue type	Foliage, stem tips, stubble	Foliage	Straw	Foliage
N fertiliser (kg N $ha^{-1}y^{-1}$)	80	-	121	99
P fertiliser (kg P $ha^{-1}y^{-1}$)	15	20[c]	28	22
K fertiliser (kg K $ha^{-1}y^{-1}$)	130	20[c]	30	116
Lime (kg CaO $ha^{-1}y^{-1}$)	-	256[d]	-	-
Biocides (kg a.i. $ha^{-1}y^{-1}$)	-	-	3.1	4.3
Diesel (l $ha^{-1}y^{-1}$)	84	48	48	83
Sources of input use	Experiments (Lewandowski et al., 1995)	Experiments (Grünewald et al., 2009); (Grünewald et al., 2007)	Brandenburg Statistics (LVLF, 2010)	Brandenburg Statistics (LVLF, 2010)

[a] average over a plantation cycle, spring harvest (Miscanthus)
[b] calculated using harvest indices (Landwirtschaftskammer Nordrhein-Westfalen, 2011)
[c] applied as 100 kg, once every 5 years
[d] applied once as 6150 kg CaO ha^{-1}, before plantation establishment; only required on mine soils

of *Miscanthus* (Lewandowski et al., 2003). *Miscanthus* soil cover development and evapotranspiration were simulated with the crop growth model MICROSIM (MIscanthus CROp SImulation Model; Vleeshouwers, 2001), based on the LINGRA grassland model (Schapendonk et al., 1998), which uses a light use efficiency approach. Simulated key processes are light utilization, leaf formation, leaf elongation and carbon partitioning (storage, shoot, root). Source- and sink-limited growth are simulated independently. Sink-limited growth is characterized by temperature-dependent leaf expansion, whereas source-limited growth is determined by the photosynthetic light use efficiency of the canopy and the remobilization of stored carbohydrates in the stubble (Schapendonk et al., 1998). MICROSIM was calibrated with data from field experiments in the Netherlands (Vleeshouwers, 2001). Simulated water-limited yields over 25 years were 20.7 Mg ha^{-1} and correspond well with the reported average actual yield of 19 Mg DM ha^{-1} that we used in the calculations.

Yield and production system of black locust were based on coppicing trials over nine years with this species on reclaimed mine soils in Lusatia, Brandenburg (Grünewald et al., 2007; Grünewald et al., 2009). As a legume crop, black locust needs no N fertilisation. The productive lifetime of black locust plantations is estimated at 27 years (Grünewald et al., 2009). Stems are harvested every three years during winter; average annual dry matter production is assumed to be 3 and 4.8 Mg DM $ha^{-1}y^{-1}$ during the 1st and 2nd 3-year growing period, respectively; from the third harvest on, it is assumed to be 7.2 Mg DM $ha^{-1}y^{-1}$. Diesel consumption by agricultural machinery was assumed similar to that of short rotation coppice from poplar (LVLF, 2010), but adjusted for coppicing every third year instead of every fifth year. We found no reported use of biocides in black locust. The model SACROSIM (SAlix CROp SImulaton Model; Vleeshouwers, 2001) for willow was modified for black locust and used for simulating LAI and estimating ET_{season} under the assumption that phenology of the two species is roughly the same if grown for SRC (cf. biomass partitioning over leaves and stems; Boring and Swank, 1984; Cannell et al., 1987). SACROSIM is based on earlier willow models (Cannell et al., 1987; Eckersten, 1994) and uses the concept of light use efficiency. Relationships for the growth and development of LAI (leaf production and leaf fall), and the partitioning of assimilates to different plant organs were modelled explicitly (Vleeshouwers, 2001). We modified SACROSIM by adjusting the maximum light use efficiency parameter until average productivity over the period 1982-2006 matched that of mature black locust SRC in the case study area of 7.2 Mg DM ha^{-1} y^{-1} (Grünewald et al., 2009). Reduced light use efficiencies in crops may be caused by growth limiting factors, i.e. water and nutrient shortages.

For sugarbeet and winter oilseed rape we assessed the current production system in Brandenburg; yields and input use (LVLF, 2010) are summarized in Table 5.2.

Sugarbeet fields are ploughed in the autumn prior to sowing (Elzebroek and Wind, 2008), we assumed on 1 October. We used 1 April as sowing date and assumed that the field is bare until crop emergence in mid-April. Biocide usage data were not directly available from LVLF (2010), hence we relied on other sources. Biocide usage in sugarbeet was estimated at 4.3 kg a.i. ha^{-1}; the average herbicide application is 3.7 kg a.i. ha^{-1} (Coyette et al., 2002) and herbicides make up 86% of the biocide usage in German sugarbeet cultivation (Roßberg, 2007). Winter oilseed rape in Germany is normally sown in the end of August or the beginning of September (UFOP, 2011); we used 1 September as the sowing date. Harvest takes place in July; the straw normally remains in the field (UFOP, 2011). Biocide application in rapeseed was set at 3.1 kg active ingredient (a.i.) ha^{-1} (Moerschner et al., 2003).

Water-limited crop growth of rapeseed and sugarbeet was simulated using the dynamic crop growth model WOFOST, which uses a leaf photosynthesis approach (Van Diepen et al., 1989; van Ittersum et al., 2003). Since rapeseed overwinters as a green crop and WOFOST is only able to simulate rapeseed growth and development that occur after winter, we used measured LAI data (Gabrielle et al., 1998) for autumn and winter. According to these data, the crop emerges two weeks after sowing and reaches a LAI of 0.5 at 40 days after sowing and an aboveground biomass of 0.4 Mg DM ha^{-1}. During winter, this LAI and biomass are maintained until in spring crop growth recommences. From this moment, LAI is simulated by WOFOST. Simulated average crop yields over 25 years were 3.7 Mg DM of rapeseed (4.1 Mg fresh, at 90% DM content) and 12.9 Mg DM of sugarbeets (51.7 Mg fresh at 25% DM content); these correspond reasonably well with reported yields in Table 5.2.

5.2.3 Processing

Rapeseed and sugarbeet are assumed to be processed by the VERBIO biodiesel and bio-ethanol factories in Schwedt (capacity of 250,000 Mg biodiesel y^{-1} and 200,000 Mg ethanol y^{-1}; VERBIO, 2011a; VERBIO, 2011b). Transport distance to the main rapeseed and sugarbeet growing area in the north of Brandenburg was assumed 50 km. For processing, we used European standard values for conversion efficiencies, energy requirements and GHG emissions (BioGrace, 2010).

For conversion, *Miscanthus* and black locust biomass were assumed to be processed in the CHOREN processing facility, located in Freiberg, just across the border with Saxony (capacity of 18000 m^3 of BtL y^{-1}; CHOREN, 2011b). Here, biomass is converted into syngas in two stages (van Vliet et al., 2009) and then synthesized into Fischer Tropsch diesel (FTD) using Shell Middle Distillate Synthesis; the target energetic efficiency of the whole process is 0.54 MJ FTD MJ^{-1} of feedstock. The factory supplies enough waste heat for drying the feedstock to the required moisture content of 15% (Reinhardt et al., 2006). The transport distance from Lusatia to CHOREN is approximately 100 km.

As an alternative to BtL, we also assessed conversion into cellulosic ethanol, although currently no cellulosic ethanol plants are present yet in the region. In our calculations, we assumed a conversion efficiency of 0.45 MJ ethanol MJ^{-1} of feedstock (Aden et al., 2002; Huang et al., 2009); feedstock transportation distance was assumed 100 km, similar to the BtL system.

5.3 Calculation of the sustainability indicators

5.3.1 Net energy

The gross energy yield, i.e. the energy in the produced biodiesel or bioethanol was calculated as

$$E_{gross} = Y_{dry\ product} \cdot \eta_{conversion} \tag{5.1}$$

with E_{gross} the gross energy yield (GJ ha^{-1} y^{-1}), $Y_{dry\ product}$ the dry product yield (Mg dry matter ha^{-1} y^{-1}; Table 5.2) and $\eta_{conversion}$ the conversion efficiency from harvested product to biofuel (MJ of biofuel MJ^{-1} of feedstock; Table 5.3)

The net energy can then be calculated according to:

$$E_{net} = E_{gross} - E_{fert} - E_{pest} - E_{diesel} - E_{transp} - E_{conv} \tag{5.2}$$

with

E_{net}	the net energy yield (GJ ha^{-1} y^{-1})
E_{fert}	the energy requirements for producing fertilisers (GJ ha^{-1} y^{-1})
E_{pest}	the energy requirements for producing biocides (GJ ha^{-1} y^{-1})
E_{diesel}	the (diesel) energy consumed by farm machinery (GJ ha^{-1} y^{-1})
E_{transp}	the energy (diesel) required for transporting the feedstock to the conversion facility (GJ ha^{-1} y^{-1})
E_{conv}	the energy requirfed for converting the feedstock into biofuel (GJ ha^{-1} y^{-1})

Specific energy requirements for production of inputs and for transportation were derived from BioGrace (2010). The energetic value of crop residues (straw, foliage) was not taken into account: crop residues are assumed to be left in the field, contributing to SOC maintenance and N_2O emissions. Apart from their main product, rapeseed

Table 5.3 *Crop-specific coefficients used in the simulations*

	Miscanthus	**Black locust**	**Winter oilseed rape**	**Sugarbeet**
C content residues (% of DM)	47 (Kahle et al., 2001)	47 (Bross et al., 1995)	Not used	Not used
N content residues (% of DM)	0.43 (Christian and Haase, 2001)	2.5 (Bross et al., 1995)	1.3 (Nuttall et al., 1989)	2.4 (Nijhoff, 1987)
Specific leaf area (SLA), ha kg^{-1}	0.002 (Dohleman et al., 2009)	0.004 (Xu et al., 2009)	0.002 (van Diepen et al., 1988)	not used[&]
Max. rooting depth (m)	2 (Neukirchen et al., 1999)	2 (Peng et al., 2004)	1.5 (Vamerali et al., 2003)	1 (Bonari et al., 1995)
LHV[£] of feedstock dry matter (MJ kg^{-1})	18.5 (Lewandowski et al., 1995)	16.5 (Grünewald et al., 2009)	26.4 (BioGrace, 2010)	16.3 (BioGrace, 2010)
$\eta_{conversion}$ (MJ biofuel MJ^{-1} of feedstock dry matter)	0.54 (BtL; Reinhardt et al., 2006) 0.44 (cellulosic ethanol; Huang et al., 2009; Humbird et al., 2011)	0.54 (BtL; Reinhardt et al., 2006) 0.44 (cellulosic ethanol; Huang et al., 2009; Humbird et al., 2011)	0.61 (BioGrace, 2010)	0.54 (BioGrace, 2010)

[£] LHV: lower heating value

[&] see description of Equation 11

and sugarbeet processing yields co-products such as beet pulp, rapeseed meal and glycerine; we did not take into account the energetic value of these co-products since the focus of this work is on obtaining liquid transportation fuels, rather than other types of energy (savings) or animal feed.

5.3.2 SOC dynamics

Farmers in Germany receiving EU direct payments are obliged by law to maintain their land in an agriculturally and ecologically sound condition (Bundestag, 2004b). Part of this responsibility is preventing a decline in soil organic matter content. To this end, a SOC balance calculation method has been developed that quantifies the effect of different crops, residues and manures on SOC (the 'VDLUFA' method; Körschens et al., 2004); it is used for designing 'SOC-neutral' crop rotations and for compliance with the German Ordinance on Direct Payments (Direktzahlungen-Verpflichtungenverordnung; Bundestag, 2004b). Rapeseed and sugarbeet are be grown in crop rotations, and we assume these are close to 'SOC-neutral'. Since in Western Europe, generally little new land is opened up for agriculture, we may safely assume that for rapeseed and sugarbeet in Brandenburg, there are no GHG emissions from direct land use change.

For black locust and *Miscanthus* however, there is a distinct change of land use: black locust is grown on reclaimed mine soils that were previously hardly vegetated and *Miscanthus* is assumed to be grown on poorly productive agricultural land that may have been used to grow annual crops like rye or potato (LVLF, 2010). Therefore, we simulated SOC dynamics under these perennial crops with the RothC 26.3 model (cf. Coleman et al., 1997; Jenkinson et al., 1999). RothC-26.3 is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total organic carbon (Mg ha^{-1}), microbial biomass carbon (Mg ha^{-1}) and Δ14C (from which the radiocarbon age of the soil can be calculated) on a years to centuries timescale. It needs few inputs and those it needs are easily obtainable (Coleman and Jenkinson, 2007). We assumed an annual residue input from black locust equal to the amount of foliage produced; densely planted young black locust does not produce any branches yet during the first four years after planting (Boring and Swank, 1984) and when coppicing takes place every 3 years, shoots never exceed this age. Foliage biomass was related to stem biomass based on measurements in 4-year old black locust trees in dense stands in North Carolina, USA (Boring and Swank, 1984):

$$DW_{leaves} = 0.31 \cdot DW_{stem} \qquad (5.3)$$

where DW_{leaves} is the dry weight of the foliage (kg) and DW_{stem} the dry weight of the stems (kg).

The average annual input of residues over a plantation cycle calculated in this way is 4.0 Mg DM $ha^{-1}y^{-1}$. Little other data on foliar biomass of black locust are available, although results from Burner et al. (2006) of two year old trees seem to indicate a substantially higher foliage/stem biomass ratio. Root turnover and litterfall during the season were not taken into account, since such data were not available.

Miscanthus residues consist of foliage that falls off during winter (spring harvest) and of unharvestable stem parts (stubble and shoot tips, ca. 25% of stem DM; Kahle et al., 2001); root turnover was not taken into account. All aboveground biomass produced during the establishment year is assumed to enter the residue pool since it is not harvested (Vleeshouwers, 2001). The estimated average annual input of residues over a plantation cycle, based on an autumn yield of 19 Mg DM ha^{-1} (Clifton-Brown et al., 2001) is 7.1 Mg DM $ha^{-1}y^{-1}$.

RothC was initialized using long-term average weather data for Brandenburg over 1982-2006. Simulations were carried out for a topsoil layer of 20 cm; the size of the inert organic carbon pool for loamy sand (Table 5.1) was estimated at 1.15 Mg ha^{-1}, using Falloon's (1998) formula. For *Miscanthus* residues, the ratio between decomposable and resistant plant material (DPM/RPM) was set at 1.35, the value for maize straw (Van Wesemael et al., 2010); for black locust residues we used 0.50, based on the study by Lawrey (1977) on decomposition of black locust leaves. Residue C content of both crops was set at 47% (Bross et al., 1995; Kahle et al., 2001).

5.3.3 GHG emissions

The GHG emissions indicator (GHG_{Egross}) is expressed in kg CO_2 eq. GJ^{-1} gross energy according to Bundestag (2009) and Chapter 2 and is calculated as:

$$GHGIND = (GHG_{fert} + GHG_{pest} + GHG_{diesel} + GHG_{transp} + GHG_{conv} + GHG_{SOC} + GHG_{N2O} + GHG_{liming}) \,/\, E_{gross} \qquad (5.4)$$

where

GHG_{Egross}	the total GHG emissions from the system, expressed per unit of gross energy (kg CO_2 eq. GJ^{-1})
GHG_{fert}	the emissions from fertiliser production (kg CO_2 eq. ha^{-1})
GHG_{pest}	the emissions from biocide production (kg CO_2 eq. ha^{-1})
GHG_{diesel}	the emissions from fuel consumption by farm machinery (kg CO_2 eq. ha^{-1})
GHG_{transp}	emissions from transporting the feedstock from farm to conversion facility (kg CO_2 eq. ha^{-1})
GHG_{conv}	emissions from converting the feedstock into biofuel (kg CO_2 eq. ha^{-1})
GHG_{SOC}	emissions (or sequestration) from changing SOC content of the soil (kg CO_2 eq. ha^{-1})
GHG_{N2O}	emissions from denitrification of N in applied fertilisers and crop residues N (kg CO_2 eq. ha^{-1})
GHG_{lime}	emissions from application of carbonate lime to the soil (only applicable for black locust on reclaimed mine soils)
E_{gross}	the gross energy yield (GJ ha^{-1} y^{-1})

Specific GHG emission coefficients were taken from BioGrace (2010). Analogous to the calculation of net energy (Eq. 2), no GHG emission credits were allocated to the generated co-products. GHG_{SOC} for rapeseed and sugarbeet is zero, since we assumed these crops are grown in 'SOC-neutral' crop rotations. GHG_{SOC} for *Miscanthus* and black locust was estimated as the average annual change in SOC over the first plantation cycle of the new land use:

$$GHG_{SOC} = \Delta\ SOC_{cycle} / L_{cycle} \cdot F_{CO2} \tag{5.5}$$

with

L_{cycle}	the length of a plantation cycle (years; 15 years for Miscanthus, 27 years for black locust)
$\Delta\ SOC_{cycle}$	the simulated change in SOC after one plantation cycle of the crop (kg C ha^{-1})
F_{CO2}	the conversion factor from C to CO_2 (3.66 kg CO_2 kg^{-1} C);

GHG emissions from denitrification were estimated according to IPCC (2006) as:

$$GHG_{N2O} = EF_1 \cdot (N_{fert} + N_{res}) \cdot F_{N2O} \cdot GWP_{100,N2O} \tag{5.6}$$

with

EF_1	the emission factor for N2O emissions from N inputs (0.01; IPCC, 2006)
N_{fert}	the N fertiliser application (kg N ha^{-1})
N_{res}	the annual amount of N in crop residues, calculated from data in Table 5.2
F_{N2O}	the conversion factor from N to N_2O (1.57 kg N_2O kg^{-1} N);
$GWP_{100,N2O}$	the 100-year global warming potential of N_2O (296 kg CO_2 eq. kg^{-1} of N_2O; Ehhalt et al., 2001)

GHG emissions from liming were estimated according to IPCC (2006) as:

$$GHG_{lime} = M_{limestone} \cdot EF_{limestone} \cdot F_{CO2} \tag{5.7}$$

where

$M_{limestone}$	the annual amount of calcic limestone ($CaCO_3$) applied (kg ha^{-1});
$EF_{limestone}$	the emission factor of limestone (0.12 kg C kg^{-1} of $CaCO_3$);
F_{CO2}	the conversion factor from C to CO_2 (3.66 kg CO_2 kg^{-1} C).

5.3.4 Soil erosion

We used the soil-loss ratio (SLR, -) from the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1996) as an indicator for the erosion hazard. The SLR is an estimate of the ratio of soil loss under actual conditions to losses experienced under the reference conditions defined by Wischmeier (1978): tilled continuous fallow. The annual SLR of the assessed systems is calculated as the sum of the monthly values; these were calculated according to:

$$SLR_{month} = CC \cdot F_{EI30,\ month} \cdot SC \qquad (5.8)$$

with

CC	the canopy cover subfactor, ranging from 0 to1 (-);
$F_{EI30,\ month}$	the fraction of the annual rainfall erosivity occurring in the concerning month (-);
SC	the surface-cover subfactor (-)

$F_{EI30,\ month}$ was derived from Rogler (1981), cited by Auerswald (1989). Although applying to Bavaria, distribution patterns in temperate areas in the Northern hemisphere generally follow similar patterns, with most erosive rains occurring during summer, as apparent from data presented by e.g. Auerswald (1989), Wischmeier (1978) and Gabriels (2003).

The canopy-cover sub factor is calculated as:

$$CC = 1 - F_c \cdot e^{(-0.328h)} \qquad (5.9)$$

with

F_c	the fraction of land surface covered by canopy; it was calculated from LAI simulated by the crop growth models according to $F_c = LAI/3$, with a maximum value of 1 (complete cover; Haverkort et al., 1991);
h	the distance that raindrops fall after striking the canopy (m); we set it

at 0.3 m for rapeseed and sugarbeet and at 1.0 m for black locust and *Miscanthus*.

For estimating the effect of mulching pruned fronds, we calculated the SC factor:

$$SC = e^{\left[-b \cdot S_p \cdot \left(\frac{0.61}{R_u}\right)^{0.8}\right]} \qquad (5.10)$$

with

b	an empirical coefficient; it was set at 0.025 for fields dominated by

interrill erosion (Renard et al., 1996)

S_p the percentage of land area covered by surface cover (residues);

R_u the surface roughness (cm); it was set at 0.61 cm, the value for unit plot conditions of clean cultivation smoothed by extended exposure to rainfall of moderate intensity.

S_p may be calculated as:

$$100 \cdot [1 - e^{-\alpha \cdot B_s}] \quad (5.11)$$

with

α the ratio of the area covered by a piece of residue to the mass of that residue (ha kg^{-1}). We used the specific leaf area (SLA) as an estimate (Table 5.2)

B_s the dry weight of crop residue on the surface (kg ha^{-1}); It was estimated as the quantity of resistant plant material (RPM) in one season's simulated production of foliage. For *Miscanthus* we used a fraction RPM of 0.42 (Van Wesemael et al., 2010); for black locust we used 0.66 (Lawrey, 1977).

5.3.5 Water productivity

We defined the water productivity of a biofuel as the amount of net biofuel energy that is produced with 1 m^3 of water lost through evapotranspiration:

$$WP = E_{net} / ET_{season} \quad (5.12)$$

with

WP the water productivity of the concerning biofuel (GJ of net energy m^{-3})

E_{net} the net energy yield (GJ $ha^{-1}y^{-1}$); its calculation was explained above.

ET_{season} the cumulative crop evapotranspiration over the growing season (m^3 ha^{-1})

To estimate ET_{season}, we used the above mentioned crop growth models. Since WOFOST is only able to simulate rapeseed growth and development that occur after winter, evapotranspiration for this crop during autumn and winter was estimated separately using the 'FAO56' approach (Allen et al., 1998), multiplying the reference evapotranspiration with a crop factor of 0.35 for immature rapeseed (Allen et al., 1998); it was then added to the evapotranspiration during the main growing season that was simulated by WOFOST. Water availability during autumn and winter was considered non-limiting, as rainfall substantially exceeded the relatively low crop evapotranspiration in all years.

5.3.6 Use of nitrogen and biocides

To facilitate intercomparison of systems with and without application of biocides or N, we use the specific N fertiliser requirement (SNR) as an indicator, instead of the nitrogen use efficiency that was employed in Chapter 2. SNR is calculated as:

$$SNR = N_{applied} / E_{net} \qquad (5.14)$$

with

SNR	the specific N fertiliser requirement (kg N applied GJ^{-1} of net energy)
$N_{applied}$	the N application rate (kg $ha^{-1}y^{-1}$, Table 5.2)

Similarly, we calculate the specific biocide requirement as:

$$SPR = PC_{applied} / E_{net} \qquad (5.15)$$

with

SPR	the specific biocide requirement (kg a.i. GJ^{-1} of net energy kg^{-1})
$PC_{applied}$	the biocide application rate (kg a.i. ha^{-1}, Table 5.2)

5.3.7 N leaching

Residual N not taken up by the crop is potentially prone to leaching. However, precise simulation of the soil N balance requires more data than available and closer integration of crop and soil models, in which N availability and crop uptake can be computed over relatively small time steps. We used a simplified approach and assumed that fertilizer N not taken up by the crop is N potentially available for leaching; it was calculated from N fertiliser rates (Table 5.2) assuming a recovery of 50% for all crops (Destain et al., 1993; MacDonald et al., 1997; Schjoerring et al., 1995). Aboveground crop residues of rapeseed and of cereal straw, which has similar composition as *Miscanthus* residues, contribute little to N leaching and may even reduce it due to immobilization (Mitchell et al., 2001), hence we did not take their effect into account. Sugarbeet residues however may cause some increase in N leaching; Mitchell et al. (2001) measured that incorporating sugarbeet foliage increased leaching by ~10 kg N ha^{-1} y^{-1} over two years in a sandy loam in the UK. We include this effect by adding 10 kg N $ha^{-1}y^{-1}$ to the final amount of leached fertiliser N that we calculate for sugarbeet. This may represent a slight overestimation; rainfall in Brandenburg is lower than in the UK and we assessed sugarbeet on loam instead of sandy loam. Very high leaching was measured under virtually unfertilized bean on a silty clay loam in Southeast England (MacDonald et al., 1997); this was attributed to the fact that N mineralized by the soil under beans during the period when N fixation was vigorous (and afterwards, during senescence of the crop) was not taken up by the crop and accumulated in the topsoil.

Therefore, we assumed that for black locust, all of the N in crop residues is potentially available for leaching. The N that is actually leached (NL, kg N $ha^{-1}y^{-1}$), was calculated according to the method of Shaffer et al. (2010) as:

$$NL = NAL \cdot (1.0 - e^{-k \cdot WAL / [(1-(BD/PD)) \cdot Dleach]}) \tag{5.16}$$

with

NL	annual N leaching (kg N $ha^{-1}y^{-1}$)
NAL	N potentially available for leaching (kg N $ha^{-1}y^{-1}$); it is calculated as 50% of the applied fertilizer N, except for black locust, where it was set equal to the N contained by the crop residues
k	empirical constant (1.2)
WAL	water available for leaching (cm)
BD	soil bulk density (Table 5.1; Mg m^{-3})
PD	soil particle density (Mg m^{-3}); we used a general value of 2.65 (Reid, 1973)
D_{leach}	leaching depth (cm): the depth beyond which N may be considered leached

WAL was estimated as *annual precipitation (cm) – simulated annual crop evapotranspiration (cm)*. D_{leach} was set equal to the approximate maximum rooting depth of the crops assessed (Table 5.3).

5.3.8 Model sensitivity

A sensitivity analysis was carried out to investigate to what extent important parameters and assumptions influence the sustainability indicator outcomes. One by one, values of input parameter were changed by 20% above and below their original value; with each change, the relative changes in all sustainability indicator values were recorded. Relative sensitivity was calculated as:

$$(\Delta I_{PAR+20\%} + \Delta I_{PAR\ -20\%})/40 \tag{5.17}$$

with

$\Delta I_{rel,PAR\pm20\%}$	the relative change in indicator value (%) with a 20% increase (+) or decrease (-) in the value of the parameter (PAR) investigated

Relative sensitivity of 1 means that the indicator value varies to the same extent as the changed parameter (±20%); values greater/smaller than 1 imply that the indicator changes more/less respectively. A relative sensitivity of zero implies that the sustainability indicator is not sensitive to changes in the concerning parameter. As an example: raising or lowering the water holding capacity of the soil by 20% by adjusting the relative volumetric water content at field capacity may result in x% higher or y% lower feedstock yield, based on simulations with the crop growth models. After simulation, these relative yield changes are implemented manually in the calculations for the sustainability indicators. If the indicator value increases by u% with a 20% higher soil water holding capacity and declines by v% with a 20% lower capacity, the relative sensitivity of the indicator is (u+v)/40. Similarly, parameters relevant for the calculation of SOC were changed in RothC 26.3 hence impacted SOC simulations; remaining parameters were only changed in the calculations of the sustainability indicators and directly affected the sustainability indicators or not.

5.3.9 Synthesis of results

For the sake of overview, indicator results have been scaled as percentages of the best performing indicator across all systems and represented in four cobweb diagrams, hence the best system scores a value of 100. For the GHG indicator, the emission reduction relative to the replaced fossil fuels is displayed however, while for soil erosion we plotted 100 – SLR.

5.4 Results

5.4.1 Net energy

Net energy yield of *Miscanthus* is almost twice that of the other crops. Although its gross energy yield per ha (the energy in the fuel produced from 1 ha, length of entire column in Figure 5.1) is lower than that of sugarbeet (Figure 5.1), no fossil energy is consumed in processing, hence the difference. Energy for the second generation processes is derived from the renewable feedstock itself; 46% and 56% of the feedstock energy content is consumed for processing energy in the BtL and cellulosic ethanol process, respectively; the remainder is harnessed as biofuel energy. Black locust also has a relatively high net energy yield due to the use of feedstock energy in the second generation conversion processes. Additionally, it has an extensive cropping system that consumes little energy. Black locust needs no N fertiliser since it is a legume species; also little diesel is used since tillage is absent and harvest takes place only once per three years.

The conversion efficiency of sugarbeet into ethanol is similar as from ligno-cellulosic biomass to FTD (0.54 MJ biofuel MJ^{-1} of feedstock dry matter Table 5.3). The difference is that in sugarbeet, the non-converted biomass is not used for energy purposes; instead, fossil energy is used, hence the lower net energy of sugarbeet. More energy is also consumed in feedstock transport; beet roots contain ca. 75% water. Rapeseed has a relatively high net energy yield in relation to its gross energy yield

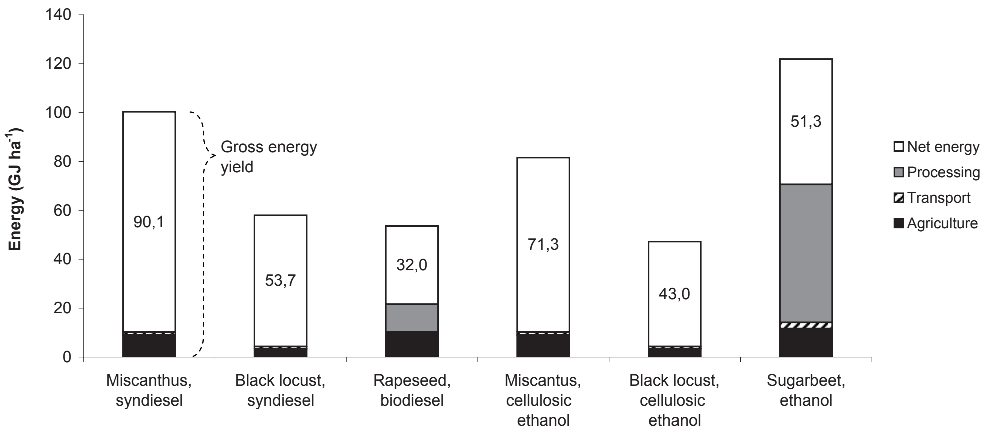


Figure 5.1 *Net energy yield and energy consumption in the production chains of the assessed systems.*

(favourable energy ratio); processing biodiesel production generally is less energy consuming than ethanol production since no distillation is required.

5.4.2 Soil organic carbon

Under *Miscantus*, simulated SOC over the first 15 year plantation cycle doubled from 16 Mg ha^{-1} (0.5%) to 32.1 Mg ha^{-1} (1.0%); the average annual increase in SOC was 1.08 Mg C ha^{-1} y^{-1} (Figure 5.2). SOC under black locust over the first 27-year cycle increased less rapidly at an average annual rate of 0.57 Mg C $ha^{-1}y^{-1}$. Under rapeseed and sugarbeet, it is assumed that no net sequestration or decomposition of SOC occurs, since they are part of rotations in which such changes are compensated.

5.4.3 GHG emissions

Miscanthus and black locust cause the lowest GHG emissions (Figure 5.3). The second generation conversion processes for these crops are powered from renewable feedstock, hence causes no emissions (the emissions for feedstock production are already attributed to agricultural management). Further, for these systems, emissions from agricultural management and transport are compensated for by the relatively large SOC sequestration. Emissions from the rapeseed system are highest due to N_2O emissions from relatively high N applications. Under rapeseed and sugarbeet, it is assumed that no net sequestration or decomposition of SOC occurs, since they are part of rotations in which such changes should be compensated.

5.4.4 Soil erosion

Erosion risk increases in the order *Miscanthus* < black locust < rapeseed < sugarbeet; calculated annual SLRs are 0.02 for the perennial species, 0.16 for rapeseed and

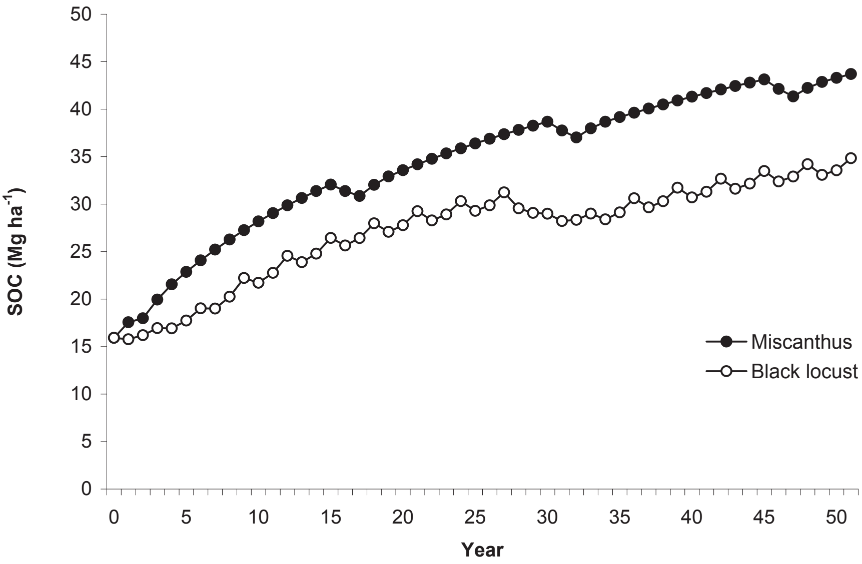


Figure 5.2 *Simulated soil organic carbon under Miscanthus and black locust*

0.43 for sugarbeet. *Miscanthus* and black locust canopies provide complete soil cover before the summer rains (Figure 5.4); there is also a strong protective effect of the litter layer that accumulates on the soil surface; without it, SLRs would be 0.21 and 0.26, respectively. Erosion risk for these crops will be significantly greater in the establishment year, but this was neglected since it concerns only one out of every 15 years. In the sugarbeet system, after soil preparation on October 1, the soil is left bare hence there is no erosion protection; winter rainfall erosivity is low however. During spring and early summer, sugarbeet does not provide full soil cover yet while rainfall erosivity increases, hence substantial erosion risk, with a sharp peak in May and June (Figure 5.4).

Under rapeseed, the greatest erosion risk occurs in September, when the crop has been sown but there is no crop cover present yet on the very fine seedbed (Figure 5.4). In the subsequent months, the rapeseed canopy starts to provide partial soil cover (LAI ~ 0.5) and thereby reduces erosion risk; erosivity of winter rains is also low however (Figure 5.4). After winter, the advantage of the headstart obtained by pre-winter germination and growth becomes clear: the rapeseed canopy provides full soil cover well before the erosive summer rains set in. When the crop starts to senesce in the second half of May, canopy cover decreases; however, this is compensated for by the simultaneous increase of litter and straw cover.

5.4.5 Water productivity

Miscanthus and black locust had substantially higher annual evapotranspiration than the annual crops: 517 mm and 486 mm, respectively. Simulated average annual

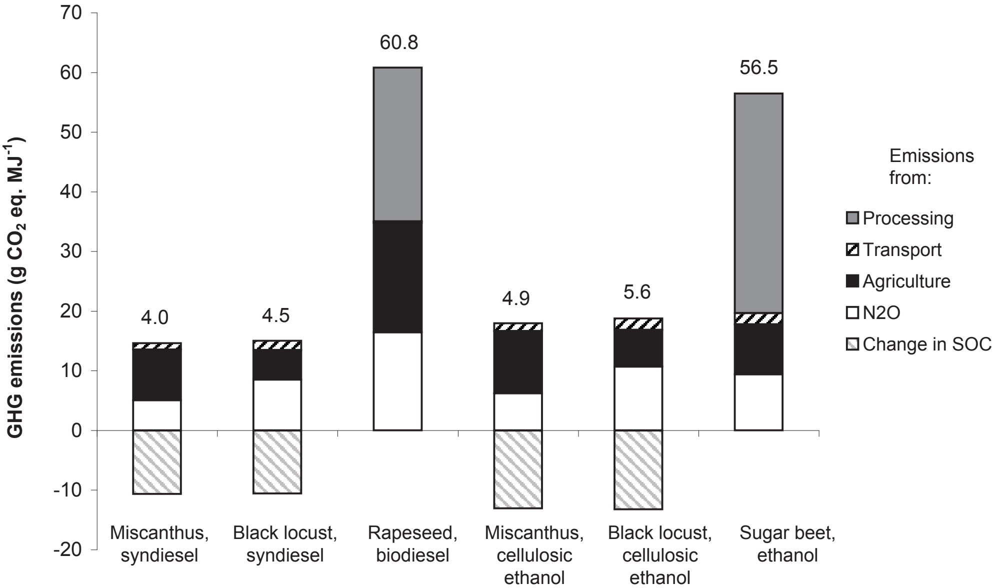


Figure 5.3 *GHG emissions of the assessed systems (labels above columns indicate total net emissions of systems in g CO_2 eq. MJ^{-1}); for Miscanthus and black locust, results for the first 20 years after crop establishment are displayed.*

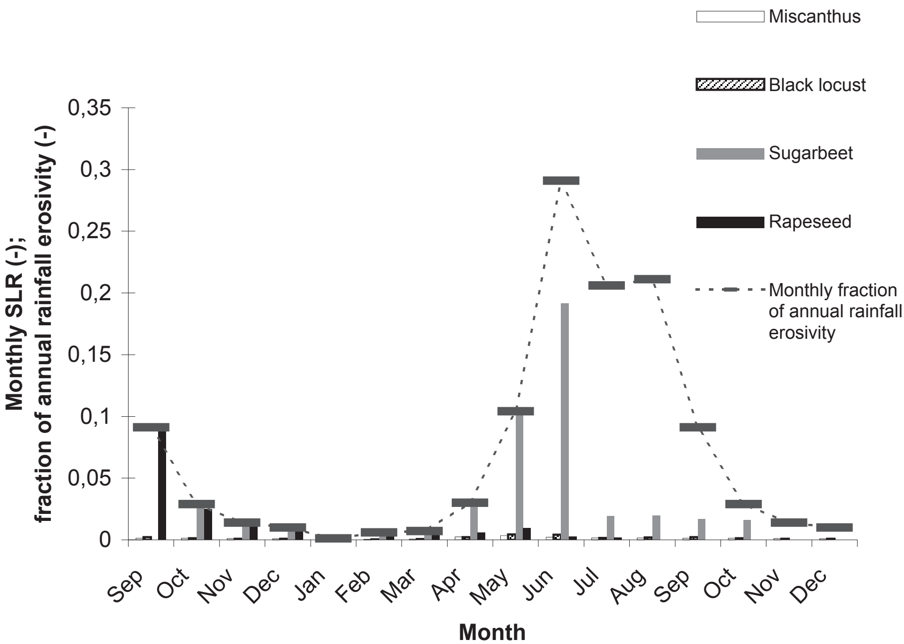


Figure 5.4 *Simulated soil erosion under the four feedstock crops; the sum of the monthly SLRs (Soil Loss Ratio) gives the annual value. Also displayed is the monthly occurring fraction of annual rainfall erosivity.*

evapotranspiration was 417 mm for sugarbeet and 304 mm for rapeseed. *Miscanthus* has the best WP (24.1 MJ m^{-3}). Between the other systems, WP differed little and decreased in the order sugarbeet (12.3 MJ m^{-3}) > black locust (11.1 MJ m^{-3}) < rapeseed (10.5 MJ m^{-3}).

5.4.6 N use efficiency and biocide use efficiency

Black locust needs no N fertiliser hence has the lowest SNR (0 kg N GJ^{-1} of net energy). *Miscanthus* also performs rather well (0.7 kg N GJ^{-1}). Although fertiliser applications in this crop are relatively high, its net energy is very high. Due to relatively low N concentration in its biomass, it produces relatively high amounts of biomass with little N. SNR of sugarbeet (1.93 kg N GJ^{-1}) is better than of rapeseed (3.79 kg N GJ^{-1}); the latter crop has the highest N fertilisation and the lowest net energy yield.

Since normally, no biocides are applied in *Miscanthus* and black locust, these crops have SPRs of 0 kg a.i. GJ^{-1}. Sugarbeet and rapeseed perform rather similar with SPRs of 0.08 and 0.10 kg a.i. GJ^{-1}.

5.4.7 N leaching

Simulated NL decreased in the order rapeseed (59 kg N $ha^{-1}y^{-1}$) > sugarbeet (29 kg N $ha^{-1}y^{-1}$) > black locust (6 kg N $ha^{-1}y^{-1}$), *Miscanthus* (1 kg N $ha^{-1}y^{-1}$). For sugarbeet, N leaching from fertiliser N only was 19 kg N $ha^{-1}y^{-1}$; 10 kg N $ha^{-1}y^{-1}$ was added to account for the foliage that was left in the field.

5.4.8 Model sensitivity

Results of our study are relatively sensitive to changes in yield, residue yield and processing efficiency (Table 5.4). Increases in these parameters have a beneficial effect on net energy yield, greenhouse gas emissions, specific N requirement (SNR) and water productivity. Increase in feedstock yield results in higher net energy yield and hence improved sustainability indicators; increase in residue yield results in increased C sequestration, but also in higher N_2O emissions. Whichever effect is stronger depends on C and N contents of the residues. Changing the water holding capacity of the soil by adjusting the soil water content at field capacity changed simulated water-limited yield, LAI and evapotranspiration, hence also soil erosion and water productivity; the impact is particularly strong for black locust that is relatively low-yielding and has relatively low LAI. Effects were very small for rapeseed and sugarbeet. Rapeseed experienced little water stress even if the water holding capacity was decreased by 20%, despite the relatively dry climate.

5.5 Discussion

5.5.1 Comparison with other research findings

Net energy yields of sugarbeet and rapeseed systems match closely with values reported in Chapter 2. GHG emissions that we calculated in the current study are higher, but lower than the default European values of 56 and 76 CO_2 eq. MJ^{-1} from BioGrace (2010); in our assessment rapeseed does not meet the requirement of 30% emission reduction (Bundestag, 2009). Co-product allocation by energy content would reduce emissions by ~30% however (BioGrace, 2010), bringing GHG reduction within the required range. For Miscanthus, GHG emission results are in the same range as reported by Lewandowski (1995) and Smeets (2009). Net energy yield is smaller than reported by e.g. Ercoli (1999); however they harvested the crop at its peak yield in autumn and did not consider conversion into biofuel. For Robinia, no figures for direct comparison are available yet, but estimated GHG emissions are in the same range as values for willow- and poplar-based fuel coppice systems reported by Matthews (2001).

Simulated water use efficiency of mature *Miscanthus* of 0.15 m^3 kg^{-1} of biomass DM is in the middle of the range reported by Zub and Brancourt-Hulmel (2010). Although for assessing black locust we used an adapted willow model, the relatively poor water productivity of 0.42 m^3 kg^{-1} DM of a mature crop that we found corresponds well with experimental findings (0.47 m^3 kg^{-1} of DM; Daiqiong et al., 1992). For rapeseed, we simulated a water use of rapeseed of 0.95 m^3 kg^{-1} of seeds; this is lower than simulated by Van Der Velde (2009) for Eastern Germany; however it is well within the range of measured values reported by Robertson (2005). For sugarbeet, we calculated a value of 0.21 m^3 kg^{-1} of DM biomass; this is close to the 0.20 m^3 kg^{-1} for central Europe mentioned by Märländer (2003).

Simulated N leaching for rapeseed on loamy sand (59 kg N $ha^{-1}y^{-1}$) and sugarbeet on loam soils (29 kg N $ha^{-1}y^{-1}$) corresponds well with findings by Beaudoin et al. (2005) and by Nieder et al. (1995), who analysed 205 plots in Germany from 1986 to 1988 and calculated losses from 16 kg N $ha^{-1}y^{-1}$ in clayey or loamy soils to 63 kg N $ha^{-1}y^{-1}$ in sandy soils. Addition of 10 kg N $ha^{-1}y^{-1}$ to the sugarbeet estimate to account for N leached from foliage may have caused some overestimation for this crop in our study. Similar to our findings, substantially greater N leaching under rapeseed than under sugarbeet was measured by Mitchell et al. (2001), MacDonald et al. (1997) and Beaudoin et al. (2005). Rowe et al. (2009) and Hall (2003) mention relatively high nitrate leaching in the first year of Miscanthus establishment but low losses in subsequent years, suggesting that Miscanthus can lead to reduced nitrate leaching compared with arable crops post establishment; low leaching due to high evapotranspiration, similar to our findings, was mentioned by Christian et al. (1997).

Table 5.4 *Results of the sensitivity analysis. Relative sensitivity of 1 means that the outcomes varies to the same extent as the changed parameter (±20%); values greater/smaller than 1 imply that the relative change is greater/less respectively. If the relative sensitivity is zero, no change occurs. Cells are coloured in three shades of grey; from light to dark they indicate absolute values of the relative sensitivity of 0.25-0.5, 0.5-1 and >1; white colour indicates an absolute value of the relative sensitivity <0.25. Indicator abbreviation are: NE net energy; SC soil carbon; Gr GHG emission reduction; Nr specific N fertiliser requirement; Er soil erosion; W water productivity; NL N leaching.*

System	**Miscanthus, syndiesel**							**Robinia, syndiesel**						
Indicator	*NE*	*SC*	*Gr*	*Nr*	*Er*	*W*	*NL*	*NE*	*SC*	*Gr*	*Nr*	*Er*	*W*	*NL*
Yield & residue yield	1,1	1,2	0,2	-1,2	0,0	1,0	0,0	1,1	1,3	0,2	0,0	0,0	1,1	1,0
Yield	1,1	0,0	0,0	-1,2	0,0	1,0	0,0	1,1	0,0	0,1	0,0	0,0	1,1	1,0
Residue yield	0,0	1,2	0,1	0,0	0,0	0,0	0,0	0,0	1,3	0,1	0,0	0,0	0,0	0,0
Diesel consumption	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
N fertilisation	0,0	0,0	-0,1	1,0	0,0	0,0	1,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
N content residues	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-0,1	0,0	0,0	0,0	1,0
Lime application	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
N2O emission factor	0,0	0,0	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	-0,1	0,0	0,0	0,0	0,0
Processing efficiency	1,1	0,0	0,1	-1,2	0,0	1,0	0,0	1,1	0,0	0,1	0,0	0,0	1,1	0,0
Initial SOC	0,0	-0,2	0,0	0,0	0,0	0,0	0,0	0,0	-0,3	0,0	0,0	0,0	0,0	0,0
Inert SOC	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RPM/DPM ratio	0,0	-0,3	0,0	0,0	0,0	0,0	0,0	0,0	-0,2	0,0	0,0	0,0	0,0	0,0
Water holding capacity	0,3	0,3	0,0	-0,3	-0,4	0,5	0,0	0,5	0,3	0,0	0,0	-0,8	0,3	0,0

System	**Rapeseed, biodiesel**							**Miscanthus, cellulosic**						
Indicator	*NE*	*SC*	*Gr*	*Nr*	*Er*	*W*	*NL*	*NE*	*SC*	*Gr*	*Nr*	*Er*	*W*	*NL*
Yield & residue yield	1,3	0,0	1,1	-1,4	0,0	1,3	0,0	1,1	1,2	0,2	-1,2	0,0	1,0	0,0
Yield	1,3	0,0	1,3	-1,4	0,0	1,3	0,0	1,1	0,0	0,0	-1,2	0,0	1,0	0,0
Residue yield	0,0	0,0	-0,2	0,0	0,0	0,0	0,0	0,0	1,2	0,2	0,0	0,0	0,0	0,0
Diesel consumption	-0,1	0,0	-0,1	0,1	0,0	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
N fertilisation	-0,2	0,0	-0,9	1,2	0,0	-0,2	1,0	-0,1	0,0	-0,1	1,1	0,0	0,0	1,0
N content residues	0,0	0,0	-0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Lime application	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
N2O emission factor	0,0	0,0	-0,6	0,0	0,0	0,0	0,0	0,0	0,0	-0,1	0,0	0,0	0,0	0,0
Processing efficiency	0,1	0,0	0,0	-0,2	0,0	0,1	0,0	1,2	0,0	0,1	-1,2	0,0	1,0	0,0
Initial SOC	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-0,2	0,0	0,0	0,0	0,0	0,0
Inert SOC	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RPM/DPM ratio	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-0,3	-0,1	0,0	0,0	0,0	0,0
Water holding capacity	0,2	0,0	0,2	-0,3	0,0	0,2	0,0	0,3	0,3	0,1	-0,3	-0,4	0,3	0,0

System	**Robinia, cellulosic**							**Sugarbeet, ethanol**						
Indicator	*NE*	*SC*	*Gr*	*Nr*	*Er*	*W*	*NL*	*NE*	*SC*	*Gr*	*Nr*	*Er*	*W*	*NL*
Yield & residue yield	1,1	1,3	0,2	0,0	0,0	1,1	1,0	1,2	0,0	0,4	-1,3	0,0	1,2	0,0
Yield	1,1	0,0	0,1	0,0	0,0	1,1	1,0	1,2	0,0	0,6	-1,3	0,0	1,2	0,0
Residue yield	0,0	1,3	0,1	0,0	0,0	0,0	0,0	0,0	0,0	-0,2	0,0	0,0	0,0	0,0
Diesel consumption	0,0	0,0	-0,1	0,0	0,0	0,0	0,0	-0,1	0,0	-0,1	0,1	0,0	-0,1	0,0
N fertilisation	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-0,1	0,0	-0,3	1,1	0,0	-0,1	1,0
N content residues	0,0	0,0	-0,1	0,0	0,0	0,0	1,0	0,0	0,0	-0,2	0,0	0,0	0,0	0,0
Lime application	0,0	0,0	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
N2O emission factor	0,0	0,0	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	-0,3	0,0	0,0	0,0	0,0
Processing efficiency	1,1	0,0	0,1	0,0	0,0	1,1	0,0	2,4	0,0	2,0	-3,1	0,0	2,4	0,0
Initial SOC	0,0	-0,3	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Inert SOC	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RPM/DPM ratio	0,0	-0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Water holding capacity	0,5	0,3	0,1	0,0	-0,8	0,3	0,0	0,5	0,0	0,1	-0,5	0,0	0,3	0,0

Simulated soil loss ratios for Miscanthus of 0.02 are lower than the value of 0.1 mentioned by Smeets (2009), but higher than the value of 0.003 used by Ng et al. (2010). The value of 0.43 for sugarbeet is close to that for grain corn (Smeets et al., 2009).

5.5.2 Comparison of second and first generation systems

The second generation biofuel production chains that we assessed for Brandenburg performed better than first-generation systems based on rapeseed and sugarbeet for nearly all sustainability indicators (Figure 5.5). An exception is the better water productivity of sugarbeet ethanol compared to cellulosic ethanol from black locust. Additionally, sugarbeet evapotranspiration is relatively high, hence there is little water available for drainage. Sugarbeet is known to be relatively water efficient (Märländer et al., 2003), also in terms water use per unit net energy produced (Chapter 2). The good performance of second generation systems for the remaining indicators is due to the absence of fossil fuel use in the processing stage, quick establishment of soil cover by the crop canopy and formation of a litter layer, absence of tillage, relatively low or absent N fertilisation, high biomass production (*Miscanthus*) and water-efficient C4 photosynthesis (*Miscanthus*).

5.5.3 Scope for improving first generation systems

Some scope exists for improving the performance of the first generation systems, albeit not up to the level of the second generation systems studied here. Erosion under sugarbeet can be reduced by conservation tillage, which is currently practiced on 25% of the German beet area; this method also reduces the fuel required for agricultural operations (Märländer et al., 2003). Further, cover crops may be grown in autumn; this is done on 40% of the German sugarbeet area (Cariolle and Molard, 2004). Sugarbeet leaves, while contributing little to maintaining SOC, cause significant N_2O emissions due to their high N content. Net energy yield and GHG emission reduction could be significantly improved by removing the leaves from the field and converting them into biogas by anaerobic digestion; the biogas can be used for generating electricity or as a transport fuel. It also possible to convert the entire sugarbeet harvest into biogas, which can be liquefied or compressed for use as a transport fuel. Converting sugarbeet into biogas instead of ethanol performs better in terms of net energy yield and GHG emissions reduction (Corré and Langeveld, 2008). Taking into account the economic or energetic value of co-products would also substantially improve the picture for the first generation crops. Sugarbeet pulp may be used to feed cattle, thereby reducing resource use in the cultivation of dedicated fodder crops; also, part of the digestate is fed back to agricultural land for maintaining soil fertility.

One of the main aspects that contribute to the poor sustainability of the rapeseed system is the high N fertiliser requirement. However, a large fraction of this N ends

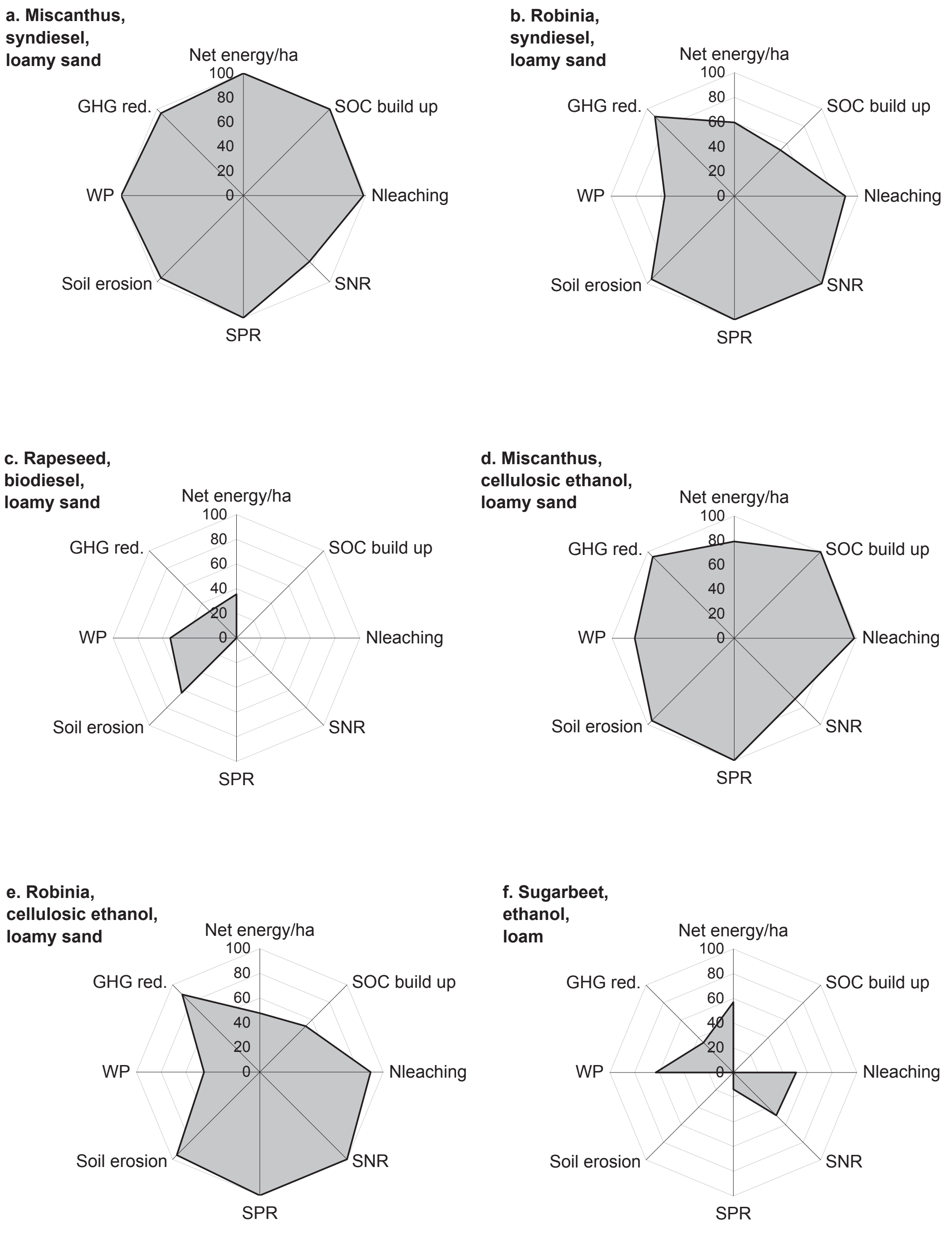


Figure 5.5 *Relative production-ecological sustainability of the assessed systems, based on 8 indicators. Values are indexed in percentages relative to the best indicator value calculated for that indicator across all 10 systems. For 'GHG reduction' the percentage of emission reduction relative to replaced fossil fuels is plotted. For soil erosion, 1- soil loss ratio was plotted. SNR,SPR: specific N, pesticide requirement.; WP: water productivity.*

up in the presscake that remains after the oil has been extracted from the seeds. Presscake is a valuable and protein-rich animal feed and its use may substantially reduce energy and other resources required for cultivating dedicated fodder crops. If co-products would be included in the analysis, then the generated excess electricity from second generation processes should also be taken into account. However, this is relatively insignificant (1.2% and 3.5% of the feedstock energy for BtL and cellulosic ethanol respectively; Humbird et al., 2011; Reinhardt et al., 2006).

5.5.4 Risks of crop failure

Of the second generation systems, *Miscanthus* performed better than black locust except for the SNR; black locust does not need N fertilisation. However, one of the biggest obstacles to *Miscanthus* crop establishment is the ability of the crop to survive the first winter, especially in middle and Northern Europe (Christian and Haase, 2001; Clifton-Brown et al., 2001). The most disturbing illustration of this problem was the total crop loss in Brandenburg, Germany of ca. 150 ha *Miscanthus* in 1991-1993; it was one of the reasons for the drastic slowdown of the large German *Miscanthus* research programme, with a budget of 32 million Deutschmarks for the period 1991-94 (Jørgensen and Schwarz, 2000). Investigations have shown that despite winter frost, plants remain viable until the following spring, but if the first shoots produced are killed by late spring frosts, the plants do not re-sprout, possibly due to a lack of rhizome reserves (Christian and Haase, 2001). Winter survival may depend on the sequestering of a critical amount of metabolic reserves in the rhizomes at the end of the previous growing season. Another potential problem in the first year is the lack of dormancy at the end of the growing season; plants can regrow in winter when temperatures rise to about 10°C. In climates which have winter temperatures that fluctuate rapidly between sub-zero and +10°C, it has been assumed that death occurs in a cold spell immediately after a warm period (Clifton-Brown et al., 2001). To get an impression of these risks in Brandenburg, we examined the weather data (from 1982-2006), with special attention for the years 1991-1993, when serious crop losses were experienced; based on our weather data, spring frost (in °C d) was most severe in 1993. More severe spring frost than in 1993 occurred in 8 other years out of the 25. Winter temperature fluctuations between sub-zero and +10°C occurred during 12 out of 25 years, including 1991, 1993 and 1994. It seems that all of the potential risk factors that endanger *Miscanthus* crop establishment are present in Brandenburg: spring frost, winter temperature fluctuations and incidence of low yields/ low rhizome reserves. Hence, before further embarking on large-scale cultivation of this crop, more research should be dedicated to assessing the risk of crop loss, breeding frost tolerant varieties or developing agronomic practices that can provide frost protection. Recently, Zub et al. (2012) reported that among the *Miscanthus* spp., clones exist that are more frost-tolerant than *Miscanthus x giganteus*.

Contrary to *Miscanthus*, black locust has no problems with (winter) survival; it originates in the North American mountain ranges hence is frost-proof and in addition, the species is drought-resistant, tolerates poor soils, and has shown wide site adaptability (Tauer, 2007). However, black locust has an invasive character. Contrary to *Miscanthus*, which is a triploid interspecific hybrid and therefore practically sterile (Christian and Haase, 2001), black locust can propagate both generatively and vegetatively; it has become a widespread species in the temperate and subtemperate climates (Rahmonov, 2009). Increased spreading of black locust, caused by planting of the species for bioenergy purposes could have undesired effects on species composition of European forest ecosystems.

5.5.5 SOC sequestration

In our analysis, we assumed that any changes in SOC content under rapeseed and sugarbeet are compensated for by other crops in the rotation that produce a relatively large quantity of crop residues, like cereals. However, cereal straw has an economic value (currently 9.5 €/Mg; LVLF, 2010) and may also be converted into bioenergy, including second generation biofuels. Therefore, the cost of leaving extra straw in the field to compensate for negative changes in SOC should be attributed to the crop that causes that negative change. Calculated according to the earlier mentioned VDLUFA method using data from Table 5.2, one season of rapeseed with crop residues left in the field positively contributes to SOC with 0.21 Mg C $ha^{-1}y^{-1}$; this may improve the GHG indicator with -14.3 g CO_2 eq. MJ^{-1} or alternatively leaves some room for utilizing part of the straw for energy purposes. In contrast, sugarbeet has a negative impact of 0.45 Mg C $ha^{-1}y^{-1}$ (13.5 g CO_2 eq. MJ^{-1} emission increase) and hence is a net emitter of GHG emissions from the soil. If these emissions were taken into account, sugarbeet ethanol would not meet the requirement of 35% GHG emission reduction (Bundestag, 2009).

The average annual sequestration of 1.36 Mg C $ha^{-1}y^{-1}$ that we simulated over the first six years of *Miscanthus* is slightly lower than the 1.87 Mg C $ha^{-1}y^{-1}$ measured in Northeast Germany by Kahle (2001) over six years. Since biomass yields in both cases were similar, the discrepancy could be caused by the fact that we did not simulate C input from root turnover. Virtually all literature on SOC sequestration under black locust relates to forestry rather than bioenergy plantations. Therefore, we compared C sequestration under black locust grown for short rotation coppice with sequestration under unfertilized short rotation coppice plantings of willow and poplar on cambisols in Northeast Germany (Kahle et al., 2007). The measured C sequestration was 0.5-0.75 Mg C $ha^{-1}y^{-1}$ over 12 years; we simulated 0.72 Mg C $ha^{-1}y^{-1}$. On relatively poor soils and without fertilisation, black locust may yield better than willow or poplar (Grünewald et al., 2009) hence also provide more residue C; Kahle et al. (2007) provide no yield data for comparison however.

5.5.6 Declining groundwater tables in Brandenburg

Declining groundwater tables are a problem in most parts of Brandenburg (Landesumweltamt Brandenburg, 2009). Therefore, the water productivity of biofuels is an important sustainability indicator in this study. Planting energy crops with relatively low evapotranspiration like rapeseed leaves more water available for replenishing aquifers. However, at the same time, due to relatively low net energy yield and water productivity of this crop, more hectares of rapeseed and in total more water are required to meet a certain energy target than of e.g. *Miscanthus or Robinia.* Since rapeseed also performs relatively poor for the other sustainability indicators, this may have negative effects on the environment, especially regarding N leaching (Figure 5.5c). For reaching the same energy target, fewer hectares of *Miscanthus* or Robinia would suffice. However, whether this strategy would actually reduce water use would depend on the use of the 'saved' land.

5.5.7 Energy supply by second generation systems in Brandenburg

With an average yield of 6.5 Mg DM ha^{-1} over a plantation cycle (Table 5.2), approximately 10 700 ha of black locust would be needed to feed the CHOREN processing plant; this seems somehow feasible from the 77 000 ha of mine soils and 77 000 of marginal agricultural land. In terms of contribution to the total Brandenburg energy consumption (600 PJ y^{-1}; Landesumweltamt Brandenburg, 2009), CHOREN only makes a minor contribution; 18000 m^3 of BtL contains ca. 0.6 PJ of energy. Planting black locust on 154 000 ha, would supply 8.3 PJ, or 1.4% of the total energy consumption. Planting of 77000 ha of marginal land with *Miscanthus* would yield 6.9 PJ, or 1.2% of the total energy consumption. Relative contributions to transportation energy are somewhat more significant; in Germany this constitutes 27% of the total energy consumption (EU, 2010). After rehabilitating reclaimed mine soils with one or two cycles of black locust, soil properties may have improved enough for planting other crops, including *Miscanthus*, hence higher net energy yields may then be obtained.

At the time of writing, the largest obstacle to second generation biofuels is the economic profitability (Naik et al., 2010); CHOREN has launched insolvency proceedings. The insolvency administrators intend to keep group business operations running and unaffected during initial proceedings (CHOREN, 2011c). As an alternative to the production of liquid biofuels, Miscanthus or black locust biomass may also be used for co-firing in one of several lignite-powered electricity plants in the region, hence reducing the carbon footprint of electricity. It has been reported that generating electricity from ligno-cellulosic feedstock crops, if used in electric cars, yields much higher net energy per hectare and greater GHG emission reductions than converting the feedstock into cellulosic ethanol, even if taking into account the emissions and energetic cost of producing and recycling car batteries (Campbell et al., 2009).

5.6. Conclusions

Based on our assessment of eight sustainability indicators, we found that in Brandenburg, second generation biofuel production systems based on *Miscanthus* and black locust perform substantially better than first generation systems based on rapeseed and sugarbeet. They contribute much more to GHG emission reduction, had much higher net energy yields and better resource use efficiencies; soil erosion and N leaching were also lower. *Miscanthus* performed better than black locust, except for its N use efficiency; it is the most water-efficient species, which is important in a region with declining groundwater tables. However, in Brandenburg, low temperatures during winter and early spring are often threatening to survival of first-year *Miscantus* plantings; there have been disastrous experiences in the past. Black locust has no problems with winter survival and has the advantage that it is drought-resistant, tolerates poor soils and has shown wide site adaptability; hence it may be used on marginal soils and for rehabilitating reclaimed mine soils. The drawback of black locust is that it has invasive characteristics.

Of the first generation systems, rapeseed has large N requirements per unit of energy produced and performed poor for N leaching. N leaching is aggravated by the relatively low evapotranspiration of the crop, which leaves more water for drainage below the root zone than the other crops. Erosion hazard in rapeseed is especially present after the seedbed has been prepared in the end of summer. However, erosion risk in sugarbeet is greater due to its late canopy closure.

Choices between the crops that we assessed will not only depend on sustainability aspects, but also on farmers' preferences and economic risks and opportunities; currently, second generation biofuels are not profitable because of technological barriers in conversion processes.

chapter 6

General Discussion

This thesis had a dual goal. Firstly, it aimed to assess the production-ecological sustainability of a number of biofuel production systems that represent as much as possible the diversity in feedstock crops, climatic and bio-physical environments in the world. The second aim was to produce a general methodology that enables assessments of the production-ecological sustainability of systems with minimum land use change, aid in the development of such systems and could potentially form a basis for sustainability certification of biofuels.

After having assessed resource use efficiencies and environmental performance of major first generation biofuel production systems in the world (Chapter 2), the work focused on assessing systems in three regions of the world (Chapters 3-5), including the most promising systems of the initial assessment. There were considerable differences in production systems and the availability of data and models between the three case studies. Therefore, it was necessary to use a variety of calculation tools and sustainability indicators. In this chapter, from the work done, a general methodology for assessing the production-ecological sustainability of a biofuel production system is distilled (Section 6.4). This chapter contains a synthesis of the research findings (Section 6.1), a discussion of the scope for minimising land use change and competition with food production (Section 6.2), a reflection on the research (Section 6.3), discussions on the employed methodology (Section 6.4) and societal relevance of the work (Section 6.5) and finally the general conclusions of the work (Section 6.6).

6.1 Research findings - best performing systems

When the major first generation biofuel production systems across the globe were compared (Chapter 2), systems based on oil palm and sugarcane emerged as performing well for the sustainability indicators employed in this thesis. This is confirmed by the more in-depth analysis in the case studies in Chapters 3-5. The highest net energy yields are achieved with sugarcane and oil palm (Table 6.1). Table 6.1 summarises the results of Chapters 3-5 for all systems analysed; calculation methods and units of sustainability indicators from different case study chapters were harmonised to this end. For cassava (Chapter 2) processing energy requirements and greenhouse gas (GHG) emissions are now included in the indicator calculations. Nitrogen use efficiency (NUE) was converted into specific nitrogen requirement (SNR), now excluding soil N mineralisation from N supply from the results of chapter 2. Soil organic carbon (SOC) sequestration is given in kg C $ha^{-1}y^{-1}$, soil erosion in Mg soil $ha^{-1}y^{-1}$.

Crop	Temperate/ Tropical (Tem/Tro)	Type of biofuel produced	Management	Soil type	Previous land use	Net energy yield GJ ha^{-1}	ΔSOC kg C ha^{-1}y^{-1}	GHG emissions g CO_2 eq. MJ^{-1}	SNR kg N GJ^{-1} of net energy	N leaching kg N ha^{-1} y^{-1}	Erosion Mg ha^{-1}y^{-1} of soil loss	Water productivity MJ of net energy m^{-3}
Oil palm	Tro	D	BMP	Sandy clay loam	anthropogenic savannah	154,4	725,9	-101,6	0,9	0,0	3,7	12,7
Sugarcane	Tro	E	mulch, drip irr.	Sand	agriculture	162,8	5,5	9,0	1,0	40,8	0,1	14,3
Oil palm	Tro	D	BMP	Sandy clay loam	oil palm (replanting)	154,4	4,1	11,1	0,9	0,0	3,7	12,7
Oil palm	Tro	D	BMP	Sandy clay loam	secondary forest	154,4	287,7	30,4	0,9	0,0	3,7	12,7
Oil palm	Tro	D	average practice	Sandy clay loam	anthropogenic savannah	99,0	650,7	-130,6	1,3	0,0	7,0	8,8
Miscanthus	Tem	FTD	BMP	Loamy sand	agriculture	90,1	1076,0	4,0	0,9	1,0	0,4	19,6
Miscanthus	Tem	E	BMP	Loamy sand	agriculture	71,3	1076,0	4,9	1,1	1,0	0,4	15,9
Black locust	Tem	FTD	low input	Loamy sand	lignite mining	53,7	567,0	7,8	0,0	6,0	0,4	11,1
Black locust	Tem	E	low-input	Loamy sand	lignite mining	43,0	567,0	9,7	0,0	6,0	0,4	8,8
Sugarcane	Tro	E	mulch, drip irr.	Sand	woodland	162,8	-419,8	21,5	1,0	40,8	0,1	14,3
Sugarcane	Tro	E	burnt, rainfed	Sand	agriculture	128,5	-0,1	10,7	0,9	22,5	0,7	15,1
Oil palm	Tro	D	average practice	Sandy clay loam	secondary forest	99,0	212,5	69,2	1,3	0,0	7,0	8,8
Oil palm	Tro	D	smallholder	Sandy clay loam	anthropogenic savannah	67,9	604,8	-123,9	1,9	0,0	8,0	7,2
Sugarcane	Tro	E	burnt, pivot irr.	Sand	agriculture	155,7	-3,5	16,5	1,1	31,9	0,7	13,2
Sugarcane	Tro	E	burnt, pivot irr.	Sand	woodland	155,7	-652,9	29,0	1,1	31,9	0,7	13,2
Sugarcane	Tro	E	burnt, rainfed	Sand	woodland	128,5	-652,9	27,1	0,9	22,5	0,7	15,1
Oil palm	Tro	D	average practice	Sandy clay loam	oil palm (replanting)	99,0	2,0	33,1	1,3	0,0	7,0	8,8
Oil palm	Tro	D	smallholder	Sandy clay loam	secondary forest	67,9	166,6	160,6	1,9	0,0	8,0	7,2
Cassava	Tro	E	no inputs	Loamy sand	woodland	10,1	-629,6	136,2	0,0	0,4	67,4	1,2
Cassava	Tro	E	no inputs	Loamy sand	agriculture	10,1	2,4	23,4	0,0	0,4	67,4	1,2
Cassava	Tro	E	200:300:400, mulch, drip irr.	Sand	agriculture	69,7	175,5	37,9	2,9	47,3	0,2	5,5
Cassava	Tro	E	200:300:400, mulch, drip irr.	Sand	woodland	69,7	-473,9	54,3	2,9	47,3	0,2	5,5
Oil palm	Tro	D	Smallholder	Sandy clay loam	oil palm (replanting)	67,9	-0,5	48,7	1,9	0,0	8,0	7,2
Cassava	Tro	E	40:150:0; mulch	Sandy clay loam	agriculture	51,2	153,1	23,4	0,8	18,7	2,3	5,6
Cassava	Tro	E	40:150:0	Sandy clay loam	agriculture	51,2	40,5	28,6	0,8	12,9	9,2	5,6
Cassava	Tro	E	40:150:0; mulch	Sandy clay loam	woodland	51,2	-496,5	52,5	0,8	18,7	2,3	5,6
Cassava	Tro	E	40:150:0	Sandy clay loam	woodland	51,2	-609,1	57,7	0,8	12,9	9,2	5,6
Sweet sorghum	Tro	E	mulch, rainfed	Sand	agriculture	46,2	101,3	13,2	1,9	20,9	0,2	8,3
Sweet sorghum	Tro	E	mulch, rainfed	Sand	woodland	46,2	-548,0	54,9	1,9	20,9	0,2	8,3
Cassava	Tro	E	no inputs	Sandy clay loam	agriculture	34,2	22,5	22,3	0,0	1,6	26,6	3,8
Cassava	Tro	E	no inputs	Sandy clay loam	woodland	34,2	-626,6	66,9	0,0	1,6	26,6	3,8
Sugarbeet	Tem	D	average practice	Loam	agriculture	51,3	0,0	56,5	1,9	29,0	4,7	12,3
Cassava	Tro	E	100:150:200; mulch	Loamy sand	agriculture	46,2	107,0	31,5	2,2	33,5	1,9	4,9
Cassava	Tro	E	100:150:200	Loamy sand	agriculture	46,2	28,9	35,7	2,2	28,2	7,4	4,6
Cassava	Tro	E	100:150:200; mulch	Loamy sand	woodland	46,2	-525,2	60,0	2,2	33,5	1,9	4,9
Cassava	Tro	E	100:150:200	Loamy sand	woodland	46,2	-603,3	64,9	2,2	28,2	7,4	4,6
Rapeseed	Tem	D	average practice	Loamy sand	agriculture	32,0	0,0	60,8	3,8	59,0	3,2	10,5

Table 6.1 *Performance of biofuel production systems assessed in Chapters 3-5 for six sustainability indicators. Per indicator (column), the top 10 values are highlighted in grey. Production systems (rows in the table) were sorted based on the number of top 10 indicator values they score; however, systems with the same number of top 10 indicators are displayed in random order. Calculations have been harmonised to make the indicators comparable (see text, p 1). Indicators not considered in this thesis (e.g. biodiversity) may be prohibitive for certain systems, such as planting oil palm after secondary forest. Abbreviations: D: biodiesel; E: bioethanol; FTD: Fischer-Tropsch diesel*

SOC sequestration rates in the three case studies (Table 6.1) depend on the combination of the supply of crop residue C and previous land use; the greatest sequestration rates were simulated for degraded soils that are low in SOC. On such soils with a SOC content of 0.5 – 0.8%, the greatest sequestration of SOC was simulated for *Miscanthus.* Although this crop produces a similar quantity of residues as oil palm or sugarcane grown under good agricultural practice, different residue quality and slower decomposition under dry-temperate conditions explain the greater sequestration under *Miscanthus*.

High C sequestration rates help to achieve low GHG emissions, but GHG emissions also strongly depend on consumption of fossil energy for processing and to a lesser extent agricultural input use. Therefore, C sequestration and GHG emissions are not unequivocally correlated (Table 6.1). Also, the reducing effect of soil C sequestration on GHG emissions is temporary; after two or three decades, generally, new equilibrium SOC contents are reached.

For processing sugarcane, oil palm, *Miscanthus* and black locust, biomass energy is used instead of fossil energy, which greatly contributes to their favourable performance in this respect. High net energy yields contribute to favourable SNRs for oil palm, sugarcane and *Miscanthus*; black locust has a SNR of zero due to its ability to fix N from the atmosphere. Simulated N leaching was least under crops with high evapotranspiration, since this leads to a small rainfall surplus and little availability of water for leaching; this is the case with oil palm, *Miscanthus* and black locust. Sugarcane also fits in this category, however in Chapter 3, N leaching was estimated with transfer functions from Smaling et al. (1993); in these functions, crop characteristics are not taken into account. Therefore, N leaching in sugarcane is probably overestimated. Soil erosion is lowest in (semi-) perennial crops with relatively low canopy height. These cover the soil during a large part of the year; the potential advantage of a tropical perennial such as oil palm over a temperate species such as black locust is that oil palm does not shed its leaves during winter. However, under black locust and other temperate perennials, there is continuous mulch cover from fallen litter, and absence of soil disturbance, generally. Very high erosion rates were simulated for zero-input (smallholder cassava) in Mozambique. The highest water productivity is achieved in C4 crops (sugarcane, *Miscanthus*), systems with high net energy yield (oil palm under best management practice, “BMP”) and sugar beet. Specific pesticide requirement (SPR) was only assessed in Chapters 2 and 5. Based on the collected data, pesticide application rates in kg active ingredient ha^{-1} vary within a relatively narrow range (~2-5 kg a.i. ha^{-1}; e.g. Fig. 6, Chapter 2); therefore SPR is largely determined by the net energy yield.

It is concluded that perennial nature, favourable harvest indices and C4 photosynthesis (sugarcane) are favourable traits for biofuel/bioenergy crops. In addition, under average or good management practices, oil palm, sugarcane and the second generation crops produce so much biomass that in addition to producing a high biofuel yield per hectare, enough biomass remains for maintaining SOC and supplying ample energy for processing. However, sugarcane and oil palm are at the same time controversial due to their expansion causing direct (cf. Nellemann et al., 2007) and indirect (cf. Sparovek et al., 2009) land use change and habitat destruction. The disadvantage of *Miscanthus* is its frost sensitivity, while black locust has characteristics of an invasive species.

First generation systems in temperate areas generally have rather low net energy yields and poor resource use efficiencies compared with ligno-cellulosic (*Miscanthus*, black locust) and tropical crops. Therefore, their production is relatively land- and resource consuming.

6.2 Scope for minimising land use change and competition with food production

If biofuel feedstock is cultivated on existing agricultural land, it may displace existing production of crops. Relocation of this crop production to other regions ultimately may lead to conversion of uncultivated land such as forests or grasslands into agricultural land. Conversion of uncultivated land for cultivation of crops displaced elsewhere is often referred to as indirect land use change ('ILUC'; cf. Croezen et al., 2010; Searchinger et al., 2009). The converted land may have high biodiversity value or contain high carbon stocks; in the latter case, significant GHG emissions may arise from ILUC. When GHG emissions from ILUC calculated by Croezen et al. (2010) or the European Commission (2010) are added to the GHG indicator values calculated in this thesis, only sugarcane and oil palm on degraded agricultural soils (Table 6.1) would meet the EU requirement of 35% emission reduction; for black locust no ILUC estimates are available yet. However, Croezen et al. (2010) state that use of marginal, severely degraded or abandoned land which has not been used for food production in the last 5 years may be considered to cause no ILUC; therefore, emissions from systems on degraded soils remain much lower than on agricultural soils. According to the authors, intensification of production above the 2% per year required for food output (over an average period of 5 years) may also be considered to cause no ILUC. Hence, two opportunities exist for increasing crop production for biofuels (and other commodities) without direct or indirect land use change: (i) the rehabilitation of degraded soils that are currently of little or no agricultural or ecological value, and

(ii) the 'ecological intensification' of cropping systems. Ecological intensification may be defined as the achievement of substantially higher yields relative to both land area and time, involving concomitant improvements in nutrient use efficiency, especially of N, water use efficiency and energy efficiency (Cassman, 2006). Both (i) and (ii) are explicit political goals mentioned in the Biofuels Directive, which states that "biofuels should be promoted in a manner that encourages greater agricultural productivity and the use of degraded land" (European Parliament, 2009; articles 78, 85). In this thesis, a number of systems were assessed that fall either under (i) or (ii), i.e. rehabilitating anthropogenic savannahs in Indonesia by introducing oil palm and planting of black locust on reclaimed lignite mine soils in Brandenburg, Germany, are examples of (i); introduction of best management practices (BMP) in oil palm and intensification of (smallholder) cassava systems in Mozambique fall under (ii).

Rehabilitation of degraded soils by planting oil palm (tropics) or black locust (temperate regions) has great advantages, especially in terms of soil fertility and C sequestration, while the energetic and economic (Fairhurst and McLaughlin, 2009) investments required are rather similar to those of planting on 'normal' soils. Ecological intensification by introducing BMP in oil palm results in significant improvement of sustainability indicator values compared to average practices: SOC sequestration, GHG emissions, NUE, water productivity and net energy yield improve significantly. For cassava, ecological intensification on different soil types was assessed; the performance differed. Intensification required more N fertilisation hence led to increased N leaching, especially on sandy soils. On these soils, ecological intensification will likely be more difficult and costly to achieve than on heavier soils. Introduction of drip irrigation favourably affected most sustainability indicators, however, GHG emissions and N leaching increased somewhat. Additionally, introduction of this technology with smallholders often meets maintenance problems. However, before cassava is used a biofuel feedstock, food security should be secured; over the years 2005-2007, 38% of the Mozambican population was malnourished (FAO, 2010) and root and tuber crops supply 34% of the calories in the national diet (FAO, 2008). ; over the years 2005-2007, 38% of the Mozambican population was malnourished (FAO, 2010) and root and tuber crops supply 34% of the calories in the national diet (FAO, 2008). Nevertheless, new factory that produces ethanol from cassava supplied by smallholder farmers is scheduled to become operational by March 2012; the produced ethanol is intended to replace kerosene for domestic (cooking) use (AfriqueAvenir.org, 2011; AllAfrica.com, 2011).

No estimates of GHG emissions from ILUC are available yet for second generation biofuel crops such as *Miscanthus* or black locust. However, if GHG emissions are expressed per unit gross energy produced, it seems likely that they perform better than annual crops such as sugar beet and rapeseed in this respect, due to higher net energy yields hence smaller requirements of agricultural land. It would particularly be favourable where marginal agricultural land is cultivated or rehabilitated. In the case of densely populated Western Europe, land is subject to competing claims from nature conservation, agriculture and urban planners, etc. Therefore, production of biofuel crops in a multifunctional agricultural way seems preferable; in such a context, cropping systems provide as much as possible the spatial and temporal diversity characteristic of natural ecosystems and successional sequences (Cook et al., 1991). Perennial species like willow, poplar or *Miscanthus* contribute seem to offer the best opportunities in this respect; they contribute more to biodiversity than arable crops (cf. Kuemmel et al., 1998; Rowe et al., 2009; Skarback and Becht, 2005; Smeets et al., 2009; Tilman et al., 2006; Volk et al., 2004) and supply bioenergy at the same time. However, the perennials that were assessed in temperate reasons in this thesis have other disadvantages, such as frost sensitivity (*Miscanthus*) and invasive characteristics (black locust).

6.3 A reflection on this research

6.3.1 Limitations – sustainability indicators

From this research, no conclusion can be drawn on whether a certain biofuel production system is in the end beneficial or harmful, neither on a global scale nor for any one of the three case study assessments. The reason is that in this thesis, the economic, social and environmental dimensions of sustainability are not fully assessed (see Chapter 1). Such an endeavour would require the engagement of experts in all of these fields. Designing systems that are sustainable in three dimensions is challenging; often, trade-offs exist between different dimensions. Such is the case for instance with the second generation systems that perform well in terms production-ecological sustainability (Chapter 5), but are presently not cost-effective (Naik et al., 2010). Another example is sugarcane: this crop generally scores well for production-ecological sustainability, but often has poor social sustainability because of poor working conditions where cane is harvested by hand (Smeets et al., 2006).

In this work, the production-ecological sustainability of biofuel production systems was assessed; it is only a part of one of the three dimensions of sustainability (General Introduction, Figure 1.2). The set of sustainability indicators employed in the assessments was selected based on scientific literature and indicator selection by multi-stakeholder platforms such as the roundtables for sustainable biofuels, palm oil and responsible soy (Chapter 1). As with any selection, inevitably some indicators were left out. A long list of indicators could have been developed to account for all thinkable production-ecological impacts of agriculture, but this might have hindered practical implementation (Jansen et al., 1995). For operationalisation of sustainability in studies such as the present one, a clear definition is needed with a limited number of indicators (Jansen et al., 1995). Examples of relatively common indicators that are part of the production-ecological domain but were not considered in this thesis are soil compaction, NH_3 emissions, (partial) N, P and K balances, phosphorus use, acidification/soil pH, air quality aspects such as emissions of fine particulate matter, CO and O_3 emissions (McBride et al., 2011), salinisation (Pieri et al., 1995) and wind speed buffering (Van Cauwenbergh et al., 2007). Some of these indicators can only be assessed in more specific case studies, such as a particular farm of field; others could not be assessed due to model and data limitations. As an example, phosphorus fertiliser requirements are strongly influenced by previous management, as the carry over effect of residual P may last decades. Only in a zero-input system such as smallholder cassava production in Mozambique, it could safely be assumed that there had been no past P applications; indeed, in Chapter 3, FIELD was used to determine P fertilisation requirements. Similarly, salinisation risk strongly depends on specific aspects of irrigation management and may vary from (sugarcane) plantation to plantation. Omitting essential indicators can be prevented by starting the assessment with a thorough analysis of the conditions in the area of interest, and of the information available (Jansen et al., 1995; Saifi and Drake, 2008).

Among the sustainability indicators that were selected in this study, the relative importance may depend on the biophysical and socio-economic context. For instance, water productivity may be more important in Brandenburg and Mozambique where rainfall is relatively low, as opposed to Sumatra. Similarly, erosion may be more important in Sumatra and Mozambique than in Brandenburg, were terrain is relatively flat. In this thesis, little attention was paid to this issue; in the presentation of results in the spiderweb charts in Chapters 2-5, equal weight was attached to each indicator. Weighting of indicators may be done on the basis of expert knowledge of the scientists involved in the assessment, or in an interactive process with stakeholders (Fraser et al., 2006). Among the suitable platforms for carrying out such a weighting exercise are the roundtables for sustainable biofuels and related commodities. In these roundtables, plantations, processors and NGOs are represented and they have established their own indicator frameworks (Table 1.1, General Introduction). Some indicators are of universal importance in biofuel production systems: net energy production and GHG emission reduction are two of the reasons for initiating biofuel production in the first place; hence these indicators need to be substantially positive. Therefore, GHG emissions from ILUC are an important subject for future study.

In each of the thesis chapters, it was attempted to determine which of several biofuel production systems is the most sustainable. However, it was not, for any of the given systems, determined whether it meets sustainability indicator thresholds in the absolute sense (cf. Lewandowski and Faaij, 2006; Woodhouse et al., 2000).

6.3.2 Limitations – biofuel production pathways that were not assessed

In this thesis, not all possible pathways for the production of biofuels or renewable transport energy in general were assessed. Therefore, no recommendations are made on the most sustainable biofuel production system or on the sustainability of biofuels compared with other forms of renewable transport energy. However, characteristics of sustainable biofuel production chains can be identified.

Technology in this field progresses rapidly. Compared to the priorities identified in the proposal for the current research, some biofuel production pathways have gained importance over the past few years. For instance, the production of biogas from sugar beet or its residues was not investigated, while it performs better than ethanol produced from this crop in terms of net energy yield and GHG emissions reduction (Corré and Langeveld, 2008), but especially in terms of fuel costs (Roland Berger Strategy Consultants, 2011). A disadvantage is the different infrastructure that this fuel requires (Roland Berger Strategy Consultants, 2011).

Similarly, it has been reported that generating electricity from ligno-cellulosic feedstock crops, if used in electric cars, yields much higher net energy per hectare and greater GHG emission reductions than converting the feedstock into cellulosic ethanol, even if the emissions and energetic cost of producing and recycling car batteries are taken into account (Campbell et al., 2009). Apart from stating that "with more research and incentives, we can break our dependence on oil with biofuels", President Obama stated "becoming the first country to have 1 million electric vehicles on the road by 2015" as an explicit goal in his 2011 State of the Union address, since "few technologies hold greater promise for reducing the world's dependence on oil" (The White House, 2011). Similarly, promoting new technologies including electric and hybrid cars are mentioned in the EU growth strategy for the next 10 years (Commission of the European Communities, 2010). Making second generation biofuels a competitive alternative to fossil fuels, while respecting the sustainability of their production is listed as the #1 key EU technology challenge until 2017 (Commission of the European Communities, 2007).

6.4 The methodology developed in this thesis

6.4.1 Crop-soil models

In Chapter 2, sustainability indicators were used that were calculated in a fairly simple way from secondary data, without use of detailed calculations and computer modelling. Although this approach sufficed for comparing crops on a global scale, relatively little information is obtained on the mechanisms underlying the obtained indicator values, on the influence of different soils, climates and crop management, and on the scope for improvement. For these reasons, in the three case study assessments, approaches were followed in which the influence of soil, climate and management was integrated by calculations in simulation models.
For Mozambique (Chapter 3), a new application for the crop-soil model FIELD (Tittonell et al., 2010) was developed. It was used to assess cassava production for biofuels in smallholder fields; in such fields in Mozambique, normally no fertilisers or other inputs are applied. Based on soil and climate data, FIELD estimates the water- and nutrient-limited cassava yields and predicts the crop's response to fertilisers or irrigation over a longer period of time. The calculation sequence is: climate, soil properties and input use > water and nutrient availability > crop nutrient uptake, crop and residue yield > crop residue return, sustainability indicators > updated soil properties, etc. (Tittonell et al., 2010). This approach, is similar to that of e.g. the CENTURY model (Parton et al., 1988) in that it takes into account the feedback between SOC and crop yield, which is essential in low-input agricultural systems. In such systems, nitrogen become available mainly through decomposition of SOC (leading to depletion), whereas in high-input agricultural systems most nutrients required by crops are supplied by chemical fertilisers (Gijsman et al., 2002).

Where ecological intensification with increased fertilisation is introduced, the importance of SOC as a supplier of nutrients is diminished and the feedback between SOC and crop yield is much less important. In such situations, a different approach was used: crop production could be simulated by existing stand alone crop models for water-limited production (Van Ittersum and Rabbinge, 1997). Simulated crop residue yields were then used as input for a SOC model. SOC content was not fed back to the crop growth model since it does not influence crop yields in this situation; it may still influence fertiliser requirements however. This approach was used for the relatively high-input *Miscanthus* cultivation in Brandenburg (Chapter 5), where suitable crop growth models and the required data were readily available. For rapeseed and sugar beet in this case study, no change in SOC was assumed due to SOC-neutral crop rotations, hence it sufficed to simulate crop production with a crop growth model for water-limited production. Only for black locust in Brandenburg, which is grown without fertilisation on infertile reclaimed mine soils, a feedback between SOC and

crop yield could be expected. However, black locust symbiotically fixes nitrogen from the air rather than to depend on soil N supply. P and K supply in temperate regions are much less SOC-dependent than N; moreover, as a pioneer plant species, black locust is likely rather insensitive to low supply of these nutrients; also, P and K fertilisation generally had little impact on the analyses in this thesis in terms of energy expenditures and GHG emissions.
Instead of using crop growth models, in high-input systems, where the feedback between SOC and crop yield is largely absent, recorded data of actual yields and residue input can also be used for calculating SOC and other sustainability indicators. This was done in the assessment of sugarcane and sweet sorghum ethanol in Mozambique (Chapter 3) and of oil palm biodiesel in Indonesia (Chapter 4). In the latter two systems, SOC content is initially low and supplies little nutrients; however, under good agricultural management, sufficient fertilisers are applied for alleviating any nutrient shortages (Goh et al., 1999; Henson and Chang, 2007; Meyer et al., 2004), hence no feedback between SOC and crop yield is present. The special characteristics of black locust that were mentioned above allowed using the same approach for this species in Brandenburg.

6.4.2 Calculation of the sustainability indicators

Across the different thesis chapters, calculation of the sustainability indicators varies, depending on the applied models, assessed systems and data availability. However, for calculation of net energy yield per hectare, there are no substantial differences across the chapters.

GHG emission calculations differ between chapters, depending on the way emissions from land use change (LUC) are taken into account. In the initial general assessment (Chapter 2), LUC was not taken into account, as this study was not sufficiently location-specific to do so. In the case studies in Mozambique, Sumatra and Brandenburg (Chapters 3-5), SOC emission or sequestration due to LUC was included in the GHG indicator. In the oil palm case study in Sumatra, (Chapter 4), not only included changes in SOC brought about by LUC were included, but also the change in standing biomass, which may large if anthropogenic savannah or tropical rainforest are converted into oil palm plantation. Another difference is in the N_2O emissions; N_2O emissions from crop residues were only taken into account in Chapter 5, where sugar beet and black locust produce large quantities of crop residues with a high N content.

In Chapter 2 the Effective Organic Matter (EOM) was used as a measure of SOC maintenance; it is defined as the quantity of organic matter that is still present in the soil one year after application of the residues (Timmer et al., 2004). In the remaining chapters, the change in SOC simulated by the FIELD (Chapters 3,4) and RothC 26.3 (Chapter 5) models was used as indicator. It appeared that the amount of C sequestration from a certain quantity of C input depends strongly on initial SOC content and soil texture; degraded soils with little SOC stock offer much larger potential for sequestration than soils with higher C content. Therefore, it can be concluded that EOM is a better indicator for general assessments and merely indicative of quality and quantity of crop residues and climate, while simulated SOC indicates the C sequestration potential from those crop residues in specific cases. Compared with FIELD (Tittonell et al., 2007), the advantage of RothC 26.3 is that this model does not need recalibration each time it is applied in a different environment; instead it uses empirical functions to quantify the impact of soil texture, temperature, humidity and soil cover on SOC decomposition; it does so quite reliably over a wide range of environments cf. (Shirato et al., 2005; Smith et al., 1997).

Soil erosion was calculated by the Universal Soil Loss Equation (Chapter 2) and the Revised Universal Soil Loss Equation (Chapters 3-5). Although principles behind both equations are similar, the RUSLE mostly uses formulae suitable for application in computerised models, rather than hardcopy lookup tables that were more useful in the pre-PC era when the USLE was developed.

NUE was calculated as E_{net}/N_{fert} (a) or, where systems with zero fertilisation were assessed, as its reciprocal value N_{fert}/E_{net}, which is referred to as specific N requirement (SNR). However, in Chapter 3 advantage was taken of having an integrated crop-soil model and NUE was calculated as $E_{net}/N_{available}$ (b); $N_{available}$ includes mineralised N from SOC and crop residues. Indicator (a) is more simple to calculate in the absence of integrated models.

For estimating N leaching in Chapter 3, transfer functions derived by Smaling et al. (1993) were used to estimate the fraction of soil and fertiliser N that is leached to the groundwater based on soil texture and seasonal rainfall; insufficient data were available for more detailed approaches. However, it was already concluded in section 6.1 that a shortcoming of this method is that it does not take into crop evapotranspiration, which greatly depends on crop type and yield level. In Chapter 4, where daily weather data were available, a daily soil water balance was simulated; the volume of water draining below the oil palm root zone was assumed to be correlated with N leaching. It appeared negligible however, due to high palm evapotranspiration. Of the three case studies, the highest risk of N leaching was expected in Brandenburg (Chapter 5), where soils are mostly sandy and cropping systems are high-input: for sugar beet and rapeseed, N applications are high and NUE poor (Chapter 2). Here, the methodology from the NLEAP model was used (Shaffer et al., 2010), which may be used to estimate N leaching on a daily basis. However, to take full advantage of the method, daily simulation of the soil N balance is required. The employed models did not cater for this and could not easily be adapted; therefore a seasonal estimate was calculated (Shaffer et al., 2010).

Water productivity was calculated as E_{net} /ET (i), except for Chapter 3, where it was calculated as E_{net} /$Water_{available}$ (ii). The different indicator in Chapter 3 was chosen to taken into account the efficiencies of the different irrigation systems[$] that were studied; indicator (ii) combines precipitation and irrigation water in a single indicator. This indicator is relevant in areas where water availability strongly limits agricultural productivity (Mozambique, Chapter 3); it is less relevant in Sumatra (Chapter 4), for instance. Also, efficient water use at the field level does not always translate into efficient water use at regional scale (Bouman, 2007); recapture of drainage and runoff flows may play an important role at larger scales (cf. Loeve et al., 2004).

Pesticide use efficiency, strictly speaking an incorrect term since crops do not really utilise pesticides, was calculated similar to NUE as GJ net energy/kg a.i.

6.4.3 Implications for the biofuels sustainability assessment framework

From the previous section, it may be concluded that the precise definition and calculation methods for assessing the production-ecological sustainability of biofuel production systems should depend on the characteristics of the systems assessed (e.g. importance of land use change, presence of irrigation), the spatial scale of the case (Chapter 2 a region vs. Chapters 3-5 a part of a country vs. a specific field) and on the availability of data and suitable models. Therefore, an assessment framework suitable for application in locations around the world should offer a wide range of options in choosing sustainability indicators and calculation methods, or allow the user to modify these, if required.

Several existing modelling tools for agricultural production systems allow assessment of the impact of agricultural production systems on sustainability indicators similar to the ones used in this thesis. For instance, the CropSyst model (Stockle et al., 1994) aims at evaluating BMPs by providing information regarding the ability of given management practices to increase productivity while also estimating the environmental impacts. CropSyst is a daily time step, multiyear, multicrop simulation model designed to predict crop growth and development, crop yield, daily residue loss, nitrogen leaching, and erosion in response to soil conditions, weather, and management practices such as irrigation, fertilization, residue management and tillage. APSIM (Agricultural

[$] Surface irrigation, center pivot irrigation and drip irrigation

Production Systems Simulator; Keating et al., 2003), EPIC (Erosion-Productivity Impact Calculator; Williams, 1990) and DSSAT (Decision Support System for Agrotechnology Transfer; Jones et al., 2003) can also do this; DSSAT has also been adapted for application in low-input tropical systems (cf. Dzotsi et al., 2010; Gijsman et al., 2002).

There is a substantial overlap in the methodology that was used for assessing some of the indicators and the methodology used in these modelling tools. Nevertheless, for several reasons, none of these tools were deemed suitable for application in this research. For instance, none of them catered for simulating growth of *Miscanthus*, black locust, oil palm, or severely nutrient-limited cassava. Other aspects that are missing are the calculation of GHG emissions or energy balances. Also in this assessment, processing efficiency has a substantial impact on such outcomes. For researchers without advanced programming skills, it is not possible to modify these modelling systems to include these aspects; also, in many cases, users do not have the rights to make such modifications. Hence, there is a definite need for an assessment framework that is flexible and simple enough to allow modification or addition of model components by the researchers, while at the same time building on the knowledge that was accumulated in the afore-mentioned modelling frameworks. The model presented in Chapter 3 (Figure 3.1), which was also used in strongly modified form in Chapter 4, may serve as a first example of such a framework. Its core is a SOC model, which can be linked to different models that estimate plant production and production of crop residues, and to modules that calculate the sustainability indicators. The seasonal time step that was used in the framework in Chapter 3 put limits to the detail of calculation sustainability indicators such as N leaching and soil erosion (compare with Chapter 5); given the absence of daily weather data, more detailed calculations could not be carried out in this case however. Another potential drawback is that the employed SOC simulation model cannot be transferred to other climates and soils without recalibration. On the other hand, its simple programming language (FST; Rappoldt and Van Kraalingen, 1996) allows user modification and linking to existing crop growth models such as WOFOST, MICROSIM and SACROSIM (Chapter 5), while the SOC model could be modified in the future to include more features from e.g. RothC 26.3 (Chapter 5). The procedure followed in developing it can be generalised (Figure 6.1); it may form a basis for future assessments of the production-ecological sustainability of biofuel production chains or in the development of new frameworks that serve this purpose. The intuitive graphic representation of results that was used, i.e. the cobweb diagrams in Chapters 2-5 enable the reader to see differences between systems at a glance. However, a disadvantage of this method is that the area covered by the web is not proportional to the cumulated sustainability scores of all indicators; also changes in some indicators may have more impact than in others, due to the mathematical transformations that were used to capture indicator values in percentages. In this respect, sorting systems based on the number of top scoring indicators per system (Table 6.1) seems a less problematic approach.

6.5 Relevance for society

6.5.1 Biofuels versus other options to reduce GHG emissions

If the prime goal of biofuel production is GHG emission reduction, then there may be strategies that have higher reduction potential and are more cost-effective than the production of biofuels. For instance, Nauclér and Enkvist (2009) pointed

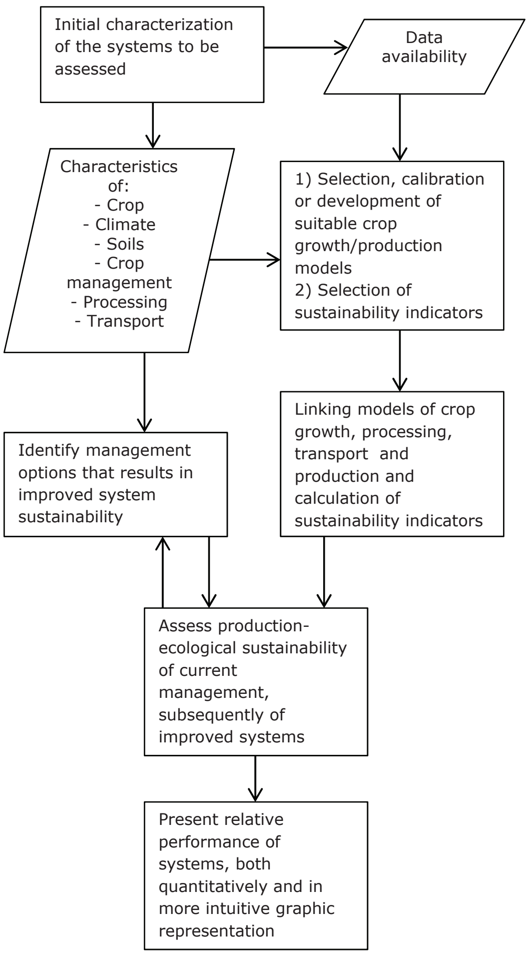


Figure 6.1 *The procedure followed in developing a framework for assessing the production-ecological sustainability of biofuel production systems presented in Chapter 3, and employed in a modified form in Chapter 4.*

out that there is still massive potential of reducing GHG emissions by reducing energy consumption in general. Reducing energy consumption generally not only saves energy but also money and is therefore a cost-negative way of reducing GHG emissions. In their assessment, Nauclér and Enkvist (2009) estimate that 1st generation biofuels based on sugarcane are also slightly cost-negative, i.e. provide energy that is somewhat cheaper than their fossil alternatives while at the same time reducing emissions. Sugarcane ethanol has been found to be the most cost-effective biofuel (cf. Deconti, 2008; Fairley, 2011). Second generation biofuels, although having higher GHG abatement potential, at the same time have higher cost (Nauclér and Enkvist, 2009). Other options in the agricultural sector for reducing GHG emissions, some with greater estimated global abatement potentials than biofuel production, include improved cropland nutrient management, improved tillage and residue management and rehabilitation of degraded land; the beneficial effect of several of these strategies on a hectare basis was estimated for several production systems in this thesis. As demonstrated in Chapters 3 and 4, combining these BMPs in biofuel production may substantially improve its environmental performance and GHG abatement potential.

6.5.2 The future

Among the general public in the European Union, there is considerable public support for biofuels; 72% of the people think that they should be encouraged, while 83% are in favour of encouraging *sustainable* biofuels (Robbins, 2011). Despite strong public support, governments worldwide differ in financial support for biofuels and their progress towards meeting targets. According to projections by OECD and FAO (2011), global ethanol production will increase from ~90 billion liters per year in 2009 to ~ 155 billion liters per year in 2020. By then it is expected that 44% of global ethanol is produced from coarse grains (mainly maize, representing 12% of its global production) and 36% from sugarcane; cellulosic ethanol production is expected to represent only 5% of global production.

Global biodiesel production is expected to grow from 17 billion liters per year in 2009 to 36 billion liters per year in 2020. OECD and FAO (2011) expect that more than 75% of global biodiesel production will come from vegetable oil in 2020, representing 16% of the global production of vegetable oils. The most important biodiesel feedstocks in the developing world are expected to remain palm oil and soybean oil. Second generation biodiesel production (BtL) is expected to grow in developed countries from 2018 and to represent about 10% of global biodiesel in 2020; the remainder is from non-agricultural feedstocks.

The expected future dominance of maize, sugarcane, soybean and palm oil as biofuel feedstock crops has consequences for production-ecological sustainability (e.g. Figure 2.8). Findings in Chapter 2 indicate that, if adverse land use change is absent, maize and soybean perform much poorer than oil palm and sugarcane. All crops that will be major suppliers of biofuel feedstock in the coming decade, at least according to the projections by OECD and FAO (2011), entail substantial GHG emissions from ILUC (Croezen et al., 2010). Maize and soybean have relatively low net energy yields (Chapter 2), hence enormous land areas will be involved in their producing a major share of global biofuel production in 2020; based on their ILUC emissions (Croezen et al., 2010), this will have serious consequences in terms of indirect land use change. Based on the results of this thesis, substantial research efforts should therefore be directed towards further investigation of the second generation biofuels, among others from *Miscanthus* and black locust. Priority would be to investigate the indirect land use change associated with cultivation of these crops; other relevant aspects would be the biodiversity impacts of black locust outside its continent of origin, and the frost sensitivity and economics of *Miscanthus* systems. Secondly, more research should be dedicated to investigating the prospects of rehabilitating degraded land for cultivating oil palm (Chapter 4) or black locust (Chapter 5); and towards ways to get this practice implemented on a wider scale through political and economic stimuli or certification systems. One way could be to make rehabilitation eligible for credits in the UN REDD+ scheme (UN-REDD programme, 2010). Finally, other pathways for converting feedstock from these crops into transportation energy should remain under investigation, especially anaerobic digestion and use of biomass to generate electricity for propelling electric vehicles.

Finally, if more agricultural commodities were subject to sustainability criteria comparable to those laid down for biofuels, indirect land-use change could be limited. The reason for this is that the indirect land-use change effect of biofuels is the direct land-use change of another commodity. The attention that is currently paid to the sustainability of biofuels, both in science and in the media may in the longer term have a beneficial effect on the sustainability of agricultural products in general.

6.6 General conclusions

Biofuel production systems using feedstock from sugarcane, oil palm and second generation crops *Miscanthus* and black locust performed much better than first generation production using feedstock from arable crops in temperate areas. Sugarcane, oil palm, *Miscanthus* and black locust under good agricultural practice produce so much biomass that they have high gross energy yields, provide enough biomass for powering the conversion process which contributes to high net energy yields, and at the same time supply ample crop residues for maintaining SOM. In contrast, first generation systems in temperate areas generally have rather low net energy yields and poor resource use efficiencies and perform relatively poorly for the sustainability indicators that were assessed. Therefore, their production is relatively land- and resource consuming and has relatively high environmental impact.

When estimates of GHG emissions from indirect land use change are added to the GHG emissions figures calculated in this thesis, most systems would not reach the 35% reduction of GHG emissions compared with fossil fuels that the EU currently demands, except for some crops that can be grown on degraded lands. Findings in this thesis indicate that rehabilitation of degraded soils by planting oil palm (tropics) or black locust (temperate regions) has great advantages, especially in terms of GHG emission reduction, C sequestration and soil fertility, while the energetic or economic investments required are rather similar to those of planting on 'normal' soils. However, the economic risk of frost damage in *Miscanthus* and invasive character of black locust are aspects that need further research. Also, the reducing effect of soil C sequestration on GHG emissions is temporary; after two or three decades, generally, new equilibrium SOC contents are reached.

Ecological intensification by introducing BMP in oil palm results in significant improvement of sustainability indicator values compared to average practices: SOC sequestration, GHG emissions, NUE, water productivity and net energy yield improve significantly. BMP should therefore not only be applied in oil palm production for biodiesel, but also in production for food and other purposes. More research should be dedicated towards ways to get rehabilitation of degraded soils and introduction of BMP implemented on a wider scale, and towards investigating any practical limitations to this approach.

From the research, it also became apparent that there is a definite need for a framework to assess the sustainability of biofuel production systems which is flexible and simple enough to allow user modification or addition of model components, while at the same time building on existing modelling frameworks. In this thesis, a first version of such a framework was presented; suggestions for its further application and improvement are also made.

References

ADEME. (2002) Energy and Greenhouse Gas Balances of Biofuels' Production Chains in France - Executive Summary, Agence de l'Environnement et de la Maîtrise de l'Energie - French Environment and Energy Management Agency, Angers, France. pp. 9.

Aden A., Ruth M., Ibsen K., Jechura J., Neeves K., Sheehan J., Wallace B. (2002) Lignocellulosic Biomass-to-Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover, Technical report, (NREL) National Renewable Energy Laboratory, Golden, Colorado. pp. 154.

AfriqueAvenir.org. (2011) Mozambique to begin producing ethanol from cassava. http://www.afriqueavenir.org/en/2011/09/13/mozambique-to-begin-producing-ethanol-from-cassava/; consulted 12 December 2011, AfriqueAvenir.org.

Agus F., Runtunuwu E., June T., Susanti E., Komara H., Syahbuddin H., Las I., Van Noordwijk M. (2009) Carbon dioxide emissions in land use transitions to plantation. Jurnal Litbang Pertanian 28:119-126.

Ahmed I., Decker J., Morris D. (1994) How Much Energy Does it Take to Make a Gallon of Soydiesel?, Institute for Local Self-reliance (ILRS), Minneapolis. pp. 15.

AllAfrica.com. (2011) Mozambique: factory to produce ethanol from cassava. http://allafrica.com/stories/201109140139.html; consulted 12 December 2011.

Allen R.G., Pereira L.S., Raes D., Smith M. (1998) Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements - FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations (FAO), Rome. pp. 300.

Anderson J.M. (2008) Eco-friendly approaches to sustainable palm oil production. Journal of Oil Palm Research:127-142.

Anonymous. (2008) Don't take diseases and pests lightly. Ganoderma causes about RM280 mln in losses nationwide: East Malaysia Planters Association, The Borneo Post Online, Kuching, Malaysia.

Aref S., Pike D.R. (1998) Midwest farmers' perceptions of crop pest infestation. Agronomy Journal 90:819-825.

Armstrong A.P., Baro J., Dartoy J., Groves A.P., Nikkonen J., Rickeard D.J. (2002) Energy and Greenhouse Gas Balance of Biofuels for Europe - An Update, CONCAWE. (The Oil Companies' European Association for Environment, Health and Safety in Refining and Distribution), Brussels. pp. 18.

Arndt C., Pauw K., Thurlow J. (2010) Biofuels and Economic Development in Tanzania, IFPRI Discussion Papers 00966, IFPRI, Washington, DC. pp. 34.

Arndt C., Benfica R.U.I., Tarp F., Thurlow J., Uaiene R. (2009) Biofuels, poverty, and growth: a computable general equilibrium analysis of Mozambique. Environment and Development Economics 15:81-105.

Auerswald K. (1989) Predicting nutrient enrichment from long-term average soil loss. Soil Technology 2:271-277.

Aweto A.O. (1995) Organic carbon diminution and estimates of carbon dioxide release from plantation soil. The Environmentalist 15:10-15.

Azapagic A., Perdan S. (2005) An integrated sustainability decision-support framework - Part I: Problem structuring. The International Journal of Sustainable Development and World Ecology 12:98-111.

Baede A.P.M., Ahlonsou E., Ding Y., Schimel D.S. (2001) The climate system: an overview, in: B. Bolin and S. Pollonais (Eds.), Climate Change 2001: The Scientific Basis, Cambridge University Press, Cambridge, UK. pp. 85-98.

Barbanti L., Grandi S., Vecchi A., Venturi G. (2006) Sweet and fibre sorghum (Sorghum bicolor (L.) Moench), energy crops in the frame of environmental protection from excessive nitrogen loads. European Journal of Agronomy 25:30-39.

Basiron Y. (2007) Palm oil production through sustainable plantations. European Journal of Lipid Science and Technology 109:289-295.

Basiron Y., Weng C.K. (2004) The oil palm and its sustainability. Journal of Oil Palm Research 16:1-10.

Batidzirai B.B., Faaij A.A.P.C., Smeets E.E.M.W. (2006) Biomass and bioenergy supply from Mozambique. Energy for Sustainable Development 10:54-81.

Beaudoin N., Saad J.K., Van Laethem C., Machet J.M., Maucorps J., Mary B. (2005) Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations. Agriculture, Ecosystems & Environment 111:292-310.

Bengtson R.L., Magdi Selim H. (2007) USLE "C" values for Louisiana sugarcane, ASABE Annual International Meeting, ASABE (American Society of Agricultural and Biological Engineers), 17-20 June 2007, Minneapolis Convention Center, Minneapolis, Minnesota.

Benjumea P., Agudelo J., Agudelo A. (2008) Basic properties of palm oil biodiesel-diesel blends. Fuel 87:2069-2075.

Bernoux M., Cerri C.C., Neill C., de Moraes J.F.L. (1998) The use of stable carbon isotopes for estimating soil organic matter turnover rates. Geoderma 82:43-58.

Bezuidenhout C., Lecler N., Gers C., Lyne P. (2006) Regional based estimates of water use for commercial sugar-cane in South Africa. Water SA 32:219-222.

BioGrace. (2010) Harmonised Calculations of Biofuel Greenhouse Gas Emissions in Europe - Complete List of Standard Values, Version 3 - Public, www.biograce.net.

Blanco-Canqui H., Lal R. (2007) Soil and crop response to harvesting corn residues for biofuel production. Geoderma 141:355-362.

Bloomberg. (2011) Energy & Oil Prices: Natural Gas, Electricity and Oil. www.bloomberg.com/energy, consulted 11 November 2011, Bloomberg.

Bockus W.W., Shroyer J.P. (1998) The impact of reduced tillage on soilborne plant pathogens. Annual Review of Phytopathology 36:485-500.

Böhm C., Quinkenstein A., Freese D. (2011) Yield prediction of young black locust (Robinia pseudoacacia L.) plantations for woody biomass production using allometric relations. Annals of Forest Research 54:1-13.

Bonari E., Mazzoncini M., Peruzzi A. (1995) Effects of conventional and minimum tillage on winter oilseed rape (Brassica napus L.) in a sandy soil. Soil and Tillage Research 33:91-108.

Boring L.R., Swank W.T. (1984) The role of black locust (Robinia Pseudo-Acacia) in forest succession. Journal of Ecology 72:749-766.

Bos H. (2008) Agrificatie en de Biobased Economy Agrotechnology & Food Sciences Group, Wageningen, Wageningen.

Bouman B.A.M. (2007) A conceptual framework for the improvement of crop water productivity at different spatial scales. Agricultural Systems 93:43-60.

Breure C.J. (1985) Relevant factors associated with crown expansion in oil palm (Elaeis guineensis Jacq.). Euphytica 34:161-175.

Brinkmann Consultancy. (2009) Greenhouse Gas Emissions from Palm Oil Production. Literature Review and Proposals from the RSPO Working Group on Greenhouse Gases, Hoevelaken, The Netherlands. pp. 57.

Bross E., Gold M., Nguyen P. (1995) Quality and decomposition of black locust (Robinia pseudoacacia) and alfalfa (Medicago sativa) mulch for temperate alley cropping systems. Agroforestry Systems 29:255-264.

Brundtland G.H. (1987) Our Common Future, UN World Commission on Environment and Development, Nairobi. pp. 374.

Bundestag. (2004) Direktzahlungen-Verpflichtungenverordnung. Bundesgesetzblatt Teil I:1763-1776.

Bundestag. (2004) Bundesberggesetz. Bundesgesetzblatt Teil I:1310.

Bundestag. (2009) Verordnung über Anforderungen an eine nachhaltige Herstellung von Biokraftstoffen. Bundesgesetzblatt Teil I:3182.

Bungart R., Hüttl R.F. (2004) Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey-sandy mining substrate with respect to plant nutrition and water budget. European Journal of Forest Research 123:105-115.

Burner D., Pote D., Ares A. (2006) Foliar and shoot allometry of pollarded black locust, Robinia pseudoacacia L. Agroforestry systems 68:37-42.

Caliman J.-P., De Kochko P. (1987) Quelques techniques culturales et amenagements speciaux realisables en plantation des palmiers a huile pour limiter l'érosion et le ruisselement. Oléagineux 42:99-106.

Camp C.R. (1998) Subsurface drip irrigation: a review. Transactions of the ASAE 41:1353-1367.

Campbell J.E., Lobell D.B., Field C.B. (2009) Greater transportation energy and GHG offsets from bioelectricity than ethanol. Science 324:1055-1057.

Cannell M.G.R., Milne R., Sheppard L.J., Unsworth M.H. (1987) Radiation interception and productivity of willow. Journal of Applied Ecology 24:261-278.

Cariolle M., Molard M.R. (2004) Sugar Beet in Europe: an Environmentally Friendly Crop for Sustainable Plant Production Systems. Version 7, International Institute for Beet Research, Brussels. pp. 30.

Carter C., Finley W., Fry J., Jackson D., Willis L. (2007) Palm oil markets and future supply. European Journal of Lipid Science and Technology 109:307-314.

Cassman K.G. (2006) Ecological intensification of agriculture and implications for improved water and nutrient management, International symposium on fertigation, September 20-24, 2006, Beijing.

Cassman K.G., Liska A.J. (2007) Food and fuel for all: realistic or foolish? Biofuels, Bioproducts and Biorefining 1:18-23.

Casson A. (2003) Oil Palm, Soybeans & Critical Habitat Loss. A Review Prepared for the WWF Forest Conversion Initiative, WWF, Zurich, Switzerland. pp. 21.

Chang K.C., Chow C.S. (1985) Some questions of the leaching losses of soil nutrients from mature oil palm fields in Malaysia. Oleagineux 40:233-240.

Chapagain A.K., Hoekstra A.Y. (2004) Water Footprints of Nations. Volume 1: Main Report, Value of Water Research Report Series, UNESCO-IHE Institute for Water Education, Delft. pp. 76.

Cheesman O.D. (2004) Environmental Impacts of Sugar Production. The Cultivation and Processing of Sugarcane and Sugar Beet. CABI publishing, WWF International (Freshwater Programme), Wallingford, UK.

CHOREN. (2011) Beta Plant; http://www.choren.com/en/carbo-v/references/beta-plant/, CHOREN, Freiberg.

CHOREN. (2011) Energy Wood from Agriculture, http://www.choren.com/en/carbo-v/feedstock-supply/short-rotation-coppice/, CHOREN, Freiberg.

CHOREN. (2011) Press release Kübler GbR: CHOREN Group - KÜBLER prepares investor solution, http://www.choren.com/en/information-and-press/press-releases/, CHOREN, Freiberg.

Christian D.G., Haase E. (2001) Agronomy of Miscanthus, in: M. B. Jones and M. E. Walsh (Eds.), Miscanthus for Energy and Fibre, James & James (Science Publishers) Ltd., London. pp. 21-45.

Christian D.G., Poulton P.R., Riche A.B., Yates N.E. (1997) The recovery of 15N-labelled fertilizer applied to Miscanthus × giganteus. Biomass and Bioenergy 12:21-24.

Clay J. (2003) World Agriculture and the Environment : a Commodity-by-Commodity Guide to Impacts and Practices Island, Washington, DC.

Clifton-Brown I.J., Long S.P., Jørgensen U. (2001) Miscanthus productivity, in: M. B. Jones and M. E. Walsh (Eds.), Miscanthus for Energy and Fibre, James & James (Science Publishers) Ltd., London. pp. 46-67.

Coleman K., Jenkinson D.S. (2007) ROTHC-26.3. A Model for the Turnover of Carbon in Soil. Model Description and Users Guide, IACR Rothamsted, Harpenden, Herts, UK. pp. 47.

Coleman K., Jenkinson D.S., Crocker G.J., Grace P.R., Klír J., Körschens M., Poulton P.R., Richter D.D. (1997) Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. Geoderma 81:29-44.

Commission of the European Communities. (2007) A European Strategic Energy Technology plan (SET-plan). Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Brussels. pp. 14.

Commission of the European Communities. (2010) EUROPE 2020. A Strategy for Smart, Sustainable and Inclusive Growth. Communication from the Commission, Brussels. pp. 34.

Conselho do Ministros. (2009) Resoluçao no. 22/2009, Boletim da Republica, Maputo. pp. 14 - 21.

Cook R.J., Haglund W.A. (1991) Wheat yield depression associated with conservation tillage caused by root pathogens in the soil not phytotoxins from the straw. Soil Biology and Biochemistry 23:1125-1132.

Cook J.H., Beyea J., Keeler K.H. (1991) Potential impacts of biomass production in the united-states on biological diversity. Annual Review of Energy and the Environment 16:401-431.

Corley R.H.V. (2004) Can the sustainability of oil palms be improved?, Second KULIM conference, West New Britain, Papua New Guinea.

Corley R.H.V. (2009) How much palm oil do we need? Environmental Science & Policy 12:134-139.

Corley R.H.V., Gray B.S. (1976) Yield and yield components, in: R. H. V. Corley, et al. (Eds.), Oil palm research, Elsevier Scientific Publishing Co., Amsterdam. pp. 78-86.

Corré W.J., Langeveld J.W.A. (2008) Energie- en Broeikasgasbalans voor Enkele Opties van Energieproductie uit Suikerbiet en Bietenblad, Plant Research International B.V., Wageningen. pp. 14.

Cox F.R., Uribe E. (1992) Potassium in two humid tropical ultisols under a corn and soybean cropping system: II. Dynamics. Agronomy Journal 84:485-489.

Coyette B.B., Tencalla F.F., Brants I.I., Fichet Y.Y., Rouchouze D.D. (2002) Effect of introducing glyphosate-tolerant sugar beet on pesticide usage in Europe.

Pesticide Outlook 13:219.
Cramer J., Wissema E., de Bruijne M., Lammers E., Dijk D., Jager H., van Bennekom S., Breunesse E., Horster R., van Leenders C., Wonink S., Wolters W., Kip H., Stam H., Faaij A., Kwant K. (2007) Toetsingskader voor Duurzame Biomassa. Eindrapport van de Projectgroep "Duurzame Productie van Biomassa", Directie Energietransitie. pp. 62.
Croezen H.J., Bergsma G.C., Otten M.B.J., Van Valkengoed M.P.J. (2010) Biofuels: Indirect Land Use Change and Climate Impact, CE Delft, Delft. pp. 62.
Dai D., Hu Z., Pu G., Li H., Wang C. (2006) Energy efficiency and potentials of cassava fuel ethanol in Guangxi region of China. Energy Conversion and Management 47:1686-1699.
Daiqiong L., Xiangdong L., Qinxiao W., Limin S., Zhongsheng G., Kejian L. (1992) An experiment and study on transpiration and water use efficiency of five shrubberies in Southern Ningxia. Research of Soil and Water Conservation 1992-2.
Damen K., Faaij A. (2006) A greenhouse gas balance of two existing international biomass import chains: the case of residue co-firing in a pulverised coal-fired power plant in the Netherlands. Mitigation and Adaptation Strategies for Global Change 11:1023-1050.
Danielsen F., Beukema H., Burgess N., Parish F., Brühl C., Donald P., Murdiyarso D., Phalan B.E.N., Reijnders L., Struebig M., Fitzherbert E. (2008) Biofuel plantations on forested lands: double jeopardy for biodiversity and climate. Conservation Biology 23:348-358.
Dastane N.G. (1978) Effective Rainfall in Irrigated Agriculture, FAO Irrigation and Drainage Papers No. 25, FAO, Rome.
de Moraes J.F.L., Volkoff B., Cerri C.C., Bernoux M. (1996) Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil. Geoderma 70:63-81.
De Vries S.C. (2008) The bio-fuel debate and fossil energy use in palm oil production: a critique of Reijnders and Huijbregts 2007. Journal of Cleaner Production 16:1926-1927.
De Vries S.C., Van de Ven G.W.J., Van Ittersum M.K., Giller K.E. (2010) Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. Biomass and Bioenergy 34:588-601.
De Vries S.C., Van De Ven G.W.J., Van Ittersum M.K., Giller K.E. (2011) The production-ecological sustainability of cassava, sugarcane and sweet sorghum cultivation for bioethanol in Mozambique. GCB Bioenergy 4:20-35.
Deasy G.F. (1942) Localization of Sumatra's oil palm industry. Economic Geography 18:153-158.

Deconti M. (2008) Estimating the Cost-effectiveness of Biofuels, Department for Environment, Food and Rural Affairs (Defra), London. pp. 13.

Degn L.T., Bertule M. (2009) Sustainability of Smallholder Palm Oil Production in Indonesia, Roskilde University, Department of Society and Globalization – International Development Studies, 6th semester project. pp. 54.

Dentener F., Derwent R., Dlugokencky E., Holland E., Isaksen I., Katima J., Kirchhoff V., Matson P., Midgley P., Wang M. (2001) Atmospheric chemistry and greenhouse gases, in: J. T. Houghton, et al. (Eds.), Climate Change 2001. The Scientific Basis, Cambridge University Press, Cambridge. pp. 239-287.

Department for Transport. (2007) Carbon and Sustainability Reporting Within the Renewable Transport Fuel Obligation. Requirements and Guidance. Draft Government Recommendation to RTFO Administrator, Department for Transport, London. pp. 169.

Destain J.P., Francois E., Guiot J., Goffart J.P., Vandergeten J.P., Bodson B. (1993) Fate of nitrogen fertilizer applied on two main arables crops, winter wheat (Triticum aestivum) and sugar beet (Beta vulgaris) in the loam region of Belgium. Plant and Soil 155-156:367-370.

Dias de Oliveira M.M., Vaughan M.B., Rykiel M.E. (2005) Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. BioScience 55:593-602.

Dohleman F.G., Heaton E.A., Leakey A.D.B., Long S.P. (2009) Does greater leaf-level photosynthesis explain the larger solar energy conversion efficiency of Miscanthus relative to switchgrass? Plant, Cell & Environment 32:1525-1537.

Donough C.R., Witt C., Fairhurst T. (2009) Yield Intensification in Oil Palm Plantations through Best Management Practice. Better Crops with Plant Food 93:12-14.

Donough C.R., Witt C., Fairhurst T. (2010) Yield intensification in oil palm using BMP as a management tool, International Oil Palm Conference, 1-3 June 2010, Yogyakarta, Indonesia.

Dzotsi K.A., Jones J.W., Adiku S.G.K., Naab J.B., Singh U., Porter C.H., Gijsman A.J. (2010) Modeling soil and plant phosphorus within DSSAT. Ecological Modelling 221:2839-2849.

Eckersten H. (1994) Modelling daily growth and nitrogen turnover for a short-rotation forest over several years. Forest Ecology and Management 69:57-72.

Eckert H., Breitschuh G., Sauerbeck D.R. (2000) Criteria and standards for sustainable agriculture. Journal of Plant Nutrition and Soil Science 163:337-351.

Econergy, Zilio J., Liddell D., Muendane C., Nogueira A. (2008) Mozambique Biofuels Assessment, final report, The World Bank, The Embassy of Italy in Maputo, Maputo, Mozambique. pp. 511.

Edwards J.H., Wood C.W., Thurlow D.L., Ruf M.E. (1992) Tillage and crop-rotation effects on fertility status of a hapludult soil. Soil Science Society of America Journal 56:1577-1582.

Edwards R., Larive J.F., Mahieu V., Rouveirolles P. (2007) Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. WELL-to-TANK Report Version 2c, March 2007, EUCAR (the European Council for Automotive R&D), CONCAWE (the oil companies' European association for environment, health and safety in refining and distribution), JRC/IES (the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre) pp. 140.

Ehhalt D., Prather M., Dentener F., Derwent R., Dlugokencky E., Holland E., Isaksen I., Katima J., Kirchhoff V., Matson P., Midgley P., Wang M. (2001) Radiative forcing of climate change, in: J. T. Houghton, et al. (Eds.), Climate Change 2001. The Scientific Basis, Cambridge University Press, Cambridge. pp. 349-416.

Elsayed M.A., Matthews R.W., Mortimer N.D. (2003) Carbon and Energy Balances for a Range of Biofuel Options, Resources Research Unit, Sheffield Hallam University pp. 341.

Elzebroek T., Wind K. (2008) Guide to Cultivated Plants CABI, Wallingford, UK.

Enete A., Nweke F., Tollens E. (2002) Contributions of men and women to food crop production labour in Africa: information from COSCA. Outlook on Agriculture 31:259-265.

Ercoli L., Mariotti M., Masoni A., Bonari E. (1999) Effect of irrigation and nitrogen fertilization on biomass yield and efficiency of energy use in crop production of Miscanthus. Field Crops Research 63:3-11.

EU. (2010) EU Energy and Transport in Figures. Statistical Pocketbook Publications Office of the European Union, Luxembourg.

European Commission. (2010) Report from the Commission on Indirect Land-Use Change Related to Biofuels and Bioliquids, European Commission, Brussels. pp. 14.

European Parliament. (2003) Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the Promotion of the Use of Biofuels or Other Renewable Fuels for Transport, Official Journal of the European Union. pp. 46.

European Parliament. (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union. pp. 16-62.

Ewing M., Msangi S. (2009) Biofuels production in developing countries: assessing tradeoffs in welfare and food security. Environmental Science & Policy 12:520-528.

Fairhurst T. (2003) Environmental aspects of fertilizer management in oil palm, MPOA seminar 2003: Good Agricultural Practice and Food Safety Management in Palm Oil Industry, 24 and 25 February 2003, Putrajaya, Malaysia.

Fairhurst T., Mutert E. (1997) The industrial use of oil palm fibre: possible effects on plant nutrient cycles and sustainability, International Planters Conference on Plantation Management for 21st Century, Incorporated Society of Planters, 21-22 May 1997, Kuala Lumpur.

Fairhurst T., McLaughlin D. (2009) Sustainable Oil Palm Development on Degraded Land in Kalimantan, WWF. pp. 45.

Fairley P. (2011) Introduction: Next generation biofuels. Nature 474:S2-S5.

Falloon P., Smith P., Coleman K., Marshall S. (1998) Estimating the size of the inert organic matter pool from total soil organic carbon content for use in the rothamsted carbon model. Soil Biology and Biochemistry 30:1207-1211.

FAO. (2007) FAOSTAT Statistical Database. faostat.fao.org, consulted September 2007.

FAO. (2008) The State of Food Insecurity in the World. 2008. High Food Prices and Food Security – Threats and Opportunities, FAO, Rome. pp. 59.

FAO. (2010) FAOSTAT Statistical Database, faostat.fao.org; consulted September 2010.

FAO. (2010) The State of Food Insecurity in the World. 2010. Addressing Food Insecurity in Protracted Crises, WFP, FAO, Rome. pp. 60.

FAO/UNESCO. (2007) Digital Soil Map of the World, FAO/UNESCO, Rome, Italy.

Fargione J., Hill J., Tilman D., Polasky S., Hawthorne P. (2008) Land clearing and the biofuel carbon debt. Science 319:1235-1238.

Farrell A.E., Plevin R.J., Turner B.T., Jones A.D., O'Hare M., Kammen D.M. (2006) Ethanol can contribute to energy and environmental goals. Science 311:506-508.

Fermont A.M. (2009) Cassava and Soil Fertility in Intensifying Smallholder Farming Systems of East Africa. PhD thesis, Plant Production Systems, Wageningen University, Wageningen. pp. 196.

Field H., Solie J. (2007) Erosion and erosion control, Introduction to Agricultural Engineering Technology. pp. 244 - 252.

Flood J., Keenan L., Wayne S., Hasan Y. (2005) Studies on oil palm trunks as sources of infection in the field. Mycopathologia 159:101-107.

FNR, BMELV. (2011) Biokraftstoffe.info: Rohstoffe, Fachagentur Nachwachsende Rohstoffe; Bundesministerium fur Ernahrung, Landwirstschaft und Verbraucherschutz.

FNR, BMELV. (2011) Biokraftstoffe.info: Biodiesel, Fachagentur Nachwachsende Rohstoffe; Bundesministerium fur Ernahrung, Landwirstschaft und Verbraucherschutz.

Folmer E.C.R., Geurts P.M.H., Francisco J.R. (1998) Assessment of soil fertility depletion in Mozambique. Agriculture, Ecosystems & Environment 71:159-167.

Fraser E.D.G., Dougill A.J., Mabee W.E., Reed M., McAlpine P. (2006) Bottom up and top down: Analysis of participatory processes for sustainability indicator identification as a pathway to community empowerment and sustainable environmental management. Journal of Environmental Management 78:114-127.

Gabrielle B., Denoroy P., Gosse G., Justes E., Andersen M.N. (1998) A model of leaf area development and senescence for winter oilseed rape. Field Crops Research 57:209-222.

Gabriels D., Ghekiere G., Schiettecatte W., Rottiers I. (2003) Assessment of USLE cover-management C-factors for 40 crop rotation systems on arable farms in the Kemmelbeek watershed, Belgium. Soil and Tillage Research 74:47-53.

Garrity D., Soekardi M., van Noordwijk M., de la Cruz R., Pathak P., Gunasena H., van So N., Huijun G., Majid N. (1996) The *Imperata* grasslands of tropical Asia: area, distribution, and typology. Agroforestry systems 36:3-29.

Garside A.L. (1997) Soil components of yield decline in sugarcane, in: R. J. MacEwan and M. R. Carter (Eds.), International Symposium on Advances in Soil Quality for Land Management: Science, Practice and Policy, 17-19 April 1996, University of Ballarat: Ballarat. pp. 93-96.

Gerritsma W., Soebagyo F.X. (1999) An analysis of the growth of leaf area of oil palms in Indonesia. Experimental Agriculture 35:293-308.

Gibbs H.K., Johnston M., Foley J.A., Holloway T., Monfreda C., Ramankutty N., Zaks D. (2009) Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. Environmental Research Letters 3:1-10.

Giebelhaus A.W. (1980) Farming for fuel: the alcohol motor fuel movement of the 1930s. Agricultural History 54:173-184.

Gijsman A.J., Hoogenboom G., Parton W.J., Kerridge P.C. (2002) Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter–residue module from CENTURY. Agronomy Journal 94:462-474.

Giller K.E. (2001) Nitrogen fixation in tropical cropping systems. 2 ed. CABI Publishing, Oxon, UK.

Giller K.E., Fairhurst T. (2003) Legume cover plants, in: T. Fairhurst and R. Härdter (Eds.), Oil Palm: Management for Large and Sustainable Yields, PPI/PPIC and IPI, Singapore. pp. 151-162.

Gnansounou E., Dauriat A., Wyman C.E. (2005) Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China. Bioresource Technology 96:985-1002.

Godoy R.A. (1992) Determinants of smallholder commercial tree cultivation. World

Development 20:713-725.

Goh K.J., Teo C.B., Chew P.S., Chiu S.B. (1999) Fertiliser management in oil palm: Agronomic principles and field practices, Fertiliser management for oil palm plantations, ISP Northeast Branch, Sandakan, Malaysia.

Greenpeace. (2007) How the Palm Oil Industry is Cooking the Climate, Greenpeace International, Amsterdam. pp. 82.

Grünewald H., Brandt B.K.V., Schneider B.U., Bens O., Kendzia G., Hüttl R.F. (2007) Agroforestry systems for the production of woody biomass for energy transformation purposes. Ecological Engineering 29:319-328.

Grünewald H., Böhm C., Quinkenstein A., Grundmann P., Eberts J., von Wühlisch G. (2009) Robinia pseudoacacia: a lesser known tree species for biomass production. BioEnergy Research 2:123-133.

Hairiah K., Saptono M., Widianto, Lusiana B., van Noordwijk M. (2005) Dynamics of tree litter in agroforestry systems, Smallholder agroforestry options for degraded tropical soils. International Consultation Workshop World Agroforestry Center (ICRAF), Malang, Indonesia.

Hall R.L. (2003) Grasses for Energy Production Hydrological Guidelines, Centre for Ecology and Hydrology, London. pp. 15.

Hamelinck C.N., Suurs R.A.A., Faaij A.P.C. (2005) International bioenergy transport costs and energy balance. Biomass and Bioenergy 29:114-134.

Hanegraaf M.C., Biewinga E.E., van der Bijl G. (1998) Assessing the ecological and economic sustainability of energy crops. Biomass and Bioenergy 15:345-355.

Hanegraaf M.C., Moolenaar S.W., Elbersen H.W., Annevelink E. (2007) Effecten van Biomassaketens op Landgebruik en Bodemkwaliteit in Nederland, Nutrienten Management Instituut NMI bv, Oosterbeek. pp. 56.

Haramoto E.E., Gallandt E.R. (2004) Brassica cover cropping for weed management: A review. Renewable Agriculture and Food Systems 19:187-198.

Haron K., Brookes P.C., Anderson J.M., Zakaria Z.Z. (1998) Microbial biomass and soil organic matter dynamics in oil palm (Elaeis guineensis jacq.) plantations, West Malaysia. Soil Biology and Biochemistry 30:547-552.

Hartemink A.E. (2006) Soil erosion: perennial crop plantations, in: R. Lal (Ed.), Encyclopedia of Soil Science, Dekker. pp. 1613-1617.

Haverkort A., Uenk D., Veroude H., Van De Waart M. (1991) Relationships between ground cover, intercepted solar radiation, leaf area index and infrared reflectance of potato crops. Potato Research 34:113-121.

Hazeu G., Elbersen B., Andersen E., Baruth B., Diepen K., Metzger M. (2010) A biophysical typology in agri-environmental modelling, in: F. M. Brouwer and M. Ittersum (Eds.), Environmental and Agricultural Modelling, Springer Netherlands. pp. 159-187.

Henson I.E. (1994) Environmental Impacts of Oil Palm Plantations in Malaysia, PORIM occasional paper 33. Palm Oil Research Institute of Malaysia, Palm Oil Research Institute of Malaysia (PORIM), Ministry of Primary Industries, Malaysia, Kuala Lumpur, Malaysia. pp. 27.

Henson I.E. (1998) Notes on oil palm productivity. I. Productivity at two contrasting sites. Journal of Oil Palm Research 10:57.

Henson I.E., Chai S.H. (1997) Analysis of oil palm productivity. II. Biomass, productivity and turnover of the root system. Elaeis 9:78-92.

Henson I.E., Chang K.C. (2007) Modelling oil palm nutrient demand, nutrient turnover and nutrient balance, MPOB Technology, MPOB (Malaysian Palm Oil Board), Kuala Lumpur, Malaysia. pp. 67.

Hill J., Nelson J.E., Tilman J.D., Polasky J.S., Tiffany J.D. (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences of the U.S.A. 103:11206-11210.

Holsten A., Vetter T., Vohland K., Krysanova V. (2009) Impact of climate change on soil moisture dynamics in Brandenburg with a focus on nature conservation areas. Ecological Modelling 220:2076-2087.

Howeler R.H., Oates C.G., Allem A.C. (2000) Strategic Environmental Assessment. An Assessment of the Impact of Cassava Production and Processing on the Environment and Biodiversity. FAO, International Fund for Agricultural Development, Rome.

Huang H.-J., Ramaswamy S., Al-Dajani W., Tschirner U., Cairncross R.A. (2009) Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis. Biomass and Bioenergy 33:234-246.

Humbird D., Davis R., Tao L., Kinchin C., Hsu D., Aden A., Schoen P., Lukas J., Olthof B., Worley M., Sexton D., Dudgeon D. (2011) Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol, Technical Report, National Renewable Energy Laboratory (NREL), Golden, Colorado. pp. 146.

Huo H., Wang M., Bloyd C., Putsche V. (2008) Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels, Energy Systems Division, Argonne National Laboratory, Argonne, Illinois. pp. 90.

IEA. (2011) Key World Energy Statistics, International Energy Agency (IEA), Paris. pp. 80.

Instituto Nacional do Açúcar. (2000) The Sugar Sector in Mozambique. Current Situation and Future Prospects, Ministério da Agricultura e Desenvolvimento Rural, República de Moçambique, Maputo, Mozambique. pp. 25.

IPCC. (2006) IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use Institute for Global Environmental

Strategies, on behalf of the IPCC, Hayama, Japan.
James Cook R. (1992) Management of wheat and barley root health in conservation tillage systems, Manitoba-North Dakota Zero Tillage Farmer's Association Workshop, Manitoba-North Dakota Zero Tillage Farmer's Association
Jansen D.M., Stoorvogel J.J., Schipper R.A. (1995) Using sustainability indicators In agricultural land-use analysis - an example from Costa-Rica agricultural land-use. Netherlands Journal of Agricultural Science 43:61-82.
Janssen B.H., Lathwell D.J., Wolf J. (1987) Modeling long-term crop response to fertilizer phosphorus. II. Comparison with field results. Agronomy Journal 79:452-458.
Janssen B.H., Guiking F.C.T., van der Eijk D., Smaling E.M.A., Wolf J., van Reuler H. (1990) A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46:299-318.
Jelsma I., Giller K.E., Fairhurst T. (2009) Smallholder Oil Palm Production Systems in Indonesia: Lessons from the NESP Ophir Project, Plant Production Systems, Plant Sciences Group, Wageningen University, Wageningen. www.foodorfuel.org/docs/NESP-OPHIR.pdf. pp. 99.
Jenkinson D.S., Meredith J., Kinyamario J.I., Warren G.P., Wong M.T.F., Harkness D.D., Bol R., Coleman K. (1999) Estimating net primary production from measurements made on soil organic matter. Ecology 80:2762-2773.
Jesse J.-H., Van der Linde C. (2008) Oil Turbulence in the Next Decade. An Essay on High Oil Prices in a Supply-Constrained World. Executive Summary, Clingendael International Energy Programme The Hague. pp. 108.
Jones M.B., Walsh M.E. (2001) Miscanthus for Energy and Fibre. James & James (Science Publishers) Ltd., London.
Jones P.G., Thornton P.K., W. Diaz W., Wilkens P.W. (2002) MARKSIM: a Computer Tool that Generates Simulated Weather Data for Crop Modelling and Risk Assessment CIAT, Cali, Colombia.
Jones J.W., Hoogenboom G., Porter C.H., Boote K.J., Batchelor W.D., Hunt L.A., Wilkens P.W., Singh U., Gijsman A.J., Ritchie J.T. (2003) The DSSAT cropping system model. European Journal of Agronomy 18:235-265.
Jørgensen U., Schwarz K.U. (2000) Why do basic research? A lesson from commercial exploitation of Miscanthus. New Phytologist 148:190-193.
Jourdan C., Rey H. (1997) Architecture and development of the oil-palm (Elaeis guineensis Jacq.) root system. Plant and Soil 189:33-48.
Jourdan C., Rey H. (1997) Modelling and simulation of the architecture and development of the oil-palm (Elaeis guineensis Jacq.) root system. Plant and Soil 190:235-246.
Kahle P., Hildebrand E., Baum C., Boelcke B. (2007) Long-term effects of short rotation forestry with willows and poplar on soil properties. Archives of

Agronomy and Soil Science 53:673-682.

Kahle P., Beuch S., Boelcke B., Leinweber P., Schulten H.-R. (2001) Cropping of Miscanthus in central Europe: biomass production and influence on nutrients and soil organic matter. European Journal of Agronomy 15:171-184.

Kaltschmitt M., Reinhardt G.A., Stelzer T. (1997) Life cycle analysis of biofuels under different environmental aspects. Biomass and Bioenergy 12:121-134.

Katzur J., Haubold-Rosar M. (1996) Amelioration and reforestation of sulfurous mine soils in Lusatia (Eastern Germany). Water, Air, & Soil Pollution 91:17-32.

Keating B.A., Carberry P.S., Hammer G.L., Probert M.E., Robertson M.J., Holzworth D., Huth N.I., Hargreaves J.N.G., Meinke H., Hochman Z., McLean G., Verburg K., Snow V., Dimes J.P., Silburn M., Wang E., Brown S., Bristow K.L., Asseng S., Chapman S., McCown R.L., Freebairn D.M., Smith C.J. (2003) An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy 18:267-288.

Kee K.K., Chew P.S. (1996) Nutrient losses through surface runoff and soil erosion—implications for improved fertiliser efficiency in mature oil palms, in: D. Ariffin, et al. (Eds.), Proceedings of the PORIM International Palm Oil Congress, Palm Oil Research Institute of Malaysia, Kuala Lumpur.

Kempenaar C., v.d. Brink L., Bus C.B., Groten J.A.M., de Visser C.L.M., Lotz L.A.P. (2003) Gangbare Landbouwkundige Praktijk en Recente Ontwikkelingen voor Vier Akkerbouwgewassen in Nederland, Plant Research International B.V., Wageningen. pp. 37.

Keskin T., Makineci E. (2009) Some soil properties on coal mine spoils reclaimed with black locust (Robinia pseudoacacia L.) and umbrella pine (Pinus pinea L.) in Agacli-Istanbul. Environmental Monitoring and Assessment 159:407-414.

Khalid H., Zin Z.Z., Anderson J.M. (2000a) Quantification of oil palm biomass and nutrient value in a mature plantation. I Above-ground biomass. Journal of Oil Palm Research 2:23-32.

Khalid H., Zin Z.Z., Anderson J.M. (2000b) Decomposition processes and nutrient release patterns of oil palm residues. Journal of Oil Palm Research 12:46-63.

Khalid H., Zin Z.Z., Anderson J.M. (2000c) Quantification of oil palm biomass and nutrient value in a mature plantation. II. Below-ground biomass. Journal of Oil Palm Research 11:63-71.

Kleter G.A., Bhula R., Bodnaruk K., Carazo E., Felsot A.S., Harris C.A., Katayama A., Kuiper H.A., Racke K.D., Rubin B., Shevah Y., Stephenson G.R., Tanaka K., Unsworth J., Wauchope R.D., Wong S.-S. (2007) Altered pesticide use on transgenic crops and the associated general impact from an environmental perspective. Pest Management Science 63:1107-1115.

Körschens M., Rogasik J., Schulz E., Bönig H., Eich D., Ellerbrock R., Franko U., Hülsbergen K.-J., Köppen D., Kolbe H., Leithold G., Merbach I., Peschke H., Prystav W., Reinhold J., Zimmer J. (2004) Humusbilanzierung. Methode zur Beurteilung und Bemessung der Humusversorgung von Ackerland., VDLUFA (Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten), Bonn, Germany. pp. 12.

Kuemmel B.B., Langer B.V., Magid B.J., De Neergaard B.A., Porter B.J. (1998) Energetic, economic and ecological balances of a combined food and energy system. Biomass and Bioenergy 15:407-416.

Landesumweltamt Brandenburg. (2009) Environmental Data Brandenburg 2008/09, Brandenburg State Office for Environment (LUA), Potsdam. pp. 130.

Landwirtschaftskammer Nordrhein-Westfalen. (2011) Humus - Bedeutung des Humusgehaltes für die Bodenfruchtbarkeit. Ratgeber 2011. www.landwirtschaftskammer.de/landwirtschaft/.../humus-pdf.pdf. pp. 5.

Law M.C., Balansundran S.K., Husni M.H.A., Ahmed O.H., Haniff Harun M. (2009) Spatial variability of soil organic carbon in oil palm. International Journal of Soil Science 4:93-103.

Law M.C., Balansundran S.K., Husni M.H.A., Ahmed O.H., Haniff Harun M. (2009) Spatial variability of soil organic carbon in oil palm: a comparison between young and mature stands. International Journal of Agricultural Research 4:402-417.

Lawrey J.D. (1977) The relative decomposition potential of habitats variously affected by surface coal mining. Canadian Journal of Botany 55:1544-1552.

LBST. (2002) GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study, Ludwig-Bölkow-Systemtechnik GmbH, Ottobrun, Germany. pp. 138.

Lecoeur J., Sinclair T.R. (2001) Harvest index increase during seed growth of field pea. European Journal of Agronomy 14:173-180.

Lewandowski I., Faaij A.P.C. (2006) Steps towards the development of a certification system for sustainable bio-energy trade. Biomass and Bioenergy 30:83-104.

Lewandowski I., Kicherer A., Vonier P. (1995) CO2-balance for the cultivation and combustion of Miscanthus. Biomass and Bioenergy 8:81-90.

Lewandowski I., Härdtlein M., Kaltschmitt M. (1999) Sustainable crop production: definition and methodological approach for assessing and implementing sustainability. Crop Science 39:184-193.

Lewandowski I., Scurlock J.M.O., Lindvall E., Christou M. (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass and Bioenergy 25:335-361.

Lewis G. (1984) Some aspects of the production of ethanol from sugar cane residues in Zimbabwe. Solar Energy 33:379-382.

Lim K.C., Zaharah A.R. (2000) Decomposition and N & K release by oil palm empty fruit bunches applied under mature palms. Journal of Oil Palm Research 12:55-62.

Lipps P.E., Dorrance A.E., Rhodes L.H. (2008) Field Crop Disease Management Bulletin 631-98, Ohioline Bulletins, Department of Pathology, The Ohio State University.

Loeve R., Dong B., Molden D., Li Y.H., Chen C.D., Wang J.Z. (2004) Issues of scale in water productivity in the Zhanghe irrigation system: implications for irrigation in the basin context. Paddy and Water Environment 2:227-236.

Londo M., Deurwaarder E. (2007) Developments in EU biofuels policy related to sustainability issues: overview and outlook. Biofuels, Bioproducts and Biorefining 1:292-302.

Lozano J.C. (1986) Cassava bacterial-blight - a manageable disease. Plant Disease 70:1089-1093.

Lugo A., Brown S. (1993) Management of tropical soils as sinks or sources of atmospheric carbon. Plant and Soil 149:27-41.

LVLF. (2010) Datensammlung für die Betriebsplanung und die betriebswirtschaftliche Bewertung Landwirtschaftlicher Produktionsverfahren im Land Brandenburg, Landesamt für Verbraucherschutz, Landwirtschaft und Flurneuordnung (LVLF), Potsdam. pp. 131.

MacDonald A.J., Poulton P.R., Powlson D.S., Jenkinson D.S. (1997) Effects of season, soil type and cropping on recoveries, residues and losses of 15N-labelled fertilizer applied to arable crops in spring. The Journal of Agricultural Science 129:125-154.

Macedo I.C., Leal M.R.L.V., Da Silva J.E.A.R. (2004) Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil, Government of the State – Governor Secretariat of the Environment, Sao Paolo, Brazil. pp. 37.

Maene L.M., Thong K.C., Ong T.S., Mokhtaruddin A.M. (1997) Surface wash under mature oil palm, in: E. Pushparajah (Ed.), Symposium Water in Malaysian Agriculture, MSSS, Kuala Lumpur. pp. 203-2216.

Magwenzi O.E. (2000) Evaluation of irrigation efficiency in the Swaziland sugar industry. Proceedings of The South African Sugar Technologists' Association:151-156.

Malça J., Freire F. (2006) Renewability and life-cycle energy efficiency of bioethanol and bio-ethyl tertiary butyl ether (bioETBE): Assessing the implications of allocation. Energy 31:3362-3380.

Manickasundaram P., Selvaraj P.K., Krishnamoorthi V.V., Gnanamurthy P. (2002) Drip irrigation and fertigation studies in tapioca. Madras Agricultural Journal 89:466-468.

Märländer B.B., Hoffmann C., Koch H.J., Ladewig E., Merkes R., Petersen J., Stockfisch N. (2003) Environmental situation and yield performance of the sugar beet crop in Germany: Heading for sustainable development. Journal of Agronomy and Crop Science 189:201-226.

Martin J. (2011) Perspective: Don't foul the water. Nature 474:S17-S17.

Matthews R.W. (2001) Modelling of energy and carbon budgets of wood fuel coppice systems. Biomass and Bioenergy 21:1-19.

Mattsson B., Cederberg C., Blix L. (2000) Agricultural land use in life cycle assessment (LCA): case studies of three vegetable oil crops. Journal of Cleaner Production 8:283-292.

McBride A.C., Dale V.H., Baskaran L.M., Downing M.E., Eaton L.M., Efroymson R.A., Garten Jr C.T., Kline K.L., Jager H.I., Mulholland P.J., Parish E.S., Schweizer P.E., Storey J.M. (2011) Indicators to support environmental sustainability of bioenergy systems. Ecological Indicators 11:1277-1289.

McManus M.-C., Hammond G.-P., Burrows C.-R. (2003) Life-cycle assessment of mineral and rapeseed oil in mobile hydraulic systems. Journal of Industrial Ecology 7:163-177.

Metzger M.J., Bunce R.G.H., Jongman R.H.G., Mücher C.A., Watkins J.W. (2005) A climatic stratification of the environment of Europe. Global Ecology and Biogeography 14:549-563.

Meyer J.H., Wood R.A., Nixon D.J., Rampersad A.L., Schroeder B.L., Schumann A.W. (2004) The SASEX fertiliser advisory service: a review of 50 years of service to the South African sugar industry. Proceedings of The South African Sugar Technologists' Association 78:359-372.

Mitchell R., Webb J., Harrison R. (2001) Crop residues can affect N leaching over at least two winters. European Journal of Agronomy 15:17-29.

Mockus V. (1972) Estimation of direct runoff from storm rainfall, National Engineering Handbook, Section 4: Hydrology. pp. 10.1-10.24.

Moerschner J., Lücke W., Ierland E.C., Lansink A.O. (2003) Energy investigations of different intensive rape seed rotations – a German case study, Economics of Sustainable Energy in Agriculture, Springer Netherlands. pp. 27-40.

Mortimer N.D., Elsayed M.A., Horne R.E. (2004) Energy And Greenhouse Gas Emissions For Bioethanol Production From Wheat Grain And Sugar Beet. Final Report for British Sugar plc, Resources Research Unit School of Environment and Development. Sheffield Hallam University pp. 180.

Mortimer N.D., Cormack P., Elsayed M.A., Horne R.E. (2003) Evaluation of the Comparative Energy, Global Warming and Socio-Economic Costs and Benefits of Biodiesel, Resources Research Unit, School Of Environment And Development, Sheffield Hallam University pp. 119.

Mulier A., Nevens F., Hofman G. (2006) Daling van de Organische Stof in Vlaamse Landbouwgronden. Analyse van mogelijke oorzaken en aanbevelingen voor de toekomst, Steunpunt duurzame landbouw, Gontrode, Belgium. pp. 63.

Mutert E. (1999) Suitability of soils for oil palm in Southeast Asia. Better Crops International 13:36-38.

Naaktgeboren A.L., van Swaaij A.C.P.M. (2007) IRS Bietenstatistiek 2006, Stichting IRS, Bergen op Zoom.

Naik S.N., Goud V.V., Rout P.K., Dalai A.K. (2010) Production of first and second generation biofuels: A comprehensive review. Renewable and Sustainable Energy Reviews 14:578-597.

Nauclér T., Enkvist P.-A. (2009) Pathways to a Low-Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve, Mc Kinsey & Company, Stockholm. pp. 190.

Ndlovu L.S. (2000) The performance of subsurface drip irrigation at Royal Swaziland Sugar Corporation during its first season. Proceedings of The South African Sugar Technologists' Association:157-161.

Nellemann C., Miles L., Kaltenborn B.P., Virtue M., Ahlenius H., (eds.). (2007) Rapid Response Assessment. The Last Stand of the Orangutan. State of Emergency: Illegal Logging, Fire and Palm Oil in Indonesia's National Parks., UNEP, UNESCO, Norway. pp. 49.

Nellesteijn J., Dekker K. (1998) Wereld Klimaat Informatie versie 2.00, KNMI - Klimatologische Dienstverlening, De Bilt, The Netherlands.

Nemecek T., von Richthofen J.-S., Dubois G., Casta P., Charles R., Pahl H. (2008) Environmental impacts of introducing grain legumes into European crop rotations. European Journal of Agronomy 28:380-393.

Neukirchen D., Himken M., Lammel J., Czypionka-Krause U., Olfs H.W. (1999) Spatial and temporal distribution of the root system and root nutrient content of an established Miscanthus crop. European Journal of Agronomy 11:301-309.

Ng T.L., Eheart J.W., Cai X., Miguez F. (2010) Modeling Miscanthus in the soil and water assessment tool (SWAT) to simulate its water quality effects as a bioenergy crop. Environmental Science & Technology 44:7138-7144.

Nguyen T.L.T., Gheewala S.H., Garivait S. (2007) Energy balance and GHG-abatement cost of cassava utilization for fuel ethanol in Thailand. Energy Policy 35:4585-4596.

Nguyen T.L.T., Gheewala S.H., Garivait S. (2007) Full chain energy analysis of fuel ethanol from cassava in Thailand. Environmental Science and Technology 41:4135-4142.

Nieder R., Kersebaum K.C., Richter J. (1995) Significance of nitrate leaching and long term N immobilization after deepening the plough layers for the N regime of arable soils in N.W. Germany. Plant and Soil 173:167-175.

Nijhoff K. (1987) The Concentrations of Macro-Elements in Economic Products and

Residues of (Sub)Tropical Field Crops. Staff Working Paper SOW-87-08, Centre for World Food Studies, Amsterdam. pp. 52.

Nkomo S., van der Zaag P. (2004) Equitable water allocation in a heavily committed international catchment area: the case of the Komati Catchment. Physics and Chemistry of the Earth, Parts A/B/C 29:1309-1317.

Noor M.M. (2003) Zero burning techniques in oil palm cultivation: an economic perspective. Oil palm Industry Economic Journal 3:16-24.

Nuttall W.F., Bowren K.E., Dawley W.K., Malhi S.S. (1989) The effect of spring and fall application of N on yield and quality of barley (Hordeum vulgare L.) and rapeseed (Brassica campestris L.). Canadian Journal of Soil Science 69:199-211.

OECD. (2001) Environmental Indicators for Agriculture. Methods and Results. Executive Summary, Organisation for Economic Co-operation and Development (OECD), Paris.

OECD, FAO. (2008) OECD-FAO Agricultural Outlook 2008-2017 - Highlights, OECD Publications, Paris. pp. 72.

OECD, FAO. (2011) OECD-FAO Agricultural Outlook 2011-2020 OECD Publ., Paris. pp. 93.

Ozara N.A. (1992) The amount of soil cover provided by a unit mass of guinea grass, banana leaf and palm leaf residues. Soil Use and Management 8:103-104.

Palaniappan S., Chin Tui L., Ilangovan K. (2004) Sustainable Palm Oil - FELDA's Perspective, 4th National Seminar 'Replant or perish', Incorporated Society of Planters, 14-15 June 2004, Ipoh, Malaysia.

Palm C.A., Swift M.J., Woomer P.L. (1996) Soil biological dynamics in slash-and-burn agriculture. Agriculture, Ecosystems & Environment 58:61-74.

Palm C.A., Houghton R.A., Melillo J.M., Skole D.L. (1986) Atmospheric carbon dioxide from deforestation in Southeast Asia. Biotropica 18:177-188.

Parton W., Stewart J., Cole C. (1988) Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5:109-131.

Parton W.J., Schimel D.S., Cole C.V., Ojima D.S. (1987) Analysis of factors controlling soil organic matter levels in great plains grasslands. Soil Science Society of America Journal 51:1173-1179.

Patzek T.W., Pimentel D. (2005) Thermodynamics of energy production from biomass. Critical Reviews in Plant Sciences 24:327 - 364.

Pellet D.M., El-Sharkawy M.A. (1997) Cassava varietal response to fertilization: Growth dynamics and implications for cropping sustainability. Experimental Agriculture 33:353-365.

Peng L., Zhong Z., Zhan-bin L. (2004) Vertical root distribution characters of Robinia pseudoacacia on the Loess Plateau in China. Journal of Forestry Research 15:87-92.

Pieri C., Dumanski J., Hamblin A., Young A. (1995) Land Quality Indicators, World Bank Discussion Papers, Worldbank, Washington DC. pp. 63.

Pleanjai S., Gheewala S.H. (2009) Full chain energy analysis of biodiesel production from palm oil in Thailand. Applied Energy 86:S209-S214.

Porter P.P., Lauer J.G., Lueschen W.E., Ford J.H., Hoverstad T.R., Oplinger E.S., Crookston R.K. (1997) Environment affects the corn and soybean rotation effect. Agronomy Journal 89:442-448.

Principle Energy. (2009) http://www.princapital.com/output/page185.asp, Consulted 6 January, 2010.

Punter G., Rickeard D., Larivé J.-F., Edwards R., Mortimer N., Horne R., Bauen A., Woods J. (2004) Well-to-Wheel Evaluation for Production of Ethanol from Wheat. A Report by the LowCVP Fuels Working Group, WTW Sub-Group, Low Carbon Vehicle Partnership (LCVP) London, UK.

Putthacharoen S., Howeler R.H., Jantawat S., Vichukit V. (1998) Nutrient uptake and soil erosion losses in cassava and six other crops in a Psamment in eastern Thailand. Field Crops Research 57:113-126.

Quencez P. (1986) Utilisation des palmes pour lutter contre l'érosion en plantation de palmiers à huile. Oléagineux 41:315-317.

Quintiliano J., Margues A., Bertoni J., Barreto G.B. (1961) Perdas por erosão no estado de S. Paulo. Brigantia 20:1143-1182.

Ragauskas A.J., Williams C.K., Davison B.H., Britovsek G., Cairney J., Eckert C.A., Frederick W.J., Hallett J.P., Leak D.J., Liotta C.L., Mielenz J.R., Murphy R., Templer R., Tschaplinski T. (2006) The path forward for biofuels and biomaterials. Science 311:484-489.

Rahman A.K.A., Abdullah R., Sharrif F.M., Simeh M.A. (2008) The Malaysian oil palm supply chain: the role of the independent smallholder. Oil palm Industry Economic Journal 8:17-27.

Rahmonov O. (2009) The chemical composition of plant litter of black locust (Robinia pseudoacacia L.) and its ecological role in sandy ecosystems. Acta Ecologica Sinica 29:237-243.

Rappoldt C., Van Kraalingen D.W.G. (1996) The FORTRAN Simulation Translator. FST version 2.0. Introduction and Reference Manual, in: B. A. M. Bouman and M. K. Van Ittersum (Eds.), Quantitative Approaches in Systems Analysis No. 5, Wageningen University and Research Center, Wageningen. pp. 178.

Razafimbelo T., Barthès B., Larré-Larrouy M.-C., Luca E.F.D., Laurent J.-Y., Cerri C.C., Feller C. (2006) Effect of sugarcane residue management (mulching versus burning) on organic matter in a clayey Oxisol from southern Brazil. Agriculture, Ecosystems & Environment 115:285-289.

Reed J.D., McDowell R.T.E., Soest P.J.v., Horvath P.R.J. (1982) Condensed tannins: A factor limiting the use of cassava forage. Journal of the Science of Food and

Agriculture 33:213-220.
Reeves. (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Research 43:131-167.
Reid I. (1973) The choice of assumed particle density values in soil tests. Area 5:10-12.
Reijnders L.L. (2006) Conditions for the sustainability of biomass based fuel use. Energy Policy 34:863-876.
Reijnders L., Huijbregts M.A.J. (2008) Palm oil and the emission of carbon-based greenhouse gases. Journal of Cleaner Production 16:477-482.
Reinhardt G.A., Gärtner S., Patyk A., Rettenmaier N. (2006) Ökobilanzen zu BTL: Eine ökologische Einschätzung, IFEU - Institut für Energie und Umweltforschung GmbH; gefördert durch das Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMELV); Projektträger: Fachagentur Nachwachsende Rohstoffe e. V., Heidelberg. pp. 100.
Reinhardt G.A., Rettenmaier N., Gärtner S., Pastowski A. (2007) Rain Forest for Biodiesel? Ecological Effects of Using Palm Oil as a Source of Energy, WWF Germany, Frankfurt am Main. pp. 50.
Renard K.G., Foster G.R., Weesies G.A., McCool D.K., Yoder D.C. (1996) Predicting Soil Erosion by Water: a Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook Nr. 703, Agricultural Research Service, United States Dept. of Agriculture (ARS-USDA), Tucson, Arizona. pp. 384.
Richards I.R. (2000) Energy Balances in the Growth of Oilseed Rape for Biodiesel and of Wheat for Bioethanol. Report for the British Association for Bio Fuels and Oils (BABFO), Levington Agriculture Ltd., Ipswich. pp. 38.
Robbins M. (2011) Policy: fuelling politics. Nature 474:S22-S24.
Robertson F. (2003) Sugarcane Trash Management: Consequences for Soil Carbon and Nitrogen. Final Report to the CRC for Sustainable Sugar Production of the project Nutrient Cycling in Relation to Trash Management (CRC Activity 2.2.1), CRC Sugar Technical Publication, Townsville. pp. 39.
Robertson M.J., Kirkegaard J.A. (2005) Water-use efficiency of dryland canola in an equi-seasonal rainfall environment. Australian Journal of Agricultural Research 56:1373-1386.
Robertson F.A., Thorburn P.J. (2007) Management of sugarcane harvest residues: consequences for soil carbon and nitrogen. Australian Journal of Soil Research 45:13-23.
Roland Berger Strategy Consultants. (2011) Potentiële Rol van Groen Gas in de Duurzame Transport Doelstellingen. Eindpresentatie, Platform Groene Grondstoffen, Amsterdam. pp. 38.
Roose E.J. (1977) Application of the Universal Soil Loss Equation of Wischmeier and

Smith in West Africa, in: D. J. Greenland and R. Lal (Eds.), Soil Conservation and management in the Humid Tropics, John Wiley and Sons, Chichester. pp. 177-187.

Roßberg D. (2007) NEPTUN oder „Wie oft wird gespritzt?". Gesunde Pflanzen 59:55-65.

Rowe R.L., Street N.R., Taylor G. (2009) Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renewable and Sustainable Energy Reviews 13:271-290.

Royal Dutch Shell plc. (2008) Responsable Energy Sustainability Report 2008. pp. 46.

RSB. (2009) RSB Principles & Criteria for Sustainable Biofuel production, version 1.0, Roundtable on Sustainable Biofuels, Lausanne. pp. 28.

RSPO. (2007) RSPO Principles and Criteria for Sustainable Palm Oil Production Including Indicators and Guidance. October 2007. pp. 53.

RTRS. (2010) RTRS Standard for Responsible Soy Production Version 1.0, The RTRS (Roundtable on Responsible Soy) International Technical Group (ITG), Sao Paulo, Brazil. pp. 4.

Rumpel C., Knicker H., Kögel-Knabner I., Skjemstad J.O., Hüttl R.F. (1998) Types and chemical composition of organic matter in reforested lignite-rich mine soils. Geoderma 86:123-142.

Saifi B., Drake L. (2008) A coevolutionary model for promoting agricultural sustainability. Ecological Economics 65:24-34.

Salassi M.E., Deliberto M.A. (2010) Sugarcane Production in Louisiana. 2010 Projected Commodity Costs and Returns, A.E.A. Information Series, Louisiana State University, Farm Management, Research & Extension, Dept. of Agricultural Economics & Agribusiness Baton Rouge, Louisiana. pp. 33.

Santosa S.J. (2008) Palm oil boom in Indonesia: from plantation to downstream products and biodiesel. CLEAN – Soil, Air, Water 36:453-465.

Santoso. (1996) Soil fertility management for reclamation of Imperata grasslands by smallholder agroforestry. Agroforestry Systems 36:181-202.

Schapendonk A.H.C.M., Stol W., van Kraalingen D.W.G., Bouman B.A.M. (1998) LINGRA, a sink/source model to simulate grassland productivity in Europe. European Journal of Agronomy 9:87-100.

Scharmer K. (2001) Biodiesel. Energy- and Environmental Evaluation. Rapeseed-Oil-Methyl-Ester, Union zur Förderung von Oel- und Proteinpflanzen e. V. (Union for Promoting Oilseeds and Proteinplants), Bonn. pp. 60.

Scherr S.J., Summit A. (2008) Environmental Manegement in the Agriculture Sector: National-Level Indicators, Ecoagriculture Partners, Washington, DC. pp. 16.

Schiettecatte W., d´Hondt L., Cornelis W.M., Acosta M.L., Leal Z., Lauwers N., Almoza Y., Alonso G.R., Díaz J., Ruíz M., Gabriels D. (2008) Influence of landuse on soil erosion risk in the Cuyaguateje watershed (Cuba). CATENA 74:1-12.

Schjoerring J.K., Bock J.G.H., Gammelvind L., Jensen C.R., Mogensen V.O. (1995) Nitrogen incorporation and remobilization in different shoot components of field-grown winter oilseed rape (Brassica napus L.) as affected by rate of nitrogen application and irrigation. Plant and Soil 177:255-264.

Schmer M.R., Vogel K.P., Mitchell R.B., Perrin R.K. (2008) Net energy of cellulosic ethanol from switchgrass. Proceedings of the National Academy of Sciences of the United States of America 105:464-469.

Schnoor J.L., Doering III O.C., Entekhabi D., Hiler E.A., Hullar T.L., Tilman G.D., Logan W.S., Huddleston N., Stoever M.J. (2008) Water Implications of Biofuels Production in the United States The National Academies Press, Washington, D.C.

Schroers J.O. (2006) Zur Entwicklung der Landnutzung auf Grenzstandorten in Abhängikeit agrarmarktpolitischer, agrarstrukturpolitischer und produktionstechnologischer Rahmenbedingungen - eine Analyse mit dem Simulationsmodell ProLand, Institut für Betriebslehre der Agrar- und Ernährungswirtschaft, Justus-Liebig-Universität, Gießen. pp. 193.

Schut M., Slingerland M., Locke A. (2010) Biofuel developments in Mozambique. Update and analysis of policy, potential and reality. Energy Policy 38:5151-5165.

Searchinger T.D., Hamburg S.P., Melillo J., Chameides W., Havlik P., Kammen D.M., Likens G.E., Lubowski R.N., Obersteiner M., Oppenheimer M., Philip Robertson G., Schlesinger W.H., David Tilman G. (2009) Fixing a critical climate accounting error. Science 326:527-528.

Shaffer M., Delgado J.A., Gross C.M., Follett R., Gagliardi P. (2010) Simulation processes for the nitrogen loss and environmental assessment package, in: J. A. Delgado and R. Follett (Eds.), Advances in Nitrogen Management for Water Quality, Soil and Water Conservation Society. pp. 361-372.

Sheehan J., Camobreco V., Duffield J., Graboski M., Shapouri H. (1998) Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus, National Renewable Energy Laboratory (NREL), NREL/SR-580-24089, Golden, Colorado. pp. 286.

Shirato Y., Paisancharoen K., Sangtong P., Nakviro C., Yokozawa M., Matsumoto N. (2005) Testing the Rothamsted Carbon Model against data from long-term experiments on upland soils in Thailand. European journal of Soil Science 56:179-188.

Shirazi M.A., Boersma L. (1984) A unifying quantitative analysis of soil texture. Soil Science Society of America Journal 48:142-147.

Singh P., Suman A., Tiwari P., Arya N., Gaur A., Shrivastava A. (2008) Biological pretreatment of sugarcane trash for its conversion to fermentable sugars. World Journal of Microbiology and Biotechnology 24:667-673.

Sitompul S.M., Hairiah K., Cadisch G., Van Noordwijk M. (2000) Dynamics of density fractions of macro-organic matter after forest conversion to sugarcane and woodlots, accounted for in a modified century model. NJAS - Wageningen Journal of Life Sciences 48:61-73.

Skarback E., Becht P. (2005) Landscape perspective on energy forests. Biomass and Bioenergy 28:151-159.

Sloggett G. (1992) Estimating energy use in world irrigation, in: R. C. Fluck (Ed.), Energy in Farm Production, Elsevier, Amsterdam. pp. 203-218.

Smaling E.M.A., Stoorvogel J.J., Windmeijer P.N. (1993) Calculating soil nutrient balances in Africa at different scales. II. District scale. Nutrient Cycling in Agroecosystems 35:237-250.

Smeets E.M.W., Lewandowski I.M., Faaij A.P.C. (2009) The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting. Renewable and Sustainable Energy Reviews 13:1230-1245.

Smeets E., Junginger M., Faaij A., Walter A., Dolzan P. (2006) Sustainability of Brazilian Bio-ethanol, Universiteit Utrecht, Copernicus Institute.; Dept. of Science, Technology and Society and State University of Campinas, Utrecht. pp. 132.

Smith M. (1993) CLIMWAT for CROPWAT: A Climatic Database for Irrigation Planning and Management, FAO Irrigation and Drainage Paper 49, FAO, Rome.

Smith E.E., Janzen H.H., Newlands N.K. (2007) Energy balances of biodiesel production from soybean and canola in Canada. Canadian Journal of Plant Science 87:793-801.

Smith P., Smith J.U., Powlson D.S., McGill W.B., Arah J.R.M., Chertov O.G., Coleman K., Franko U., Frolking S., Jenkinson D.S., Jensen L.S., Kelly R.H., Klein-Gunnewiek H., Komarov A.S., Li C., Molina J.A.E., Mueller T., Parton W.J., Thornley J.H.M., Whitmore A.P. (1997) A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81:153-225.

Sparovek G., Barretto A., Berndes G., Martins S., Maule R. (2009) Environmental, land-use and economic implications of Brazilian sugarcane expansion 1996–2006. Mitigation and Adaptation Strategies for Global Change 14:285-298.

Stirling G.R. (2008) The impact of farming systems on soil biology and soilborne diseases: examples from the Australian sugar and vegetable industries - the case for better integration of sugarcane and vegetable production and implications for future research. Australasian Plant Pathology 37:1-18.

Stockle C.O., Martin S.A., Campbell G.S. (1994) CropSyst, a cropping systems simulation model: Water/nitrogen budgets and crop yield. Agricultural Systems 46:335-359.

Suharmoko J., Indarto S., Heru S.B., Ahmad M. (2007) The cultivation of vetiver grass as soil bunds for the prevention of soil erosion in mature oil palm areas, International Conference on Oil Palm and Environment 2007, Bali, Indonesia.

Suharto R. (2009) Sustainable palm oil development in Indonesia (Indonesian Palm Oil Commission), China International Oil and Oilseeds Summit 2009, Beijing.

Sumiani Y. (2006) Renewable energy from palm oil – innovation on effective utilization of waste. Journal of Cleaner Production 14:87-93.

Syahrinudin. (2005) The Potential of Oil Palm and Forest Plantations for Carbon Sequestration on Degraded Land in Indonesia. PhD thesis, Universität Bonn, Bonn.

Tarmizi A.M., Mohd Tayeb D. (2006) Nutrient demands of tenera oil palm planted on inland soils of Malaysia. Journal of Oil Palm Research 18:204-209.

Tauer C.G. (2007) Performance of a wide-ranging collection of black locust seed sources in Western Oklahoma. Tree Planters' Notes 52:26-31.

The White House. (2011) Blueprint for a Secure Energy Future, The White House, Washington, D.C. pp. 44.

Tilman D.D., Hill J., Lehman C. (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 314:1598-1600.

Timmer R.D., Korthals G.W., Molendijk L.P.G. (2004) Teelthandleiding Groenbemesters, Praktijkonderzoek Plant en Omgeving B.V., Wageningen.

Tittonell P., Corbeels M., van Wijk M.T., Giller K.E. (2010) FIELD - A summary simulation model of the soil-crop system to analyse long-term resource interactions and use efficiencies at farm scale. European Journal of Agronomy 32:10-21.

Tittonell P., Zingore S., van Wijk M.T., Corbeels M., Giller K.E. (2007) Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. Field Crops Research 100:348-368.

Tittonell P., Corbeels M., van Wijk M.T., Vanlauwe B., Giller K.E. (2008) Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya: explorations using the crop-soil model FIELD. Agronomy Journal 100:1511-1526.

TNAU. (2007) Sweet Sorghum Production Technology, Department of Millets, Centre for Plant breeding and Genetics, Tamil Nadu Agricultural University, Coimbatore. pp. 4.

Tongaat Hulett. (2010) Financial Results March 2010 - Presentation to Investors and

Analysts.

Turner B.T., Plevin R.J., O'Hare M., Farrell A.E. (2007) Creating Markets for Green Biofuels, Energy and Resources Group, UC Berkeley

Tzilivakis J., Jaggard K., Lewis K.A., May M., Warner D.J. (2005) Environmental impact and economic assessment for UK sugar beet production systems. Agriculture, Ecosystems & Environment 107:341-358.

U.S. Congress. (2005) Energy Policy Act of 2005. http://www.epa.gov/OUST/fedlaws/publ_109-058.pdf, Washington, D.C. pp. 551.

Uexküll H.R., Mutert E. (1995) Global extent, development and economic impact of acid soils. Plant and Soil 171:1-15.

UFOP. (2011) Wo wächst das Rapsöl? http://www.ufop.de/downloads/Netz_UFOP_0804_Broschur.pdf, Union zur Foerderung von Oel und Proteinpflanzen E.V. (UFOP), Berlin. pp. 8.

UN-REDD programme. (2010) Beyond carbon. Ecosystem-based benefits of REDD+, UN-REDD programme, UNEP-WCMC, Geneva. pp. 7.

USDA. (1986) Urban Hydrology for Small watersheds. Technical Release 55, Natural Resources Conservation Service of the United States Department of Agriculture, Conservation Engineering Division. pp. 164.

USDA. (2009) Indonesia: palm oil production growth to continue. http://www.pecad.fas.usda.gov/highlights/2009/03/Indonesia/, consulted March 2011, Commodity intelligence report, USDA, Foreign Agricultural Service.

US-EIA. (2011) International Energy Statistics, http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=79&pid=79&aid=1, consulted 24 August 2011, U.S. Energy Information Administration, Washington, D.C.

Vamerali T., Ganis A., Bona S., Mosca G. (2003) Fibrous root turnover and growth in sugar beet (Beta vulgaris var. saccharifera) as affected by nitrogen shortage. Plant and Soil 255:169-177.

Van Cauwenbergh N., Biala K., Bielders C., Brouckaert V., Franchois L., Garcia Cidad V., Hermy M., Mathijs E., Muys B., Reijnders J., Sauvenier X., Valckx J., Vanclooster M., Van der Veken B., Wauters E., Peeters A. (2007) SAFE—A hierarchical framework for assessing the sustainability of agricultural systems. Agriculture, Ecosystems & Environment 120:229-242.

Van den Dungen S. (2010) Exploring Feasible Yields for Cassava Production for Food and Fuel in the Context of Smallholder Farming Systems in Alto Molocue, Northern Mozambique. MSc Thesis, Plant Production Systems, Wageningen University, Wageningen. pp. 118.

Van Der Velde M., Bouraoui F., Aloe A. (2009) Pan-European regional-scale modelling of water and N efficiencies of rapeseed cultivation for biodiesel production. Global Change Biology 15:24-37.

Van der Werf H.M.G., Petit J. (2002) Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agriculture, Ecosystems & Environment 93:131-145.

Van Diepen C.A., Rappoldt C., Wolf J., Van Keulen H. (1988) Crop Growth Simulation Model WOFOST. Documentation Version 4.1, Centre for world food studies, Wageningen. pp. 299.

Van Diepen C.A., Wolf J., van Keulen H., Rappoldt C. (1989) WOFOST: a simulation model of crop production. Soil Use and Management 5:16-24.

Van Dijk A.I.J.M. (2002) Water and Sediment Dynamics in Bench-Terraced Agricultural Steeplands in West Java, Indonesia. PhD thesis, Faculty of Earth and Life Sciences, Vrije Universiteit, Amsterdam. pp. 370.

Van Ittersum M.K., Rabbinge R. (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research 52:197-208.

van Ittersum M.K., Leffelaar P.A., van Keulen H., Kropff M.J., Bastiaans L., Goudriaan J. (2003) On approaches and applications of the Wageningen crop models. European Journal of Agronomy 18:201-234.

Van Kraalingen D.W.G., Breure C.J., Spitters C.J.T. (1989) Simulation of oil palm growth and yield. Agricultural and Forest Meteorology 46:227-244.

Van Noordwijk M., Cerri C., Woomer P.L., Nugroho K., Bernoux M. (1997) Soil carbon dynamics in the humid tropical forest zone. Geoderma 79:187-225.

van Vliet O.P.R., Faaij A.P.C., Turkenburg W.C. (2009) Fischer-Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis. Energy Conversion and Management 50:855-876.

Van Wesemael B., Paustian K., Meersmans J., Goidts E., Barancikova G., Easter M. (2010) Agricultural management explains historic changes in regional soil carbon stocks. Proceedings of the National Academy of Sciences 107:14926-14930.

Vattenfall. (2009) Corporate social responsibility report 2009, Vattenfall AB, Stockholm, Sweden. pp. 85.

Vattenfall. (2011) Responsible land use. http://www.vattenfall.com/en/land-use-and-soil-protection_60519.htm, consulted 5 August 2011.

VERBIO. (2011) VERBIO Ethanol Schwedt GmbH & Co. KG, http://www.verbio.de/en/desktopdefault.aspx/tabid-65/40_read-98/, consulted 19 August 2011, Vereinigte BioEnergie AG (VERBIO), Leipzig.

VERBIO. (2011) VERBIO Diesel Schwedt GmbH & Co. KG, http://www.verbio.de/desktopdefault.aspx/tabid-65/40_read-92/, consulted 19 August 2011, Vereinigte BioEnergie AG (VERBIO), Leipzig.

Vermeulen S., Goad N. (2006) Towards Better Practice in Smallholder Palm Oil Production, National Resource Issues Series, International Institute for Environment and Development (IEED), London. pp. 56.

Vityakon P.P. (2007) Degradation and restoration of sandy soils under different agricultural land uses in Northeast Thailand: a review. Land Degradation and Development 18:567-577.

Vleeshouwers J.L. (2001) Assessment of Biomass Energy Systems. Yield Potentials under Various Land Use Options. Study funded by the Dutch National Research Programme on Global Air Pollution and Climate Change (project code 953233), Wageningen University, Wageningen. pp. 170.

Vleeshouwers L.M., Verhagen A. (2002) Carbon emission and sequestration by agricultural land use: a model study for Europe. Global Change Biology 8:519-530.

Volk T.A., Verwijst T., Tharakan P.J., Abrahamson L.P., White E.H. (2004) Growing fuel: a sustainability assessment of willow biomass crops. Frontiers in Ecology and the Environment 2:411-418.

Von Uexküll H.R. (1992) Oil Palm, IFA World Fertilizer Use Manual, http://www.fertilizer.org/ifa/content/download/8952/133692/version/1/file/oilpalm.pdf, IFA, Paris.

Wakker E. (2005) Greasy Palms. The Social and Ecological Impacts of Large-Scale Oil Palm Plantation Development in Southeast Asia, Friends of the Earth. pp. 54.

Webster J.P.G., Bowles R.G., Williams N.T. (1999) Estimating the economic benefits of alternative pesticide usage scenarios: wheat production in the United Kingdom. Crop Protection 18:83-89.

Wechsung F., Krysanova V., Flechsig M., Schaphoff S. (2000) May land use change reduce the water deficiency problem caused by reduced brown coal mining in the state of Brandenburg? Landscape and Urban Planning 51:177-189.

Weidema B. (2000) Avoiding co-product allocation in life-cycle assessment. Journal of Industrial Ecology 4:11-33.

Weng C.K. (2005) Best-developed practices and sustainable development of the oil palm industry. Journal of Oil Palm Research 17:124-135.

Werner C. (2003) Biofuels: background, Environmental and Energy Study Institute (EESI), Washington, D.C. pp. 3.

West T.O., Marland G. (2002) A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Agriculture, Ecosystems & Environment 91:217-232.

Wicke B., Dornburg V., Faaij A., Junginger M. (2007) A Greenhouse Gas Balance from Electricity Production from Co-firing Palm Oil Products from Malaysia, Department of Science, Technology and Society, Copernicus Institute, Utrecht University, Utrecht. pp. 53.

Williams J.R. (1990) The erosion-productivity impact calculator (EPIC) model: a case history. Philosophical Transactions: Biological Sciences 329:421-428.

Wischmeier W.H., Smith D.D. (1978) Predicting Rainfall Erosion Losses - a Guide to Conservation Planning, USDA pp. 60.

Wolf J., de Wit C.T., Janssen B.H., Lathwell D.J. (1987) Modeling long-term crop response to fertilizer phosphorus. I. The model. Agronomy Journal 79:445-451.

Wood A.W. (1991) Management of crop residues following green harvesting of sugarcane in north Queensland. Soil and Tillage Research 20:69-85.

Wood B.J., Corley R.H.V. (1991) The energy balance of oil palm cultivation, in: Y. Basiron, et al. (Eds.), PORIM International Oil Palm Conference, Kuala Lumpur. pp. 130-143.

Woodhouse P., Howlett D., Rigby D. (2000) Working Paper 2. A Framework for Research on Sustainability Indicators for Agriculture and Rural Livelihoods, Sustainability Indicators for Natural Resource Manegement & Policy, Development and Project Planning Centre, University of Bradford, UK; Centre for Agricultural, Food and Resource Economics Institute for Development Policy and Management, University of Manchester, UK; Economic Policy Research Centre, Makerere Campus, Kampala, Uganda; Agricultural and Rural Development Research Institute, University of Fort Hare, South Africa, Bradford, UK. pp. 39.

Woods J. (2000) Integrating Sweet Sorghum and Sugarcane for Bioenergy: Modelling the Potential for Electricity and Ethanol Production in SE Zimbabwe. PhD Thesis, Division of Life Sciences, King's College London, University of London, London. pp. 266.

Worldbank. (2006) Mozambique Agricultural Development Strategy. Stimulating Smallholder Agricultural Growth, Worldbank. pp. 143.

Worley J.W., Vaughan D.H., Cundiff J.S. (1992) Energy analysis of ethanol production from sweet sorghum. Bioresource Technology 40:263-273.

Wydra K.K., Verdier V. (2002) Occurrence of cassava diseases in relation to environmental, agronomic and plant characteristics. Agriculture, Ecosystems & Environment 93:211-226.

Xu F., Guo W., Wang R., Xu W., Du N., Wang Y. (2009) Leaf movement and photosynthetic plasticity of black locust (Robinia pseudoacacia L.) alleviate stress under different light and water conditions. Acta Physiologiae Plantarum 31:553-563.

Zen A., Barlow C., Gondowarsito R. (2005) Oil Palm in Indonesian Socio-Economic Improvement - a Review of Options. Working Paper 11/2005, Department of Economics, Research School of Pacific and Asian Studies, Australian National University, Canberra. pp. 29.

Zhang B.Q., Yang X.B. (2000) Pathogenicity of Pythium populations from corn–soybean rotation fields. Plant Disease Vol. 84.

Zhen L., Routray J.K. (2003) Operational indicators for measuring agricultural sustainability in developing countries. Environmental Management 32:34-46.

Zingore S., Manyame C., Nyamugafata P., Giller K.E. (2005) Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. European Journal of Soil Science 56:727-736.

Zub H.W., Brancourt-Hulmel M. (2010) Agronomic and physiological performances of different species of Miscanthus, a major energy crop. A review. Agronomy for Sustainable Development 30:201-214.

Zub H.W., Arnoult S., Younous J., Lejeune-Hénaut I., Brancourt-Hulmel M. (2012) The frost tolerance of Miscanthus at the juvenile stage: Differences between clones are influenced by leaf-stage and acclimation. European Journal of Agronomy 36:32-40.

Summary

Since the year 2000, world production of biofuels, i.e. liquid transport fuels produced from agricultural products, has shown an unprecedented growth, which is projected to continue for the coming decade. In 2009, fuel ethanol production had increased to more than fourfold of its volume in 2000, to 73 billion liters per year; compared to 2000, biodiesel production increased more than fifteen-fold to 16 billion liters per year in 2009. The increased demand for biofuels is mainly caused by government targets, set because of concerns over climate change (Kyoto protocol), dependence on imported oil from politically unstable regions and to create new markets for the agricultural sector.

The side-effects of large-scale cultivation of energy crops started to attract more attention only after the biofuel targets had been in place for some time. Apart from environmental and socio-economic impacts of agriculture that were already relatively well-researched and well-understood, new issues emerged with the increasing cultivation of crops for biofuel feedstock, such as direct and indirect land use change and their impact on food prices, food security and greenhouse gas (GHG) emissions. Doubts also emerged on the effectiveness of biofuels in reducing GHG emissions and saving energy. Due to these issues, a hot scientific and societal debate arose on whether the large-scale production and use of biofuels is a sustainable endeavour, after all. A sustainable activity (i.e. biofuel production) meets the needs of the present generation without compromising the ability of future generations to meet their own needs.

This thesis aimed to assess the production-ecological sustainability of biofuel production systems that represent as much as possible the diversity in feedstock crops, climatic and bio-physical environments in the world. *Production-ecological* sustainability is a part of the environmental dimension of sustainability; for the specific purpose of the current work, it was defined by a set of sustainability indicators relating to resource use efficiency, soil quality, net energy production and greenhouse gas emissions. Secondly, the work aimed to provide a general methodology that enables such assessments of systems with minimum land use change, aid in the development

of such systems and could potentially form a basis for sustainability certification of biofuels.

Sustainability indicators used in this thesis were selected based on previous agricultural sustainability assessments, on scientific publications describing criteria for selecting useful indicators for assessing agriculture's sustainability and on the selection of similar indicators by multi-stakeholder platforms such as the roundtables for sustainable biofuels, palm oil and responsible soy.

The indicators were first assessed in a literature-based inventory of the production-ecological sustainability of nine major biofuel production systems (Chapter 2), based on current practices in major production areas in the world. Crops that performed well or seemed promising in this inventory were analysed in more detail in three region-specific case studies (Chapters 3-5). For these studies, geographic regions were chosen that represent as much as possible the diversity in climate, bio-physical and socio-economic environments existing in the world. Also, it was attempted to study as much as possible the variation that exists among plant species that may be used for the production of biofuels: perennials and annuals were included, species with C3 and C4 photosynthesis, food (first-generation) and non-food (second generation) producing species, and biodiesel and bio-ethanol yielding species. Further, smallholder systems as well as large-scale plantations were assessed.

The initial literature-based inventory (Chapter 2) indicated that under average agricultural practice, of the nine assessed crops, biofuel produced from oil palm (South East Asia; *Elaeis guineensis* Jacq.), sugarcane (Brazil; *Saccharum officinarum* L.) and sweet sorghum (China; *Sorghum bicolor* L.) is most sustainable: these crops make the most efficient use of land, water, nitrogen and energy resources, while pesticide applications are relatively low in relation to the net energy produced. Provided there is no land use change, greenhouse gas emissions of these three biofuel production systems are substantially reduced compared with fossil fuels. Maize (USA; *Zea mays* L.) and wheat (Northwest Europe; *Triticum aestivum* L.) as feedstock for ethanol perform poorly for nearly all indicators. Sugar beet (Northwest Europe; *Beta vulgaris* L.), cassava (Thailand; *Manihot esculenta* Crantz), rapeseed (Northwest Europe; *Brassica napus* L.) and soybean (USA; *Glycine max* (L.) Merr) take an intermediate position.

Systems based on sugarcane and sweet sorghum were assessed in more detail in Mozambique (Chapter 3), now additionally taking into account the influence of crop management and previous land use. Cassava was also included, as it could be a suitable crop for engaging smallholders in biofuel production. Production-ecological sustainability and labour requirements of smallholder cassava production were compared with that of feedstock production on plantations using sugarcane, sweet sorghum and cassava as benchmarks. For doing this, an assessment framework was developed, based on a simple crop-soil model; it takes into account the effects of limited availability of water and nutrients on crop growth. Such limitations are particularly relevant in zero-input smallholder systems. Results indicate that of the assessed systems, sugarcane performed better than cassava, although it requires substantial water for irrigation. Targeted use of nutrient inputs improved sustainability of smallholder cassava production. It may be regarded as ecological intensification: the achievement of substantially higher yields relative to both land area and time, involving concomitant improvements in nutrient use efficiency, especially of N, water use efficiency and energy efficiency. Cassava production systems on more fertile soils were more sustainable than those on less fertile soils; the latter required more external inputs for achieving the same output, affecting most indicators negatively and reducing the feasibility for smallholders. Cassava and sweet sorghum performed similarly, but cassava production requires much more labour per hectare than production of sugarcane or sweet sorghum. Production of bioethanol feedstock on cultivated lands was more sustainable than on newly cleared land and had potential for carbon sequestration, avoiding GHG emissions from clearing natural vegetation if new land is opened.

Oil palm was another crop that was identified as a promising option for producing biofuel feedstock in the initial inventory (Chapter 2), provided there is no land use change. Expansion of palm oil production has become increasingly controversial due to the threat to tropical rainforest. Yet due to the increasing demand for vegetable oils that is projected, further expansion is anticipated. In Chapter 4, we replaced the cop model of the assessment framework developed in Chapter 3 with an oil palm model to assess sustainability aspects of several production modes of this crop, on land with different previous uses. These comprised degraded grassland, oil palm (replanting, no land use change) and secondary forest. We show that yield increase through introduction of best management practices in existing plantations and rehabilitation of degraded grasslands are much more sustainable ways of increasing palm oil production than through encroaching into tropical forest habitats. Rehabilitation of degraded grasslands offers great potential for carbon sequestration in soil and biomass and hence could be considered for eligibility as a carbon sink in the UN's REDD+ programme (Reducing Emissions from Deforestation and forest Degradation + Conservation of forest carbon stocks, Sustainable management of forests & Enhancement of forest carbon stocks).

Scientific literature indicates that for temperate regions, biofuel production from plants predominantly containing ligno-cellulosic compounds, requiring "second generation" processing methods, may perform better than from oil, sugar and starch crops. The production-ecological sustainability of first and second generation biofuel production systems was assessed for the state of Brandenburg, Germany (Chapter 5). The assessed 1st generation fuels were biodiesel and bioethanol produced from rapeseed and sugarbeet feedstock, respectively. Assessed 2nd generation systems were based on feedstock from *Miscanthus* (*Miscanthus* x *giganteus* Greef et. Deu. ex Hodkinson et Renvoize) and black locust (*Robinia pseudoacacia* L.); for both crops conversion into cellulosic ethanol and Fischer Tropsch Diesel was assessed. Second generation biofuel production systems based on *Miscanthus* and black locust performed substantially better than first generation systems based on rapeseed and sugarbeet. They contribute much more to GHG emission reduction, had much higher net energy yields and better resource use efficiencies; soil erosion and N leaching were also lower. *Miscanthus* performed better than black locust, except for its N use efficiency; it was the most water-efficient species, which is important in a region with declining groundwater tables. However, in Brandenburg, low temperatures during winter and early spring are often threatening to survival of first-year *Miscantus* plantings; there have been disastrous experiences in the past. The drawback of black locust is that it has invasive characteristics.

From the work done, we conclude that under good agricultural practice and without adverse land use change, biofuel production systems using feedstock from sugarcane, oil palm and second generation crops Miscanthus and black locust perform much better than first generation production using feedstock from arable crops in temperate areas. Sugarcane, oil palm, *Miscanthus* and black locust under good agricultural practice produce so much biomass that they have high gross energy yields, provide enough biomass for powering the conversion process which contributes to high net energy yields, and at the same time supply ample crop residues for maintaining soil organic carbon (SOC). In contrast, first generation systems in temperate areas generally have rather low net energy yields and poor resource use efficiencies and perform relatively poorly for the other sustainability indicators that we assessed. Therefore, their production is relatively land- and resource consuming and has relatively high environmental impact.

When estimates of GHG emissions from indirect land use change are added to the GHG emissions figures calculated in this thesis, most systems would not reach the 35% reduction of GHG emissions compared to fossil fuels that the EU currently demands, except for certain crops grown on degraded lands. Findings in this thesis indicate that rehabilitation of degraded soils by planting oil palm (tropics) or black

locust (temperate regions) has great advantages, especially in terms of GHG emission reduction, C sequestration and soil fertility. However, the economic risk of frost damage in *Miscanthus* and invasive character of black locust are aspects that need further research. Also, the beneficial effect of soil C sequestration on GHG emissions is temporary; after two or three decades, generally, new equilibrium soil organic carbon (SOC) contents are reached.

Ecological intensification by introducing best management practices (BMP) in oil palm results in significant improvement of sustainability indicator values compared to average practices: SOC sequestration, GHG emissions, nitrogen use efficiency, water productivity and net energy yield improve significantly. BMP should therefore not only be applied in oil palm production for biodiesel, but also in production for food and other purposes. More research should be dedicated towards ways to get rehabilitation of degraded soils and introduction of BMP implemented on a wider scale.

Finally, it also became apparent that a framework to assess the sustainability of biofuel production systems should be flexible and simple enough to allow user modification or addition of model components, while at the same time building on existing modelling frameworks. In this thesis, we developed a first version of such a framework, based on a simple crop-soil model; it takes into account the effects of limited availability of water and nutrients on crop growth and calculates sustainability indicators. Suggestions for further application and improvement of the framework were also made.

Samenvatting

Sinds 2000 is de mondiale productie van biobrandstoffen, dit zijn vloeibare transportbrandstoffen uit landbouwproducten, op een ongeëvenaarde manier gegroeid. De verwachtingen zijn dat deze groei zich het komende decennium zal voortzetten. In 2009 was de wereld productie van bio-ethanol met 73 miljard liter per jaar verviervoudigd t.o.v. het jaar 2000; met 16 miljard liter per jaar was de productie van biodiesel het 15-voudige van die in 2000. Deze toegenomen vraag naar biobrandstoffen wordt vooral veroorzaakt door overheidsdoelstellingen voor het gebruik van hernieuwbare energie, die geformuleerd zijn met het oog op klimaatverandering (het Kyoto protocol), om de afhankelijkheid van aardolie uit politiek instabiele regio's te verminderen en ook om nieuwe afzetmarkten te creëren voor de landbouwsector.

De onbedoelde neveneffecten van het steeds grootschaliger verbouwen van energiegewassen begonnen meer aandacht te trekken nadat de overheidsdoelstellingen voor hernieuwbare energie al enige tijd ingevoerd waren. Naast al bekende effecten van landbouw op het milieu en op sociaal-economische omstandigheden doken er nieuwe problemen op, zoals directe en indirecte veranderingen in landgebruik en de effecten van deze veranderingen op voedselprijzen, voedselzekerheid en broeikasgasemissies. Er rezen ook twijfels over de terugdringing in energiegebruik en broeikasgasemissies die bewerkstelligt zou worden door biobrandstoffen. Vanwege al deze zaken ontstond er een verhit maatschappelijk en wetenschappelijk debat over de duurzaamheid van biobrandstoffen. Hoewel er vele manieren zijn om het begrip duurzaamheid te kenschetsen, kan over het algemeen een activiteit duurzaam worden genoemd als ze tegemoet komt aan de behoeften van de huidige generatie zonder daarbij die van toekomstige generaties in gevaar te brengen.

Dit proefschrift heeft tot doel om de productie-ecologische duurzaamheid te analyseren van een aantal productieketens voor biobrandstoffen die zoveel mogelijk de wereldwijde verscheidenheid aan gewassen, biofysische en overige omstandigheden weerspiegelen. Productie-ecologische duurzaamheid maakt deel uit van de milieudimensie van duurzaamheid; voor ons specifieke doel hebben we dit deelgebied gedefinieerd middels een set duurzaamheidsindicatoren die betrekking hebben op de efficiëntie waarmee schaarse grondstoffen gebruikt worden, op bodemkwaliteit, netto energieproductie en broeikasgasemissies. Een tweede doel van dit proefschrift is het formuleren van een algemene methodiek die duurzaamheidsanalyses van productieketens voor biobrandstoffen mogelijk maakt, die helpt bij het ontwikkelen van zulke systemen met een minimum aan landgebruiksverandering en mogelijk een basis zou kunnen vormen voor het certificeren van de duurzaamheid ervan.

De duurzaamheidsindicatoren in dit proefschrift zijn gekozen op basis van eerdere analyses van de duurzaamheid van landbouw, op wetenschappelijke publicaties die selectiecriteria voor indicatoren in dergelijke studies beschrijven en op de keuzes die gemaakt zijn door bijvoorbeeld de ronde tafels ('roundtables') voor duurzame biobrandstoffen, palmolie en soja.

Voor negen belangrijke productieketens zijn deze indicatoren eerst gekwantificeerd op basis van bestaande literatuur omtrent de landbouwpraktijk in gebieden waar deze ketens gangbaar zijn (hoofdstuk 2). Gewassen die als goed of veelbelovend uit de bus kwamen bij deze inventarisatie zijn vervolgens onder de loep genomen in drie meer gedetailleerde studies (hoofdstukken 3-5). Voor deze studies zijn regio's gekozen die de wereldwijde verscheidenheid in biofysische en sociaal-economische omstandigheden zo goed mogelijk weergeven. Daarnaast is ook geprobeerd zo goed mogelijk de verscheidenheid in beschikbare gewassen weer te geven: in de analyses zijn eenjarige en meerjarige gewassen meegenomen, soorten met C3 en C4 fotosynthese, voedsel- (1e generatie) en industriële (2e generatie) gewassen, en zowel gewassen die bio-ethanol als biodiesel opleveren. Tenslotte zijn productiesystemen van kleine boeren maar ook van grootschalige plantages bekeken.

De resultaten van de inleidende inventarisatie op basis van bestaande literatuur (hoofstuk 2) geven aan dat bij gemiddelde landbouwpraktijken, biobrandstoffen afkomstig van oliepalm (Zuidoost Azië; *Elaeis guineensis* Jacq.), suikerriet (Brazilië; *Saccharum officinarum* L.) en zoete sorghum (China; *Sorghum bicolor* L.) het meest duurzaam zijn van de negen geanalyseerde ketens. Deze gewassen maken het meest efficiënte gebruik van land, water en stikstof en energie, terwijl het gebruik van pesticiden laag is in verhouding tot de geproduceerde netto energie. Als er geen landgebruiksverandering optreedt zijn de emissies van productiesystemen op basis van deze drie gewassen substantieel lager dan die van fossiele transportbrandstoffen. Mais (VS; *Zea mays* L.) en tarwe (NW Europa; *Triticum aestivum* L.) als grondstof voor biobrandstoffen scoorden slecht voor bijna alle duurzaamheidsindicatoren. Gewassen die gemiddeld scoren zijn suikerbiet (NW Europe+ *Beta vulgaris* L.), cassave (Thailand; *Manihot esculenta* Crantz), koolzaad (NW Europa; *Brassica napus* L.) en soja (VS; *Glycine max* (L.) Merr).

Productieketens op basis van suikerriet en zoete sorghum in Mozambique zijn nader geanalyseerd in hoofdstuk 3; hierbij is nu ook rekening gehouden met de effecten van verschillen in landbouwpraktijk en mogelijke veranderingen in landgebruik. Verder is cassave meegenomen in deze analyse, aangezien dit een geschikt gewas zou kunnen zijn om kansen te creëren voor kleine boeren. De productie-ecologische duurzaamheid en arbeidsuren van cassaveteelt door kleine boeren zijn vergeleken met die van de teelt van cassave, suikerriet en zoete sorghum op grootschalige plantages. Om deze vergelijking mogelijk te maken werd een speciaal systeem ontwikkeld op basis van een bestaand bodem-gewas model; dit systeem houdt rekening met de gevolgen van mogelijk beperkte beschikbaarheid van water en voedingsstoffen op de opbrengst van het gewas. Dergelijke beperkingen zijn vooral van belang in het huidige teeltsysteem van kleine boeren in Mozambique. De resultaten geven aan dat voor onze indicatoren suikerriet beter scoort dan cassave, hoewel de teelt van suikerriet in Mozambique veel irrigatiewater vereist. Het gericht toedienen van meststoffen leidt tot een verbetering van de duurzaamheid van de cassaveteelt door kleine boeren. Dit kan worden gezien als ecologische intensivering: het bereiken van substantieel hogere opbrengsten terwijl tegelijkertijd meststoffen (in het bijzonder N), water en energie efficiënter gebruikt worden. Cassaveteelt op vruchtbare bodems was duurzamer dan op armere bodems; op de laatste zijn meer inputs zoals meststoffen vereist om dezelfde opbrengst te bereiken, hetgeen de meeste indicatoren negatief beïnvloedt alsmede de economische haalbaarheid voor kleine boeren. Cassave en zoete sorghum scoorden vergelijkbaar, maar de teelt van cassave vereist veel meer arbeid per eenheid landbouwoppervlak dan die van zoete sorghum of suikerriet. Teelt van gewassen voor bioethanol op landbouwgrond die reeds in gebruik was bleek duurzamer dan op nieuw ontgonnen grond en biedt mogelijkheden voor het vastleggen van koolstof terwijl broeikasgasemissies door het verwijderen van vegetatie bij het ontginnen voorkomen worden.

Oliepalm is een ander gewas dat als veelbelovend uit de inleidende inventarisatie (hoofdstuk 2) naar voren kwam, tenminste, als er geen verandering in landgebruik is. Verdere uitbreiding van het oliepalm areaal is zeer controversieel vanwege de bedreiging die dit mogelijk vormt voor de tropische regenwouden. Toch moet, gezien de verwachte toename van de vraag naar plantaardige oliën, rekening worden houden met toekomstige uitbreiding. In hoofdstuk 4 vervangen we de gewas-component van het systeem dat we ontwierpen voor hoofdstuk 3 door een model van de groei en productie van oliepalm, om zo de productie-ecologische duurzaamheid van verschillende productiesystemen van dit gewas te analyseren, in combinatie met veranderingen in landgebruik. Hoofdstuk 4 analyseert de aanplant en productie van oliepalm na gedegradeerd grasland, na oliepalm (herplanten) en na secondair regenwoud. Resultaten geven aan dat opbrengstverhoging door het invoeren van verbeterd gewasmanagement ('Best Management Practices', BMP) en rehabilitatie van gedegradeerde graslanden duurzame alternatieven zijn voor het verder ontginnen van tropisch regenwoud. Rehabilitatie van gedegradeerde graslanden heeft grote mogelijkheden voor het vastleggen van koolstof, in bodem en biomassa en zou daarom in aanmerking moeten komen voor het VN-REDD programma (Reducing Emissions from Deforestation and forest Degradation + Conservation of forest carbon stocks, Sustainable management of forests & Enhancement of forest carbon stocks).

Wetenschappelijke literatuur geeft aan dat in streken met een gematigd klimaat, productie van biobrandstoffen uit gewassen die voornamelijk uit lignine en cellulose bestaan en dus tweede generatie verwerkingsprocessen vereisen waarschijnlijk duurzamer is dan uit eerste generatie olie-, suiker- en zetmeelgewassen. In hoofdstuk 5 wordt de productie-ecologische duurzaamheid van eerste en tweede-generatie biobrandstof productiesystemen vergeleken voor de Duitse deelstaat Brandenburg. De geanalyseerde eerste generatie systemen zijn gebaseerd op koolzaad en suikerbiet. De tweede generatie systemen in dit hoofdstuk maken van gebruik van biomassa afkomstig van Miscanthus (*Miscanthus x giganteus* Greef et. Deu. ex Hodkinson et Renvoize) en *Robinia pseudoacacia* L.; voor deze beide gewassen is zowel (tweede generatie) omzetting naar bio-ethanol als naar Fischer Tropsch diesel geanalyseerd. Tweede generatie systemen gebaseerd op *Miscanthus* en *R. pseudoacacia* deden het duidelijk beter dan eerste generatie systemen gebaseerd op koolzaad en suikerbiet. Ze zijn effectiever in het terugdringen van broeikasgasemissies, hebben hogere netto-energieopbrengsten en maken efficiënter gebruik van schaarse grondstoffen; ook was er minder bodemerosie en uitspoeling van stikstof onder deze gewassen. *Miscanthus* scoorde beter dan *R. pseudoacacia*, behalve wat betreft de stikstof-gebruik efficiëntie; het was de meest water-efficiënte leverancier van biomassa, hetgeen belangrijk is in een regio met dalende grondwaterstanden. Een probleem is echter dat lage temperaturen in de winter en het vroege voorjaar er voor kunnen zorgen dat jonge *Miscanthus* aanplant afsterft in Brandenburg; er zijn wat dit betreft zeer slechte ervaringen uit het verleden. Het nadeel van *R. Pseudoacacia* is dat het een uitheemse soort is die zich gemakkelijk verspreidt. Dit onderzoek leidt tot de conclusie dat, bij goede landbouwpraktijk en in afwezigheid van schadelijke verandering in landgebruik, productieketens voor biobrandstoffen gebaseerd op suikerriet, oliepalm en de tweede-generatie gewassen *Miscanthus* en *R. pseudoacacia* veel beter scoren wat betreft productie-ecologische duurzaamheid dan productieketens gebaseerd op eerste-generatie gewassen uit gematigde streken. Onder goed gewasmanagement produceren suikerriet, oliepalm, *Miscanthus* en *R. pseudoacacia* zoveel biomassa dat ze een hoge bruto-energieopbrengst hebben, maar ook energie leveren voor de industriële verwerking, hetgeen bijdraagt aan hoge netto-energieopbrengsten; ook blijven er meer dan voldoende gewasresten over voor het op peil houden van de bodem-organische koolstof. Eerste-generatie productieketens in gematigde streken hebben juist lage netto-energieopbrengsten en maken inefficiënt gebruik van grondstoffen. Daarom scoren ze slecht voor de overige duurzaamheidsindicatoren die geanalyseerd zijn; hun productie consumeert relatief veel land en schaarse grondstoffen en heeft een grotere impact op het milieu.

Als de geschatte broeikasgasemissies ten gevolge van indirecte landgebruiksveranderingen op worden geteld bij de keten-emissies die berekend zijn in dit proefschrift, zouden de meeste geanalyseerde systemen de minimum emissie reductie van 35% die gesteld is door de EU niet halen, op enkele gewassen na die geteeld kunnen worden op gedegradeerde bodems. De bevindingen van dit proefschrift geven aan dat rehabilitatie van gedegradeerde gronden door het planten van oliepalm (in de tropen) of R. pseudoacacia (in gematigde streken) grote voordelen heeft, vooral wat betreft het terugdringen van broeikasgasemissies, vastleggen van koolstof en verbeteren van de bodemvruchtbaarheid. Het risico van vorstschade in *Miscanthus* en het zich verspreiden van de uitheemse soort *R. pseudoacacia* zijn aspecten die meer onderzoek behoeven. Het gunstige effect van koolstofvastlegging in de bodem is bovendien slechts tijdelijk; na twee of drie decennia wordt over het algemeen een nieuw evenwichtsniveau bereikt.

Ecologische intensivering door het invoeren van beter gewasmanagement (BMP) in oliepalm resulteerde in duidelijke verbeteringen in duurzaamheidsindicatoren ten opzichte van de gemiddelde praktijk; koolstofvastlegging, terugdringing van broeikasgasemissies, gebruiks-efficiëntie van stikstof, water productiviteit en netto energieopbrengst verbeterden duidelijk. BMP zou daarom ook moeten worden geïmplementeerd in de productie van palmolie voor voedsel en andere doelen dan energie; tevens zou er meer onderzoek gedaan moeten worden naar manieren om rehabilitatie van gedegradeerde graslanden en introductie van BMP op grotere schaal ingevoerd te laten worden.

Tenslotte is het duidelijk geworden dat een systeem voor het analyseren van de duurzaamheid van productieketens voor biobrandstoffen flexibel en simpel moet zijn om door de onderzoeker zelf aangepast te kunnen worden; ook moet zoveel gebruik worden gemaakt van kennis in bestaande modellen van bodem en gewas. In dit proefschrift hebben we een eerste versie van zo'n systeem ontwikkeld, gebaseerd op een simpel bodem-gewas model; het houdt rekening met de effecten van beperkte beschikbaarheid van meststoffen en water op gewasopbrengsten en berekent duurzaamheidsindicatoren. Tenslotte worden er mogelijkheden geschetst om dit systeem in de toekomst verder te verbeteren.

Acknowledgement

Rather than sitting behind a desk covered in cobwebs with no strings attached, a PhD student operates like a spider in a web (pun intended) or at times perhaps as a fly caught in it… anyway, this work would not have been possible without a skilful supervision team sending signals through the strings when necessary.
Ken, the keen interest and critical attitude with which you follow and engage in newly emerging debates in the field of agriculture, including the biofuels boom, are a great inspiration and lend a sense of the urgency to the work that is done in PPS, including this research. Your enthusiasm and outspoken opinions are really inspiring. Gerrie, you are probably one of the most diligent and persisting supervisors a PhD student could wish to have. You always read any manuscript thoroughly and timely and came up with ideas that were often one level of thinking ahead. Also, I am thankful for your personal commitment to the project in general, and particularly for the fact that you continued work even when there you encountered a very difficult family situation. Martin, during the writing process, you were often the one to come up with the most concrete suggestions of how to formulate things differently. The fact that you already seem to think of how to get work published when the research has barely started is a great asset and it surely influences journal decisions on any paper positively (fingers crossed). Importantly (and perhaps as an example), you suggested to capture the outcomes of the assessments in cobweb diagrams, which makes them a lot easier to grasp.

Apart from the daily supervision team, most closely involved in the work were Amit Walia, Angelika Voss and Iris Lewandowski of Shell Global Solutions; I would like to express my sincere gratitude towards you. You did not only show interest in the general progress of the work, but also chose to be involved with the contents, often asking questions and making recommendations and suggestions, hence contributing to the successful finishing of the thesis.

Many other contributions are essential. The crop and soil data that Sanne collected in Mozambique under sometimes very difficult conditions are the basis for chapter 3. Chapeau! Anneke, the wealth of cassava experimental data that you collected

during your PhD research and allowed us to use were also essential. It was a lucky coincidence that when we needed to fly four heavy garbage bins full of soil samples from Quelimane back to Maputo, we met soil scientist prof. Yost, who allowed us to put the excess freight under his name, thanks! Wilson and Madeleine: travelling with you in Mozambique and meanwhile discussing about typologies and gradients, drinking beer and looking for a second hand car was great fun! Armindo Cambule: thanks for making sure that the soil samples were analysed swiftly and meticulously. Hans Langeveld, thanks for animated discussions on energy balances and greenhouse gas emissions. Pablo, thanks for your initial explanation and help with the crop-soil model. Bert Janssen, thanks a lot for interesting discussions and advice on soil carbon modelling, soil sampling and about the tropics in general. Mark, thanks for your help with inverse modelling. Thomas Fairhurst, thanks for many useful comments and suggestions and for providing a lot of grey literature on oil palm research.
For chapter 5, my visit to Brandenburg and the ZALF institute proved really useful, and at the same time very enjoyable. Many thanks to Peter Zander, Anja Starick, and Johannes Hufnagel for your hospitality and for giving me clues to find the right information! Aart and Marloes, thanks for your good thesis work. Peter Leffelaar thanks for notifying me about the models and reports of Leo Vleeshouwers in the early stages of the research: without these materials, chapter 5 would have been difficult to carry out. Andy Farrow thanks for extracting Mozambique weather data from Marksim. Kevin Coleman thanks for kindly providing a copy of the RothC model. Fellow PhD's who were active in the biofuels discussion group of the Graduate School: your enthousiasm kept the group alive! May all of you soon defend! Also many thanks to the people who keep up the good the habit of informing colleagues on any interesting news related to their research topic: often I found interesting newspaper articles on my desk or my email (cf. p. 136). Thanks to the staff of the WUR (Forum) library who make sure that almost any scientific article is just a click away: the library rocks! Many thanks to Ria and Charlotte for knowing about all the paperwork and complex WUR regulations and always offering help in these issues; you mostly arrange matters before one can even ask!

Luckily there was plenty of room for fun and relaxation in and around the office. Especially in the old Haarweg building, playing ping-pong was a great pastime. Sander, Jochem, Pytrik, Peter van der Putten, Xinyou and all other ping-pong fanatics: thanks... and may there one day be a ping-pong table in Radix too! Also great fun were the everyday conversations and discussions with my office mates Sheida, Myriam and Lenny, and more briefly Michiel, Maja and Argyris. Usually discussion was continued during the coffee break where discussions with Peter Leffelaar and Joost Wolf often took interesting and unexpected directions. Apart from LOTS of coffee (thanks to all people in the supply chain of this black gold), another ingredient for a good day of science is a simple but nutritious lunch: there was always a group of people going out, browsing for food: presence of Rik, Madeleine, Marieke, Maryia, Mink, Idsert, Linus, Naomi, Jessica, Charles, Alba, Dirk, Chrispen, Aisha, André and Murilo and others made this usually an entertaining event. Rik, also thanks for demonstrating what you can do with a seemingly useless photograph (the cover picture of this thesis)!

Focussing on activities in and around the office was only possible since I knew that the staff of Kinderkunst always made sure that Lasse and Melle had fun and felt at home during the day. Hearing how they had been doing was always an uplifting moment: many thanks (also on behalf of Lasse and Melle) Loes, Sanne, Marijke, Ineke, Willeke, Sonja!

Thanks to all my friends for all the good times. Thanks also to my 'little' sister Franciska for having demonstrated how to do a PhD and for asking me to be a paranymph during her defense: at least I knew the stage already (and one of the opponents:). Thanks to my parents for always having supported me. Also thanks Henk and Tineke, Jeanette and Sander for your support and interest. Credits go to the teachers of the Christelijk Gymnasium in Leeuwarden; the solid education that I somehow got there is something that I profit from on a daily basis. René and Durk Piet: discussing the important things in life with you and playing billiards, especially during school time, was always great... thanks for being my paranymphs! Thanks also Arjan and Pepijn: I guess over the past years we not only have become true connoisseurs of San Miguel beer and Scotch whiskey, but also a highly efficient moving company. Playing guitar, drums and tennis are some activities that I particularly enjoy: thanks Bas and Jeroen for all those endless (the delay pedal?) jams; thanks also to the people of the Sunday jazz sessions in café de Zaaier, especially Laurens for organising them; and thanks to WUR bigband Sound of Science, Tha Combeau and Papaband.

At the end of the day, nothing is more important to me than my family. Lasse and Melle: your liveliness and laughter sounds better than any type of music! Jacqueline: I love sharing life with you. Like in the Cole Porter song: *you are sooo nice to come home to!*

Curriculum Vitae

Sander Cathrinus de Vries was born in Ljouwert (Leeuwarden) in 1973 and attended primary school at the Albertine Agnesschool there. Sander enjoyed secondary education at the 'Christelijk Gymnasium' in Leeuwarden, now called 'Christelijk Gymnasium Beyers Naudé '. After briefly studying Mining and Petrol Engineering at Delft University, he switched to Wageningen University. With the finishing of a MSc thesis and internship at the International Rice Research Insitute (IRRI) in the Philippines, Sander completed his studies Tropical Land Use, specialisation Tropical Agronomy in 2000. He started his professional career as a research assistant in the Plant Production Systems chairgroup of Wageningen University. After that, Sander worked as a potato agronomist in Indonesia, employed by the Peru-based International Potato Center (CIP). Work mainly comprised the selection and introduction of late-blight resistant potato varieties for Indonesia. Also he had the opportunity to travel extensively within Southeast Asia, visiting countries like Myanmar, Vietnam and North Korea. Once returned to the Netherlands, Bejo Vegetable Seeds in Warmenhuizen was the employer of choice. As a junior plant breeder, Sander worked in a team which developed new varieties of carrots, beetroots, cichory and other vegetable crops and spent many hours in field and greenhouse. Remaining in the breeding sector, he then moved back to Wageningen and worked as a laboratory assistant for Keygene N.V., until successfully applying for the PhD position that resulted in the current thesis. Since March 2012, Sander is working at the Utrecht Sustainability Institute as Junior Cluster Manager 'Resource Use and Scarcity'. Hobbies include running, cycling, playing tennis, drums and guitar. Over the years, Sander played music in many different settings, ranging from funk-hop to bigband jazz. Sander shares his life with Jacqueline Annema; together they have two sons, Lasse (4) and Melle (1).

Selected publications by the author

Peer reviewed:

De Vries, S.C., Van de Ven, G.W.J., Van Ittersum, M.K., Giller, K.E, 2012. The production-ecological sustainability of cassava, sugarcane and sweet sorghum production systems for bioethanol feedstock in Mozambique. GCB – Bioenergy 4:20-35.

De Vries, S.C., Ven, G.W.J. van de, Ittersum, M.K. van; Giller, K.E, 2010. Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. Biomass and Bioenergy 34 (2010) 588-601.

De Vries, S.C., 2008. The bio-fuel debate and fossil energy use in palm oil production: a critique of Reijnders and Huijbregts 2007. Journal of Cleaner Production 16, 1926-1927.

Other:

De Vries, S.C., Giller, K.E., Van Ittersum, M.K., Van de Ven, G.W.J. (2008). Comparing biofuel cropping options by means of sustainability indicators In: Proceedings of 8th European IFSA Symposium, Clermont Ferrand, France, 6 - 10 July, 2008.

De Visser, C.L.M., Van de Ven, G.W.J., Langeveld, J.W.A., De Vries, S.C., Van den Brink, L. (2008). Duurzaamheid van ethanolbieten: het toetsingskader toegepast. Wageningen: Wageningen UR, Application Centre for Renewable RESources (ACRRES).

De Vries, S.C. Country report on late blight in Indonesia. In: Lizzaraga, C. (ed.). Proceedings of the regional workshop on potato late blight for East and Southeast Asia and the Pacific, 24-25 August 2004, Yezin Agricultural University, p31-33. Yezin, Myanmar.

De Vries, S.C., Van Ittersum, M.K., Howden, S.M., Asseng, S., 2002. Design of simulation experiments: an example for assessing potential impact of climate change on wheat yields and deep drainage in Western Australia. In: Book of Proceedings VII Congress of the European Society for Agronomy. Córdoba, Spain, 15–18 July 2002, pp. 773–774.

Hoanh, C.T., Dieu, P.Q., Que, N.N., Kam, S.P., Bolink, P.M., De Vries, S., Son, D.K., Rala, A., Villano, L. Rice supply and demand scenarios for Vietnam. In: Sombilla, M., Hossain, M., Hardy, B., eds. 2002. Developments in the Asian rice economy. Proceedings of the International Workshop on Medium- and Long-Term Prospects of Rice Supply and Demand in the 21st Century, 3-5 December 2001, Los Baños, Philippines. Los Baños (Philippines): International Rice Research Institute. 436 p.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of Literature (4.5 ECTS)
- Sustainability aspects of biofuel production chains

Writing of Project Proposal (4 ECTS)
- Sustainable production of biomass for biofuels

Post-Graduate Courses (6 ECTS)
- Long-term dynamics of food and human development; PE&RC (2008)
- The art of modelling; PE&RC (2008)

Laboratory Training and Working Visits (4.5 ECTS)
- Biofuel crops and sustainability issues in Mozambique; Faculdade de Agronomia e Eng^{a} Florestal, E. Mondlane University, Maputo (2009)

Invited review of (unpublished) journal manuscript (2 ECTS)
- Journal of cleaner production: sustainability in Brazilian ethanol industry: results and gaps (2011)
- Energy: cropping bioenergy and biomaterials (2011)

Competence Strengthening / Skills Courses (1.5 ECTS)
- PhD Competence assessment; WGS (2007)
- Information literacy; WGS (2011)
- Scientific publishing; WGS (2011)
- Career assessment; WGS (2011)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.5 ECTS)
- PE&RC Day (2007-2011)
- PE&RC Symposium (2009)

Discussion Groups / Local Seminars and Other Meetings (5 ECTS)
- Statistics, maths and modelling in Production Ecology and Resource Conservation (2007-2008)
- Biofuels discussion group (2008-2011)

International Symposia, Workshops and Conferences (5.7 ECTS)

- F.O. Licht's 10th European Sugar Conference; Brussels (2007)
- 8th European IFSA Symposium; Clermont Ferrand (2008)
- Seminario Cientifico sobre Biocombustiveis; Maputo (2009)

Lecturing / Supervision of Practical's / Tutorials (1.5 ECTS)

- Practical mathematics L; 5 days (2008, 2009)

Supervision of MSc Students; 20 days

- Exploring feasible yields for cassava production for food and fuel in the context of smallholder farming systems in Alto Molócuè, Northern Mozambique

The research in this thesis was financially supported by Shell Global Solutions and Wageningen University. Shell Global Solutions did not play a role in the collection, analysis and interpretation of data.

Photo captions:

Cover: Center-pivot irrigated sugarcane in Mozambique, viewed from the air

Invitation: Center of a pivot irrigation system, Dombe, Mozambique

Before chapter 1: Plantation manager explaining to scientist, Dombe, Mozambique

p. 12: Spider in web with cassava plants in background, Bogor, Indonesia

p. 36: Sugarcane worker, Dombe, Mozambique

p. 72: Oil palm plantation, North Sumatra, Indonesia

p. 104: Black locust plantation on degraded mine soils, Brandenburg, Germany

p. 136: Newspaper fragments related to biofuels collected during the research