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Modelling greenhouse gas emissions and cumulative energy demand of energy crops in rotation using the Life Cycle Assessment approach – Challenges and potential solutions

A dissertation submitted to the

Faculty of Agricultural Sciences, Nutritional Sciences and Environmental

Management, Justus Liebig University Giessen,

for the degree of

Doctor of Agriculture (Dr. agr.)

Presented by

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Born in Bad Saarow, Germany

Gießen, 2017

With the consent of the Faculty of Agricultural Sciences, Nutritional Sciences and Environmental Management, Justus Liebig University Giessen

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Date of disputation: 12.06.2017

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II. Abbreviations

C	carbon
CED	cumulative energy demand
CFP	carbon footprint
CHP	combined heat and power plant
CO_2	carbon dioxide
eq	equivalent
EVA	Development and comparison of optimized cropping systems for the agricultural production of energy crops under varying site conditions in Germany
FFC	fossil fuel comparator
FQD	fuel quality directive
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
KEA	kumulierter Energieaufwand
LCA	life cycle assessment
MiLA	Model for integrated Life Cycle Assessment in Agriculture
MJ	Mega Joule
N	nitrogen
N_2O	nitrous oxide
NH_3	ammonia
NUTS2	Nomenclature des unités territoriales statistiques
RME	rape methyl ester
RED	renewable energy directive
SOC	soil organic carbon
SRREN	Special Report on Renewable Energy Sources and Climate Change Mitigation
THG-Emissionen	Treibhausgasemissionen

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1 General introduction

1.1 Background

Bioenergy production out of energy crops - a sustainable way of energy generation?

The ratified Paris Agreement from 2015 of the United Nations Framework Convention on Climate Change has once again confirmed the human influence on climate change and raises the pressure on the governments to improve and extend their renewable energy policies and their effort to reduce greenhouse gas (GHG) emissions by replacing non-renewable fossil fuels with renewable energy sources (United Nations, 2016). The use of biomass for energy production has been promoted as an environmentally friendly and energy-efficient way for heat, electricity and fuel production compared to fossil fuels. A well-considered expansion of bioenergy production can improve the sustainability of energy generation by reducing GHG emissions and by helping to secure energy supply (European Commission, 2009b).

Biomass for the supply of bioenergy can be obtained from fuelwood, crop residues and dedicated energy crops. The production of energy crops has significantly increased in recent years (Allen et al., 2014). For example in Germany in 2015, 13% of the total arable land was used for energy crop cultivation and 7.3% (1.4 million hectares) alone as biomass feedstock for anaerobic digestion (FNR, 2016).

Energy generation from energy crops has been promoted as “GHG emission neutral” since the combustion of the biomass releases the same amount of carbon dioxide (CO_2) that was captured by the crop during growth assuming a closed CO_2 cycle. However, energy crop production cannot be considered as CO_2 neutral over its whole production chain, since GHG emissions occur during crop cultivation through production and use of fertilizer, pesticides and farming machinery (Cherubini et al., 2009). Agricultural management practices have a considerable effect on the amount of GHG emissions from energy crop production and, correspondingly, on the entire biomass energy production chain (Blengini et al., 2011; Davis et al., 2013). Consequently, agriculture, including energy crop cultivation, holds significant potential for sustainable energy production, including GHG emissions mitigation.

However, in the last years, also critical voices have been raised as in the IPCC Special Report 2012 on Renewable Energy Sources and Climate Change Mitigation (SRREN report, Edenhofer et al., 2012) stating that energy crop production can cause environmental problems. A rush into energy crop production can have substantial disadvantages for biodiversity, water and food supply. In the case of Germany, the dynamic expansion of biogas production, the application of legal regulations as well as the pressure for resource-efficient farming caused a trend to maize cultivation in short rotations up to monoculture. Such practices result in diversification losses of crop rotations which can generate potential environmental damages such as soil damage through soil erosion or soil compaction, or an increased risk of nutrient leaching (European Environment Agency, 2007).

In the future, the demand for arable land for food, feed, chemical, and energy production will further increase, consequently it is important to prioritize energy cropping systems that are the most energy efficient with regard to the land area used and potential for high GHG emission reduction relative to fossil fuels (Börjesson and Mattiasson, 2008). As a result, there is a growing demand for farmers, driven by political and societal pressures, to implement sustainable cropping systems in the context of energy efficiency and GHG mitigation options. But on the other hand, establishing new cropping systems comprises agronomic, ecological and economic uncertainties and risks for farmers. Hence, there is a growing demand for scientific research, long-term experiments on energy crop systems and new modelling approaches to provide knowledge and advice for sustainable energy crop management (Edenhofer et al., 2012; Leopoldina, 2013).

Energy crops are agricultural crops solely cultivated for energy-related use. Several food crops (e.g. maize or sugar beet) can also be grown as energy crops if they have high yields and, preferably, a low demand for agrochemical inputs (Cherubini et al., 2009). Their cultivation can differ in comparison to traditional crops in terms of sowing and harvesting dates, cultivation management, e.g. increased fuel use for the whole plant harvest, tillage frequency, and fertilizer quantities as well as the use of by-products, such as digestate (Cherubini et al., 2009; Rehl et al., 2012). These special characteristics of energy crop cultivation can significantly influence the GHG emissions. Unfortunately, these special characteristics are often disregarded in available assessment tools for GHG emissions. Either these tools are not specific enough to capture farm-level analysis, or they do not take into account aspects of cultivation and plant type specific to energy crops (Peter et al., 2017b).

Crop rotations, the sequence of crops grown on the same field, are part of the current agricultural practice. Crop rotation design influences the cultivation management e.g. the amount of used fertilizer and pesticides, the length of cultivation period of the individual crops as well as the crop yield and correspondingly the amount of GHG emissions (Brankatschk and Finkbeiner, 2015). Often, studies from annual crops (Alluvione et al., 2011; Börjesson et al., 2015; Börjesson and Tufvesson, 2011) typically take only one vegetation period from seedbed preparation to harvesting into account. The influence of the previous crop on the assessed crop is often outside the system boundary. As a result, calculation systems leave out crop rotation effects, including all interactions between the previous crop and the assessed crop, such as nutrient carryover, reduction in the use of agricultural operating needs, different intensity and timing of farming activities. When looking at one vegetation period, it can be difficult to evaluate the exact nutrient supply, since each crop uses different amounts and sources of nutrients, including decomposing residues of the preceding crop, and may itself leave different residues on the field. Good farming practice uses an optimal fertilization plan including mineral and organic fertilizer, crop residues, and green manuring crops to provide the soil with an optimal nutrient amount and balance (Brankatschk and Finkbeiner, 2015). However, fertilization plans are often designed for a longer time period than one year. By disregarding this fertilization plan and the different nutrient uptake efficiency of each crop, the carryover of nutrients from one crop to the subsequent crop are neglected. This leads to a free-rider situation for crops that consume nutrients which were applied to and left over by the preceding crops. Consequently, the amount of GHG emissions and cumulative energy demand (CED) of the subsequent crop decreases, since the crop does not get charged for its true nutrient and fertilizer consumption (Brankatschk and Finkbeiner, 2015).

Long and diverse structured crop rotations can improve soil fertility, nutrient use efficiency and biodiversity as well as reduce the input of crop protection agents and increase yields (Zegada-Lizarazu and Monti, 2011). However, in the last year, there is a worldwide increasing trend to shorten crop rotations and to grow crops in monocultures (Bommarco et al., 2013). Especially in Germany, the rush into biogas production forced an unprecedented concentration and specialization in maize cropping, often in short rotations or monocultures. These agricultural trend is concerning, since it can lead to substantial environmental damages. Consequently, the key to sustainable energy crop management could be the implementation of diverse energy crop rotation along with improved resource-efficient management (Nemecek et al., 2015). Energy cropping offers various options for the diversification of agricultural land use, such as the introduction of new crops, altered harvest and sowing dates, digestate application as fertilizer and the renaissance of perennial fodder crops. But in practice, maize is still the dominate crop for biogas production, since there are uncertainties by the farmer concerning the benefit of new crops and new designed cropping systems.

At 2005 in Germany, a long-term energy cropping project named „Development and comparison of optimized cropping systems for the agricultural production of energy crops under varying site conditions in Germany", short EVA (Glemnitz et al., 2015), was initiated to reduce uncertainties regarding energy crop cultivation and to provide more reliable and scientific based information for farmers and politicians. The aim of the project was the development of regionally adapted solutions for the economically successful, resource-efficient and environmentally sound production of energy crops in rotations. Additionally, suitable agricultural alternatives to the dominant cultivation of maize were investigated. This project has been carried out in eight regions across Germany, evaluating different energy crop rotations for biogas production in extensive field trials. The experimental sites differed in their main agricultural profile, regional geomorphological and bioclimatic conditions. A major aspect of the EVA project was the assessment of different environmental and economic indicators of the various tested energy crop rotations (Glemnitz et al., 2015).

This dissertation was developed as part of the EVA project that focused on the development of regional adapted solutions for the energy-efficient and GHG emission friendly production of energy crops in rotations. The author's task was to develop a tool which was able to calculate the energy efficiency and GHG emissions from energy crop cultivation in rotation under consideration of site conditions, specification of energy crops and crop rotation effects. Furthermore, the tool should not only be used for the evaluation of the EVA project crop rotation field experiments, but also by farmers and scientists to develop regional adapted sustainable energy cropping systems.

1.2 Current approaches to sustainable energy crop management assessment

In order to cope with the challenges of sustainable energy crop management, appropriate assessment tools are needed to detect GHG mitigation options and energy efficient systems. Different environmental assessment approaches are available for the evaluation of agricultural production systems. The most widely used approach is Life Cycle Assessment (LCA) defined by ISO Standards 14040 (2006) and 14044 (Buratti and Fantozzi, 2010; ISO 14044, 2006).

1.2.1 Life Cycle Assessment and Carbon Foot Print

LCA is defined as a method for compiling and evaluating all inputs, outputs, and the potential environmental impact of a production system throughout its life cycle. It enables the user to measure and quantify the environmental impacts of a product. Furthermore, it helps to identify hot spots where the most significant impacts occur, enabling the user to develop strategies for improving the product's environmental performance (ISO 14040, 2006). According to Buytaert et al. (2011), LCA is the most suitable assessment tool to assess emissions from bioenergy production systems, especially using the specifications for GHG emissions, the Carbon Footprint (CFP).

The CFP approach defined by ISO Standard 14067 (ISO 14067, 2013) provides, in addition to the LCA guidelines, requirements and guidelines for the quantification and communication of GHG emissions in a production chain. A considerable number of calculators are available that apply the CFP approach to calculate GHG emission from agricultural products (Colomb et al., 2012, 2013; Denef et al., 2012). These calculators differ in terms of system boundary (processes included), scales (area and time) and methods used to calculate emissions during crop cultivation.

There are also various case studies that use the CFP approach to assess the GHG emissions of biomass energy production. Cherubini and Strømman (2011) reviewed these case studies and the CFP assessment methods used. They figured out, that there are wide ranges and uncertainties in bioenergy CFP case studies due to differences in methodological assumptions (e.g. different reference systems, the database used, functional units, and allocation procedures) and the many variables involved in this calculation (e.g. selection of system boundaries, including land use change and accounting for field emissions from different fertilizer types and crop residues). Some of these key parameters regarding agricultural processes (e.g. field emissions) are still not well understood and depend heavily on local and climate conditions (Cherubini and Strømman, 2011).

Furthermore, Edenhofer et al. (2012) pointed out in the SRREN report, that the GHG emissions mitigation potential from energy crop production is dependent on site conditions, crop cultivation management (including crop rotation and use of their effects) and crop type. Consequently, all these aspect should be considered in a CFP tool for energy crop cultivation assessment.

1.2.2 Methodologies to account for land-based GHG emission

The IPCC guidelines for National GHG Inventories for the Agriculture, Forestry and Other Land Use sector (IPCC, 2006) provides three calculation pathways, called Tiers, to account for land-based GHG emissions. The Tiers differ in their degree of complexity: Tier 1 is the least accurate methodology, though the simplest to use, as it provides equations and global default values; Tier 2 may use the same methodological approaches as Tier 1, but requires specific regional data and emission factors, while Tier 3 level methodologies are based on actual measurements or model simulations.

Using a higher Tier generally improves the accuracy of the inventory analysis and reduces uncertainty, but requires a higher amount and quality of input data. The estimation of GHG field emissions from fertilization and soil organic carbon (SOC) changes are challenging: at the regional level, the Tier 1 approach, based on default emission factors, insufficiently accounts for emission variability resulting from pedoclimatic conditions or management practices. However, approaches at regional or site specific level (Tier 2 and 3) are usually considered too complex to be practicable. Consequently, there is a demand for farmers, private businesses, and scientists for the application and validation of appropriate "medium effort" higher Tier methodologies, to address local issues with bioenergy and food sustainability and identify local mitigation potentials (Smith et al., 2012; Smith et al., 2007).

1.2.3 Important LCA indicators for the evaluation of energy crop cultivation

The potential for GHG emission and CED reduction relative to fossil fuels are the key drivers for promoting bioenergy production from energy crops by experts and politicians (Dressler et al., 2012). Consequently, it is a central issue for bioenergy production pathways to use energy efficiency and GHG emissions as a focal indicator to detect the most efficient production lines for the global energy supply, including sustainable energy cropping systems. Therefore, the assessment of energy crops using the LCA approach should focus on the impact categories of "climate change" and "CED".

The impact category "climate change" aggregates all GHG emissions that occur during the production process by using the indicator of "Global Warming Potential (GWP)" for a 100-year time frame following the IPCC 2013 guideline (Myhre et al., 2013). This guideline specifies the characterization factors to calculate the GWP expressed as kg CO_2 equivalent (eq) per unit.

CED comprises the total use of primary energy that is required during the production of the crop (VDI 4600, 1997). With help of the CED, it is possible to estimate the energy efficiency and the energy balance of the energy crop production as feedstock for bioenergy production compared to fossil fuels. Energy efficiency or energy return on investment (EROI) is the ratio between the sum of produced energy and the CED to produce this yield. Energy balance is calculated by subtracting the energy output from the energy input and is used to analyze and verify the transformation and use of energy resources of a production chain in detail.

1.3 Objectives and structure of the thesis

The thesis focusses on the development of a tool to calculate and analyze the GHG emissions and energy efficiency of energy crop cultivation in rotations. The publications on which this thesis is based investigated the challenges and special features of energy crop rotation modeling. Further objects were:

- To review currently available tools for GHG emission calculation from energy crop cultivation in rotation.
- Analyzing methods which are able to quantify GHG emissions from energy crop cultivation by taking into account the specific features of energy crop production, local management practices and crop rotation effects.
- To test the performance of the developed tool and show first results from the EVA project field trials evaluation.

1.3.1 Paper 1

The IPCC (2006) guidelines recommends taking all indirect (production of farming materials) and direct (field emissions) emissions occurring during the crop production into account, when calculating the CFP of crop cultivation. However, different methodologies are available to calculate GHG emissions and the selected method can have a significant impact on the CFP results. Especially the calculation of land-based GHG emissions from fertilization and soil carbon changes is very difficult but has a high impact on the total CFP study result. In the first paper (Peter et al., 2016) different methodologies to calculate GHG emissions based on the CFP approach were investigated. The aim was to detect a “readily-available” and “easy-to-implement” method to assess field emissions from fertilization and from SOC change consequent to crop management change for the inclusion into CFP assessment studies of agricultural products, in order to improve the accuracy of GHG emission estimates.

In this paper, methods which match these requirements were selected, choosing the Tier 2 method based on the Bouwman et al. (2002a,b) approach for estimating field emissions from fertilization and the Tier 3 method for SOC change assessment based on simulations with the RothC model (Coleman et al., 1997). The investigated methods have been applied to four case studies and compared with Tier 1 results and additionally with measurements, in order to test their performance. The measurements were used to confirm the validity of the tested models for the examined agro-ecosystem conditions. A further goal of the paper was to assess and compare the influence of the variability of regional inventory data on CFP results, depending on the adoption of Tier 1, Tier 2, or Tier 3 assessment methods.

The outcomes of this paper demonstrated that the development of user-friendly, crop-specific tools underpinning these modeling approaches could efficiently increase the usefulness of CFP for agricultural sustainability assessment at farm and regional landscape level.

The paper was produced in collaboration with the Italian PhD student Angela Fiore. All calculations, tables and figures included in the manuscript regarding the land-based GHG emissions from SOC change were prepared by Angela Fiore. The other half of the manuscript including preparation of the text, tables and figures as well as the publication process were done by the author of this thesis. Measurement data from the field trials in Germany were provided by Ulrike Hagemann and her team. Claas Nendel, Ulrike Hagemann and Cristos Xiloyannis critically reviewed the manuscript before submission and were included in discussions during the development process of the manuscript.

1.3.2 Paper 2

The aim of the second paper (Peter et al., 2017b) was to review currently available calculators for GHG emissions assessment from crop production and their ability to take the specific features of energy crop production, crop rotation effects, site conditions and farm specific management practices into account. During the review process 44 environmental assessment calculators for agricultural products were found, but only 18 calculators were capable of assessing GHG emissions from energy crop cultivation following the IPCC guidelines and using the LCA approach.

Additionally, only seven out of 18 reviewed calculators can calculate GHG emissions from energy crop rotations but none of these calculators is able to consider actual crop rotation effects as nutrient carryover, reductions in the use of agricultural operating needs, or the sequence and composition of crop rotations. However, CFP approaches should take more the wide range of crop rotation techniques into account since crop rotation design and the diversification of crop rotation patterns offer options to reduce GHG emissions in agricultural cropping systems (Nemecek et al., 2015). So far, no agreement has yet been achieved about whether and how crop rotation and their effects are to be included in CFP via a uniform approach. This may be due to both a lack of methodological guidance to account for crop rotations and a lack of focus on the agronomical specifics of crop rotation systems.

The review of the calculators, the preparation of text, tables and figures was done by the author alone. The development of the manuscript structure including the choice of criteria for the evaluation of the calculators was done in a joint discussion and approval process with both co-authors Katharina Helming and Claas Nendel. Both co-authors were also critically reviewing the manuscript before submission.

1.3.3 Paper 3

To overcome the shortcomings of available CFP tools for the assessment of GHG emission of crop rotations including energy crops which were detected in the second paper (Peter et al., 2017b), the author developed a new tool called “Model for integrated Life Cycle Assessment in Agriculture”, short MiLA. The tool calculates the GHG emissions and energy efficiency of energy cropping systems and takes into account all inputs and outputs related to crop management from the whole crop rotation on each field, and thus includes inter-crop relationships. Furthermore, differences in local agricultural management practices, pedoclimatic conditions, farming practices and farming technologies as well as energy crop specification are considered. In the third paper (Peter et al., 2017c), the newly developed MiLA tool was presented as well as the methods used for integrating crop rotations into LCA calculations. Furthermore, the tool was applied to a case study including two crop rotations in two different regions in Germany to demonstrate the performance of this approach on LCA results.

The preparation of the text, tables and figures of this paper were done by the author as well as the development and implementation of the MiLA tool. However, important data produced during the EVA project were integrated into MiLA. Project partners as the ATB Potsdam (Monika Heiermann and Christiane Herrmann) and the Justus Liebig University Giessen (Joachim Aurbacher, Peter Kornatz and Janine Müller) prepared these data. To acknowledge this hard work, they were made co-authors in this paper. Furthermore, all co-authors critically reviewed the manuscript before submission.

The MiLA tool, a Microsoft Excel®-based multivariate empirical tool, as well as the user's guide are freely available in English and German language and can be downloaded at http://communications.ext.zalf.de/mila.

1.3.4 Paper 4

In the fourth paper (Peter et al., 2017a) the MiLA tool was used to evaluate four crop rotations on eight sites across Germany in terms of their resource efficiency (area use, energy and economic efficiency) in order to derive options for sustainable energy crop management for biogas production. The area use and energy efficiency were calculated with the MiLA tool but the economic efficiency calculations were performed by a project partner at the Justus-Liebig University Giessen. This paper does not only demonstrate the performance of the MiLA tool but also presents a new approach to combine different indicators (from the MiLA tool and from other tools) to analyze the resource efficiency of agricultural production systems. Moreover, this paper critically evaluates if the design of crop rotations and regional adopted management practices are an appropriate steering option in land use management.

The author was responsible for 75% of the text, tables and figures the rest was done by Michael Glemnitz. The calculations of the indicators (area use and energy efficiency) were performed by the author. The calculation of the indicator "economic efficiency" was done by Janine Müller and Peter Kornatz. The statistical analysis was kindly performed by Michael Glemnitz. All co-authors were included in the development process of the manuscript and were critically reviewing the manuscript before submission.

In a follow up study, the integrative evaluation of the five standard EVA crop rotation were performed using multiple indicators which were classified to four main groups: agricultural feasibility; environmental impact; economic benefit; and resource efficiency (Glemnitz et al., 2015). The author provided modelling results performed with MiLA for the indicators: product related GHG emissions and energy efficiency. Although not part of this cumulative dissertation, this study not only demonstrated the performance of MiLA, but also the possibility to integrate the tool results in pursuing sustainability assessments.

2 Paper 1

Improving the accounting of field emissions in the carbon footprint of agricultural products: a comparison of default IPCC methods with readily available medium-effort modeling approaches

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Published in:

The International Journal of Life Cycle Assessment (2016) 21:791-805

Submitted: 29 May 2015; accepted: 4 February 2016; published online: 20 February 2016

Int J Life Cycle Assess (2016) 21:791–805
DOI 10.1007/s11367-016-1056-2

CARBON FOOTPRINTING

Improving the accounting of field emissions in the carbon footprint of agricultural products: a comparison of default IPCC methods with readily available medium-effort modeling approaches

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Received: 29 May 2015 / Accepted: 4 February 2016 / Published online: 20 February 2016

Abstract

Purpose The estimations of greenhouse gas (GHG) field emissions from fertilization and soil carbon changes are challenges associated with calculating the carbon footprint (CFP) of agricultural products. At the regional level, the IPCC Guidelines for National Greenhouse Gas Inventories (2006a) Tier 1 approach, based on default emission factors, insufficiently accounts for emission variability resulting from pedo-climatic conditions or management practices. However, Tier 2 and 3 approaches are usually considered too complex to be practicable. In this paper, we discuss different readily available medium-effort methods to improve the accuracy of GHG emission estimates.

Methods We present four case studies—two wheat crops in Germany and two peach orchards in Italy—to test the performance of Tier 1, 2, and 3 methodologies and compare the estimated results with available field measurements. The methodologies selected at Tier 2 and Tier 3 level are characterized by simple implementation and data collection, for which only a medium level of effort for stakeholders is required. The Tier 2 method consists of calculating direct and indirect N_2O, emissions from fertilization with a multivariate empirical model which accounts for pedo-climatic and crop management conditions. The Tier 3 method entails simulation of soil carbon stock change using the Rothamsted carbon model.

Results and discussion Relevant differences were found among the tested methodologies: in all case studies, the Tier 1 approach exceeded the Tier 2 estimations for fertilizer-induced emissions (up to +50 %) and the measurements. Using this higher Tier approach reduced the estimated CFP calculation of annual crops by 4 and 21 % and that of the perennial crop by 7 %. Removals related to positive soil carbon change calculated using the Tier 1 approach also exceeded the Tier 3 calculations for the studied annual crops (up to +90 %) but considerably underrated the Tier 3 estimations and measurements for perennial crops (−75 %). In this case, the impact of the selected Tier method on the final CFP results was even more relevant: an increase of 194 and 88 % for the studied annual crops and a decrease of 67 % for the perennial crop case study.

Conclusions The use of higher Tiers for the estimation of land-based emissions is strongly recommended to improve the accuracy of the CFP results. The suggested medium-effort methods tested in this study represent a good compromise between complexity reduction and accuracy improvement and can be considered reliable for the assessment of GHG mitigation potentials.

Keywords Carbon footprint · Crop management · Fertilizer field emissions · GHG accounting · Regional variability · Soil carbon change · Tier methodologies

Responsible editor: Ivan Muñoz

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1 Introduction

Agriculture accounts for one third of global greenhouse gas (GHG) emissions (Lal and Kimble 1997). If demand for food and biomasses continues to increase, annual GHG emissions from agriculture may increase proportionally, along with the vulnerability of agro-ecosystems to climate change (Xiong and Khalil 2009). However, agriculture also has a significant potential to reduce GHG emissions, as soils are the second largest carbon (C) sink after oceans (Lal and Kimble 1997). In general, there are three options for climate change mitigation in agriculture. First, GHG emissions can be reduced by improving the management of C and nitrogen (N) flows in agro-ecosystems. Second, increasing the level of temporary C storage through improved agricultural management practices can increase soil C sequestration. Third, the replacement of fossil fuels with renewable fuels such as residues from agricultural crop production also is possible.

During the last decade, the interest of companies and policy-makers in carbon footprint (CFP) as a supporting tool to assess the impact of food and biomass production on global warming processes and as a tool to design impact reduction plans has grown steadily.

Based on the completeness principle stated in ISO 14067 (2013), the most recent international reference standard about CFP, all GHG emissions and removals that provide a significant contribution to the CFP of the analyzed product system should be included in the study.

Although field emissions from fertilization and crop residue management (CO_2 and N_2O) can contribute considerably to the GHG balance of food and bioenergy products, they are often disregarded in CFP studies (Bessou et al. 2013). The same applies to CO_2 fluxes occurring due to changes in soil C stocks subsequent to crop management change (Brentrup et al. 2000; Petersen et al. 2013), which, following the ISO 14067 (2013), should be included in CFP if not already calculated as part of land use change.

For the accounting of field emissions at country level, the IPCC guidelines for National GHG Inventories (IPCC 2006a) provide, in the fourth volume dedicated to Agriculture, Forestry and Other Land Use sector (AFOLU), three calculation pathways (Tiers) characterized by different degrees of complexity: Tier 1 includes low-accuracy methodologies, which can be applied by using the default emission factors provided by the IPCC; Tier 2 methodologies require the use of national emission factors reflecting local pedo-climatic characteristics; finally, Tier 3 methodologies are based on model simulations or in situ measurements. Tiers 2 and 3 are referred to as the higher Tiers in the following text.

At present, the most common practice is using Tier 1 methodologies for field emission calculation in life cycle assessment (LCA) and carbon footprinting of food and energy crops. However, Tier 1 methodologies are intended for use at large spatial scales, and they can generate substantial errors in predictions at finer spatial scales. In fact, at regional and subregional levels, Tier 1 methods are not always sufficiently accurate to account for the spatial variability of GHG emissions due to different soil, climate, and management practices. Conversely, higher Tiers (Tiers 2 and 3) are usually considered too complex and time-consuming to be practicable in the development of LCA studies. Therefore, the IPCC guidelines recommend using a higher Tier for the key emission categories and provide decision trees to support identification of the most suitable Tier.

There is an urgent need for the application and validation of appropriate higher tier methodologies at farm, project, or plantation scales, to address local issues with bioenergy and food sustainability and identify local mitigation potentials (Smith et al. 2007; Smith et al. 2012).

The aim of the present paper is to provide to CFP practitioners higher Tier methods “readily available” and “easy to implement” (with a medium effort) to assess field emissions from fertilization and from soil carbon change consequent to crop management change for the inclusion into CFP assessment studies of agricultural products. We selected higher Tier methods which match these requirements, choosing the Tier 2 method based on the Bouwman et al. (2002a, b) approach for estimating field emissions from fertilization and the Tier 3 method for soil organic carbon (SOC) change assessment based on simulations with the Rothamsted C (RothC) model (Coleman et al. 1997); both methods are described, respectively, in Sects. 2.2 and 2.3. These methods have been applied to four case studies and compared with Tier 1 results and with measurements, in order to test their performance. The measurements were not intended to be used as Tier 3 approach, because they are not always readily available for LCA practitioners, but could be used to confirm the validity of the model for the examined agro-ecosystem conditions.

A further goal of the paper is to assess and compare the influence of the variability of regional inventory data on CFP results, depending on the adoption of Tier 1, Tier 2, or Tier 3 assessment methods. The examined case studies, two winter wheat crops in Germany and two peach orchards in Italy, are described in Sect. 2.1. The case studies were deliberately selected to represent different soil characteristics, climate conditions, and crop types (annual and perennial) in order to test how the different methodologies handle this variability.

2 Materials and methods

2.1 Field experiments

Four field trials were selected based on crop type (annual crops and perennial crops), soil, and climate conditions. Characteristics of all sites are presented in Table 2. While we assumed that no land use change occurred in our case studies, there were confirmed changes of the crop management practices.

The two winter wheat crops were cultivated at two different sites in Germany (sites 1 and 2) and for 2 years (2011–2012 and 2012–2013). They were sown after plowing at the end of September and harvested the following summer (end of June). Both cropping systems were rain fed. Site-specific rates of N fertilization were calculated based on field-sampled soil mineral N content in springtime and crop-specific target values from the official recommendation system, which reflects expected crop N uptake during the season, and split into 50 % mineral (calcium ammonium nitrate applied in cultivation period 2011–2012: 101 kg N ha^{-1} at site 1 and 73 kg ha^{-1} at site 2 and in period 2012–2013: 105 kg N ha^{-1} at site 1 and 75 kg N ha^{-1} at site 2) and 50 % organic N fertilizer (digestate applied in cultivation period 2011–2012: 135 kg N ha^{-1} at site 1 and 137 kg ha^{-1} at site 2 and in period 2012–2013: 98 kg N ha^{-1} at site 1 and 108 kg N ha^{-1} at site 2) (Table 2). At sites 1 and 2, straw management was changed in the first year of the assessment period (2011). Before the change, all straw was taken off the field to be used for energy production or animal feeding. After the change, it was left on the field and incorporated into the soil. Data on C inputs from straw and applied digestate were direct field data, and C inputs from roots (C_r) and root exudates (C_e) were calculated based on yield (Y) data, harvest index (HI), and shoot to root ratio (S:R), using the following equations (Farina et al. 2013):

$$C_{\mathrm{r}} = \left(\frac{Y}{\mathrm{HI}\cdot S/R}\right)\cdot 0.45 \tag{1}$$

$$C_{\mathrm{e}} = 0.09\cdot\left(\frac{Y}{\mathrm{HI}}\right)\cdot 0.45 \tag{2}$$

At site 1, the mean yearly yield of the two considered crop cycles (2011–2012, 2012–2013) was 6.8 t (dry matter grain) and 3.9 t (dry matter straw), while at site 2, it was 8.0 t (dry matter grain) and 5.4 t (dry matter straw). Tier 1 and Tier 2 estimates were compared with measured GHG emissions, originating from a joint research project investigating GHG emissions from energy crops fertilized with fermentation residues. In situ measurements of N_2O and NH_3 emissions were conducted from sowing of winter wheat until the sowing of the subsequent crop for the crop years 2011–2012 and 2012–2013.

Periodic N_2O measurements were conducted one to two times per month out at three permanently installed soil collars (0.75×0.75 m) at each site, with higher resolution following fertilization events. Emissions of N_2O were measured by taking four consecutive 100-ml gas samples from static non-flow-through non-steady-state opaque chambers (closure time 60 min, vol. 0.296 m^3; Livingston and Hutchinson 1995) and subsequently analyzed using a gas chromatograph. N_2O fluxes were calculated based on the ideal gas law using the R package “flux 0.2-2” (Jurasinski et al. 2012), using linear regression analysis with stepwise backward elimination of outliers. The calculated flux rates were then averaged for the respective measurement day and linearly interpolated to determine total N_2O exchange.

Ammonia volatilization was measured for 2 to 5 days immediately following fertilization using the open dynamic chamber Dräger-tube method of Pacholski et al. (2006). Four stainless steel chambers were placed on pre-installed stainless steel rings (104 cm^2). Chamber air was pumped through the system with a constant air flow (1 L min^{-1}), and the actual NH_3 concentration in the chamber air was directly determined in vol. ppm. Cumulative NH_3 losses were calculated by linear interpolation between measurements and in the end were summarized.

The perennial crop field trials were conducted at two peach orchards (sites 3a, 3b), located in Metapontino, the southern area of the Basilicata region in Italy, which is devoted to fruit production. They are characterized by the same rootstock and the same training system of canopy, as well as similar pedo-climatic conditions, orchard layout, and management regime. The orchard at site 3a was planted in 2006 and the orchard at site 3b in 1996 and removed after 15 years in 2011. In both orchards, a management change occurred in the eighth year after plantation (2013 for site 3a, 2004 for site 3b) from conventional to sustainable management. The conventional management regime consisted of soil tillage (site 3b), chemical weed control (site 3a), and the burning of pruning material. The sustainable management regime introduced some innovative elements, including no tillage (site 3b), mechanical weed control (grass cover mowed twice per year), the chipping of pruning residues to be left in the field, and the provision of 10 t of compost per hectare per year.

The life cycle of a fruit orchard can be divided into three main stages: the young stage characterized by low yield and grow of permanent structures, the mature stage characterized by stable high yield, and the senescence stage characterized by the decrease of yield. The farmers can decide in which stage the orchard will be removed and replanted, and usually, it happens at the end of the mature stage (Cerutti et al. 2010). For peach trees, the young stage lasts 2 years and the mature stage about 13 years. The amounts of C added to the soil during the mature stage of the orchards (i.e., as crop residues and organic fertilizers) were derived from direct field measurements: figures regarding the dry matter of senescent leaves, pruning residues, thinned fruit, and grass cover were retrieved from field sampling performed at site 3b from 2004 to 2010 (from 8th to 14th year after establishment) and at site 3a in 2013–2014 (8th and 9th year after establishment), assuming a mean C content of 0.45 t C per ton of dry matter, and a grass cover below-ground contribution of 20 % (Celano et al. 2003). The C input during the young stage of the orchard (senescent leaves and pruning material) was retrieved from an experiment performed in a peach orchard located in the same area, with same rootstock, same training method, comparable management regime, and adapting data to the different tree density per hectare (Sofo et al. 2005). The C input from root turnover was calculated as 30 % of the trees' above-ground biomass turnover (senescent leaves, pruning material, and fruit yield) for the first 3 years and as 25 % for all other years (Buwalda 1993).

Data collected from site 3b were used to compare SOC change estimate after crop management change, performed with Tier 1 and Tier 3 methods with measurements of soil C content, performed at the beginning of the experimental period (2004) and after 7 years of management shifted to sustainable practices (2010). Each time, 30 soil samples at 30-cm depth were taken from a 1-ha field at different distances from the tree row line. SOC was determined by the potassium-dichromate oxidation procedure (Heanes 1984). Total per-hectare C stocks in the topsoil (0–30 cm) were calculated as the weighted average of SOC measured in the 30 soil samples. For site 3a, the complete CFP was calculated using primary data from the field logbook about the amount of productive inputs used to perform all agricultural operations during the orchard establishment, as well as the young and mature phase of the orchard life cycle; the SOC change of site 3a was also estimated using Tier 1 and Tier 3 methods.

2.2 Scope of the CFP assessment

GHG emissions of sites 1, 2, and 3a were calculated and included in the CFP accounting according to ISO standards 14040 (2006), ISO 14044 (2006), and ISO 14067 (2013). Our selected functional unit was not the unit of product, but the surface unit of the cropland (1 hectare), since the focus of the study was not on the environmental efficiency of the production, but on the methodology comparison (Cerutti et al. 2015). In fact, the results of Tier 1 methods are usually expressed as emissions per unit of hectare, as their first application is intended to analyze emissions from national crop production. Therefore, the results of higher Tiers and the field measurement were calculated per hectare size, in order to become comparable with Tier 1 values. However, it is important to highlight that for global issues such as food security and global warming impact of food production, GHG emission assessment and mitigation potential per unit product are often more useful than the absolute emissions per unit area (Bennetzen et al. 2012). Since CFP calculations per unit of product can take into account the variability related to yield differences, they are particularly suitable for comparative CFP studies of the same product cultivated in different locations or with different farming practices. System boundaries were fixed from cradle to farm gate, starting with production of all productive inputs, e.g., seeds, fertilizers, pesticides, agricultural machinery, and fuels (indirect emissions), and ending with the harvest of the crop, encompassing all emissions along the production chain. Crop cultivation and processing of agricultural products can lead to multiple outputs, e.g., straw and grain from cereal harvesting or biogas and digestate from anaerobic biomass digestion. In CFP calculations, there are different methods to allocate the process emissions to different products (Benoist et al. 2012). Manure and digestate are productive input for the crop life cycle and residues (by-products) for the livestock and bioenergy life cycle. They are re-used in the same form at field (non-treated). As Rehl et al. (2012) stated, there are many ways to allocate organic fertilizer but the most logical one is the economic value. However, usually, manure and digestate are not sold by the farmers; therefore, it is difficult to determine prices because it does not exist. We followed the approach by Rehl et al. (2012) and used the open-loop allocation procedure (ISO 14067 2013, Sect. 6.4.6.3 "Allocation procedure for reuse and re cycling") and the economic indicator with the market value and assumed that the by-products are given away free of charge. Emissions from storage of organic fertilizer and on field (application of fertilizer) were considered in the crop cultivation process where these emissions occurring. The agri-footprint database (Blonk Agri-footprint BV. 2014) also considers organic fertilizer (digestate and animal manure) as residual products of biogas and animal production system, so it does not include any emissions of the biogas or animal production system, in order to avoid double counting. Conversely, for compost, the production phase was entirely included within the boundaries of the study, as it is not reused in the same form (organic urban waste), but it is the outcome of a recycling process, performed for agricultural purpose only. For the peach case study 3a, the whole life cycle of the orchard (site 3a) was included within the time boundaries, from orchard establishment until removal (15 years). This approach is coherent with the most common practice of LCA sectoral studies about fruit production from perennial tree crops (Cerutti et al. 2010; Milà i Canals and Clemente Polo 2003). The soil preparation prior to orchard establishment, the establishment and removal phase, comprising the production, and the disposal phases of materials constituting the support structure (concrete and aluminum poles, steel wire, and concrete blocks) were included in the boundaries, extrapolating data about machinery operations for the removal phase and end-of-life of trees' permanent structure from farmers' experience.

For the winter wheat case studies, direct data from two crop cycles were considered (2011–2012 and 2012–2013).

Inventory data on the amount of productive inputs (fertilizers, pesticides, fuels, machinery) were mostly retrieved directly from our on-farm experiments. GHG emissions related to the production of these productive inputs were based on the Ecoinvent database v.2.2 and v.3.0 (Ecoinvent 2013). The calculation of CO_2, CH_4, and N_2O emissions from diesel combustion was based on IPCC Tier 1 (2006b).

The considered impact category was the global warming potential (GWP)—100 years with the characterization factors from the CML 2001 method corresponding with IPCC 2007 (Ecoinvent 2013).

CFP calculations were divided into three main parts: (i) field emissions from fertilization, (ii) soil C stock change subsequent to crop management change, and (iii) all other emissions from agricultural operations. The consequences of methodological choices were analyzed by comparing the CFP results based on Tier 2 and Tier 3 approach with the reference CFP results based on IPCC Tier 1 default accounting methods.

2.3 Methodologies for the assessment of fertilization-induced field emissions

The simple IPCC Tier 1 method (IPCC 2006a) for calculating direct emission of nitrous oxide (N_2O) from managed soils simply takes into account 1 % (uncertainty range 0.3–3 %) of the anthropogenic N inputs (mineral fertilizer, organic amendments, and crop residues) at the field level. Indirect N_2O emissions take place through two pathways. The first pathway is volatilization of N as NH_3 and NO_x and their deposition onto soil and water, accounted by IPCC Tier 1 method as 10 % (0.3–3.0 % uncertainty) of kilogram N applied from mineral fertilizer and 20 % (0.5–5.0 % uncertainty) from organic amendments expressed as kilogram NH_3-N + NO_x-N. Only 1 % of these emissions from atmospheric deposition of N volatilized from managed soils are accounted as indirect N_2O-N emissions. The second pathway of indirect N_2O emissions is leaching and runoff of N from fertilizer application and crop residues, accounted by IPCC Tier 1 method only for regions where leaching and runoff occur as 30 % (10–80 % uncertainty) expressed as kilogram N. Only 0.75 % of these emissions leaching and runoff are accounted as indirect N_2O-N emissions. This Tier 1 approach completely disregards any impact of crop type, fertilizer type, management system, and local climate conditions on the GHG emissions except for the calculation approach for leaching and runoffs which takes the regional risk for leaching into account. However, considering all or some of these agricultural characteristics in the calculation of N_2O, NO, and NH_3 emissions would more accurately reflect the heterogeneity of the environmental and management conditions occurring in agriculture. This would better allow the identification of local GHG emission hotspots and to evaluate options of reduction.

We chose a Tier 2 level modeling approach used by Bouwman et al. (2002b) to determine direct and indirect N_2O emissions and the approach of Bouwman et al. (2002a) for NH_3 volatilization. A Tier 3 level modeling approach for estimating field emissions from fertilization was not tested, since to our knowledge, it does not exist at present any approach that matches our requirements to be readily available and easily implementable by the user. Both tested Tier 2 approaches have been validated on a large global dataset from measured agricultural field emissions encompassing 846 N_2O measurements from 126 studies, 99 NO measurements from 29 studies, and 1667 NH_3 measurements from 148 studies (Bouwman et al. 2002a; Bouwman et al. 2002b). These methods should therefore demonstrate better performance at the local scale and under different agricultural management systems than the Tier 1 methods, thus reducing the uncertainty of the estimates with respect to the global emission factors used in Tier 1 assessments (IPCC 2006a). However, implementing the Tier 2 approach after Bouwman et al. (2002a, b) requires more detailed data, as shown in Table 2. The multivariate empirical model of Bouwman et al. (2002b) classifies the parameters influencing N_2O and NO emissions into specific categories for each factor. For N_2O, the significant parameters are fertilizer type and application rate, crop type, soil texture, SOC, soil drainage, soil pH, and climate type, but only data regarding fertilizer type and application rate, SOC, and soil drainage are needed to calculate the NO emissions. The climate condition has less influence on the NO emissions, since these emissions appear to be more concentrated during the crop-growing season than N_2O emissions. During the growing season, climate condition varies less between climate types than during other seasons (Bouwman et al. 2001). The model for ammonia NH_3 emissions (Bouwman et al. 2002a) is similar to the Bouwman et al. (2002b) approach, but the significant parameters are fertilizer type, fertilizer application rate and method, crop type, soil texture, soil cation exchange capacity (CEC), soil pH, and climate type. The amount of indirect emissions can be converted to N_2O-N by multiplying the NO-N and NH_3-N emissions with the default value 0.01 (based on IPCC 2006a). For reporting purposes, the total N_2O-N emissions can be converted to N_2O by multiplying the kilogram of N_2O-N by 44/28 (ratio of molecular weight of N and N_2O). For the NH_3 emissions induced by organic fertilizers (i.e., slurry and manure, digestate, poultry manure), we used the more detailed model approach by KTBL (2009) for organic fertilization to calculate NH_3-N emissions, with NH_3 volatilization depending on fertilizer type, fertilizer application rate and method, daily temperature, and a binary variable indicating whether the fertilizer was incorporated within 1 h (Table 1). CO_2 emissions from the application of urea and liming were calculated based on Tier 1 IPCC (2006a) factors.

2.4 Methodologies for the assessment of emissions from soil C stock change

The default international practice about GHG accounting in the AFOLU sector (Tier 1) assumes that the soil carbon content is in equilibrium (steady state) when the last crop management change or land use change occurred more than

Table 1 Ammonia-volatilization rate (based on KTBL 2009)

Fertilizer type	NH_3 volatilization in % of the applied NH_4-N				Application method-related reduction of NH_3 emission in %				
	5 °C	10 °C	15 °C	25 °C	Drag hose (uncovered)	Drag hose (covered)	Drag shoe	Manure chisel plow	Incorporated within 1 h
Cattle slurry Digestate (thickened)	30	40	50	90	8	30	30	90	80
Pig slurry Digestate (liquid)	10	20	25	70	30	50	60	90	80
Slurry			20						
Mature manure			90						
Poultry manure			90						

20 years before the assessed time frame. In this case, it is assumed that C outputs as CO_2 emissions from organic matter decomposition equal the C inputs from organic material added to soil. As soon as the land use or management regime (tillage, soil cover, carbon input level, irrigation) changes, C input and outputs become imbalanced and either C emissions or C sequestration will occur. It may take several decades before the system returns to steady state at a new equilibrium, and the default time set by Tier 1 method is 20 years. To include the soil C change into CFP assessment, different methods are available. We tested and compared methodological approaches from Tier 1 and Tier 3, since Tier 2 national emission factors for SOC change are not always “ready available” for LCA practitioners and other existing models for both C and N cycle in soil do not match our requirement for “medium-effort modeling approaches.”

The simple Tier 1 method, explained in Chapter 5 of Volume 4 (cropland remaining cropland) of the IPCC guidelines (IPCC 2006a), requires the application of Eqs. 3 and 4. The soil organic C reference (SOC_{ref}) under native vegetation must be assigned based on six available soil types (high activity clay, low activity clay, sandy, spodic, volcanic, wetland) and nine climate regions (boreal, cold temperate dry, cold temperate moist, warm temperate dry, warm temperate moist, tropical dry, tropical moist, tropical wet, tropical montane). Three relative stock change factors further describe the site: (i) F_{LU} is related to land use (long-term cultivated, paddy rice, perennial/tree crop, set aside), (ii) F_{MG} characterizes the tillage regime (full, reduced, no tillage), and (iii) F_I describes the carbon input level (low, medium, high without manure, high with manure). These factors come with individual error ranges (between ±5 and ±50 %) and have to be defined for conditions both before and after the change in management or land use occurred.

Using Eq. 3, the soil organic carbon content before ($SOC_{initial}$) and after (SOC_{final}) the change can be calculated as follows:

$$\mathrm{SOC_t} = \mathrm{SOC_{ref}} \times \mathrm{F_{LU}} \times \mathrm{F_{MG}} \times \mathrm{F_I} \tag{3}$$

The difference between the final (new equilibrium, SOC_{final}) and the initial C stock (old equilibrium, $SOC_{initial}$) indicates the soil C stock change in the topsoil (0–30 cm) over a period of 20 years, expressed as tons of C per hectare. This amount can be converted to atmospheric CO_2 stored in or emitted from the soil by multiplying the tons of C by 44/12 (ratio of molecular weight of CO_2 and C):

$$\Delta\mathrm{SOC}\ \left[\mathrm{t\ C\ year^{-1}}\right] = \left(\mathrm{SOC_{final}}\text{-}\mathrm{SOC_{initial}}\right)/T \tag{4}$$

where

T = default time period for transition between equilibrium SOC values, 20 years

The selected Tier 3 methodology consists of a simulation of the soil C turnover using the RothC model (26.3); Coleman et al. 1997). To run the simulation, the model requires inputs regarding the soil characteristics (i.e., clay content, considered depth horizon, initial SOC), climate data (i.e., monthly average temperature, cumulative evapotranspiration, and rainfall), and monthly soil C input (in tons of C per hectare), expressed as net primary production (NPP). The output of the RothC simulation of soil organic matter decomposition process is the dynamic of C fluxes between soil carbon pools (resistant and decomposable plant material, microbial biomass, and humified organic material) and the inferred CO_2 emissions in atmosphere. The RothC simulations were run for different time perspectives (T=20, 50, 100 years) and compared with the default Tier 1 result (T=20 years). Equation 4 was used as well to include soil C change in the CFP case studies using a Tier 3 method.

Before running the simulation, the initial value of the four carbon pools (decomposable, resistant, biological, humus) constituting the SOC in the RothC model was simulated using the following procedure (initialization procedure):

The C stock of each C pool was set at 0 t C ha^{-1}. The simulation was then run to equilibrium using the C input estimated for the management regime before management change. The equilibrium values of the SOC pools were used as initial values for the simulation if the equilibrium obtained for total organic C (TOC) stocks matched the measured initial TOC; otherwise, the model was run in inverse mode to generate the required C input (CI_{req}), using the equation suggested by Mondini et al. (2012):

$$CI_{req} = CI_i \cdot \left(\frac{C_{meas} - IOM}{C_{sim} - IOM} \right) \quad (5)$$

where CI_i is the monthly C input used in the first equilibrium run, C_{meas} is the measured soil C stock to be matched, C_{sim} is the simulated soil C stock after the first equilibrium run, and IOM is inert organic matter, the small soil organic C compartment resistant to decomposition (with an equivalent radiocarbon age of more than 50,000 years), which, in absence of radiocarbon data, can be roughly estimated from total SOC using the equation provided by Falloon et al. (1998):

$$IOM = 0.049 \cdot TOC^{1.139} \quad (6)$$

With the required C input (CI_{req}), the model must be run again to equilibrium to obtain the initial value of the SOC pools.

The RothC model can only simulate heterotrophic respiration resulting from microbial decomposition of soil organic matter. However, the autotrophic respiration of plants is implicitly included as well, because the amounts of C inputs entered in the model are expressed as net primary production (NPP) of biomass, resulting from the balance between CO_2 absorbed through photosynthesis and CO_2 released through dark respiration.

The crop management changes examined in our four case studies concerned mainly the different amount of organic material returned or added to soil: In Table 3, the carbon input stock change factors selected to evaluate SOC change with Tier 1 method and the C input derived from direct field data used to implement the RothC simulation are summarized.

RothC can be considered as a reliable simulation tool of carbon turnover in soil for arable land in cool or temperate moist climates based on multiple validation campaigns (Coleman et al. 1997; Falloon and Smith 2002; Ludwig et al. 2007; Zimmermann et al. 2007), but there is a lack of model application to perennial crops (Bessou et al. 2013). Therefore, the results of RothC simulation were compared with available measurements just at site 3b and not at sites 1 and 2, due also to the unavailability of medium-long-term monitoring of SOC dynamic at these sites.

Table 2 summarizes all data required for the implementation of the four tested methodologies.

3 Results and discussion

As shown in Fig. 1, in all case studies, new SOC equilibrium after crop management change estimated using RothC model (Tier 3) was reached in more than 20 years, the default time period assumed in the Tier 1 approach. For site 1, the SOC change at equilibrium is much lower if calculated using Tier 3 approach than using Tier 1. The Tier 3 value is outside the range of uncertainty of the Tier 1 value (±51 %), resulting from the propagation of errors declared for each stock change factor in the IPCC (2006a) guidelines. For site 2, the equilibrium SOC change calculated using Tier 3 is also lower than Tier 1 but falls within the forecasted Tier 1 error (±51 %).

The Tier 1 SOC change estimate is the same for the two winter wheat case studies, as the same crop, soil (high activity clay (HAC)), climate zone (cold temperate moist), and management practices were investigated, and thus, no difference between the two sites is recognizable using the Tier 1 approach. In contrast, the curves resulting from the RothC simulation are very different, because site 1 is characterized by lower soil clay content and a moister climate, which leads to a slower rate of SOC rise due to the faster decomposition rate of soil C pools. Moreover, the different amount of straw added to soi1 as C input in the RothC simulations is higher at site 2 than at site 1 in the considered time period 2011–2013, which leads to different values of simulated SOC change. This difference in C input is not appreciable using Tier 1 method because it is only possible to choose between the qualitative C input levels “low,” “medium,” and “high” (with or without manure), as summarized in Table 3. Therefore, finer regional variation of climate, yield, and soil texture cannot be represented using Tier 1 methodology for SOC change estimates, in the case of a crop management change.

For sites 3a and 3b, the Tier 3 SOC change at equilibrium is much higher than the Tier 1 value and outside the forecasted error range of Tier 1 (±172 %). In the Tier 3 simulation, the succession of different peach orchard life cycles results in a fluctuation of SOC within the orchard life cycle due to the lower amount of crop residues during the establishment, the young phase, the senescence phase, and the removal of the orchard. The peak of SOC simulated at site 3a (Fig. 1) at the beginning of each orchard life cycle is due to the soil preparation with manure (60 t ha^{-1}). Moreover, for both orchards, the simulation reveals an overall increasing trend of SOC beyond the single orchard life cycle, if pursued with sustainable management practices.

As can be noticed in Fig. 1, the comparison of SOC change measurements with estimates at site 3b reveals that Tier 1 method underestimates the measured SOC change after 7 years of sustainable management practices of 9.73 t C ha^{-1}, while RothC simulation better represents the SOC increasing trend, with an overestimation of 6.6 t C ha^{-1}. Tier 1 C input stock change factors (Table 3) do not probably reflect the real growth of soil C input after the incorporation of crop residues, compost, and grass cover into the soil. RothC overestimation could be due to the lack of consideration in the simulation of soil condition variability across the orchard hectare: the

Table 2 Characteristics of experimental sites and comparison of data requirements by tested Tier methods

		Site 1	Site 2	Site 3a–3b	Data required to estimate			
					Field emissions from fertilization		Soil carbon change	
					Tier 1	Tier 2	Tier 1	Tier 3
Country Geographical location		Germany (south) 48° 59′ N	Germany (central) 51° 00′ N	Italy (south) 40° 14′ N; 16° 42′ E (site 3a)				
		12° 39′ E	11° 39′ E	40° 23′ N; 16° 42′ E (site 3b)				
Height above sea level (m)		431	247	16 (site 3a)				
				23 (site 3b)				
Crop	Crop type	Wheat[j]	Wheat[j]	Peach[k]		●	●	
	Amount crop residues (t DM ha^{-1} year^{-1})	3.9	5.4	6.8			Qualitatative	●
	C content crop residues (% DM)	45	45	45				●
Fertilization	Fertilizer type	CAN[a], digestate[b]	CAN[a], digestate[b]	ON[c], AS[d], NPK[e], CN[f], compost[g]		●		
	Method of fertilizer application	Broadcast, incorporated	Broadcast, incorporated	Broadcast		●		
	Fertilizer amount (kg ha^{-1})[h]	2012: 375[a], 30,400[b] 2013: 388[a], 33,000[b]	2012: 270[a], 35,000[b] 2013: 278[a], 32,000[b]	2400[c], 200[d], 370[e], 370[f], 80,000[g]	●	●		
	N content of fertilizer (%)	2012: 27[a], 0.45[b] 2013: 27[a], 0.3[b]	2012: 27[a], 0.39[b] 2013: 27[a], 0.34[b]	12.5[c], 21[d], 20[e], 20[f], 0.62[g]				
	C content of organic fertilizer (% FM)	2.5[b]	2.5[b]	40[c], 22.5[g]				●
Soil	Soil type (WRB classification)	Stagnic Cambisol (HAC)	Luvisol (HAC)	Eutric Cambisol (HAC)		●	●	
	Soil texture	Loamy sand	Silty clayey loam	Sandy loam		●		●
	Soil bulk density (g/cm^3)	1.7	1.5	1.5 (site 3a) 1.6 (site 3b)		●		●
	pH value	5.1	7.4	7.1 (site 3 a) 8.1 (site 3 b)		●		
	SOC before change	0.5	0.5	1.0		●		●
	Soil drainage	Good	Good	Good		●		
Climate	Climate region	Temperate	Temperate	Temperate		●	●	
	Precipitation (cumulative yearly in mm)[i]	957	582	525	●	●		Monthly value
	Temperature (yearly in °C)[i]	8.3	9.6	16.4		Specific days		Monthly value
	Evapotranspiration (cumulative yearly in mm)[i]	611	568	1262	●	●		Monthly value
Management	Tillage regime			Converted to no tillage during the experimental period		●	●	

[a] *CAN* calcium ammonium nitrate

[b] *digestate* fermentation of biomass from energy crops and animal slurry

[c] *ON* organic nitrogen fertilizer

[d] *AS* ammonium sulfate

[e] *NPK* nitrogen (N) + phosphorus (P) + potassium (K) compound

[f] *CN* calcium nitrate,

[g] Compost with 40 % mineralization efficiency

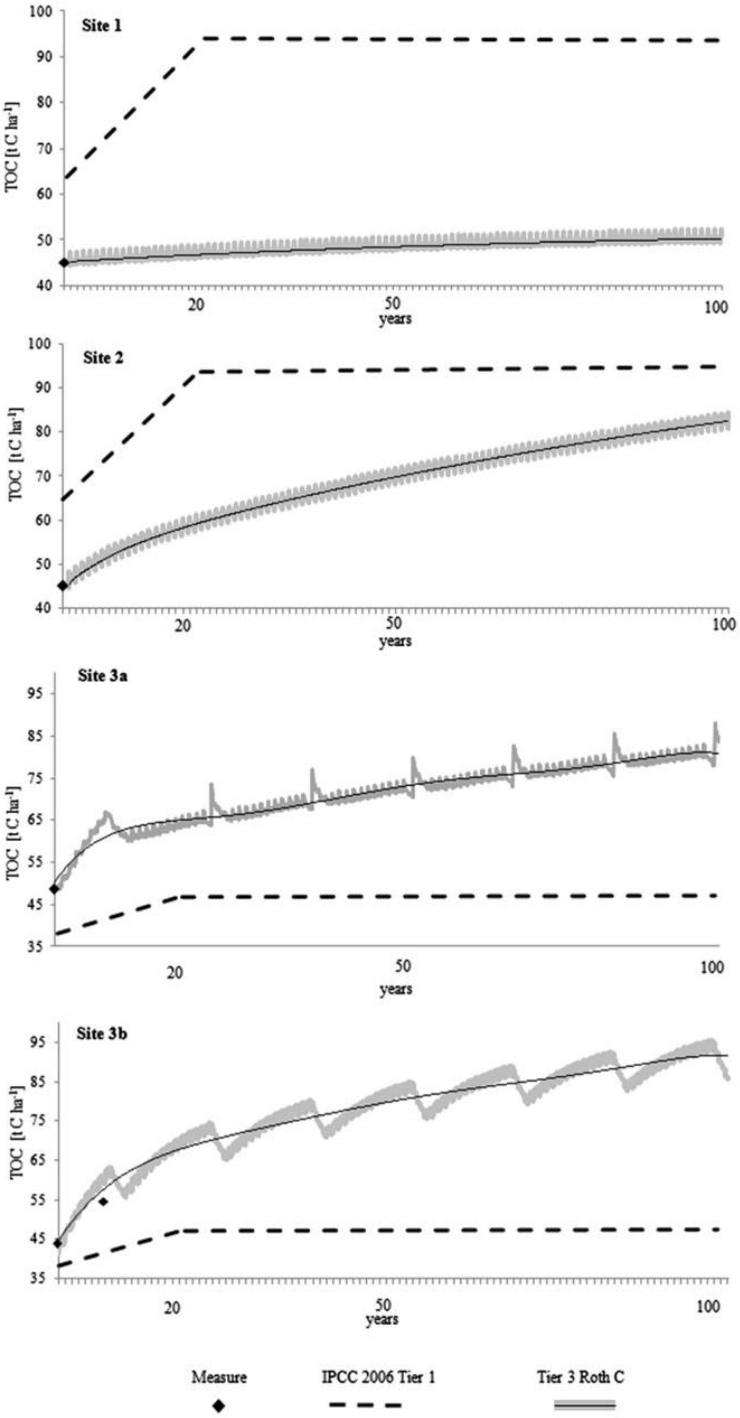
[h] Cumulative amount of fertilizers distributed within the time boundaries of the study

[i] Average values over the experimental periods

[j] Winter wheat (*Triticum aestivum* L.)

[k] Peach (*Prunus persica*)

Fig. 1 Simulations of SOC change subsequent to the shift to sustainable crop management, performed using IPCC (2006a) Tier 1 approach and using RothC 26.3 model initialized with measured SOC before management change (the *gray line* represents monthly simulation and the *black one* yearly average)



variable soil moisture with the distance from the tree line due to drip irrigation and the concentrated distribution of compost and roots along the tree line (Montanaro et al. 2012).

In Table 4, the yearly rates of SOC changes are reported for different time horizons (20, 50, 100 years). Generally, it can be stated that with a longer time horizon, the yearly rate of SOC

Table 3 Selected C input stock change factors selected to calculate SOC change with Tier 1 method and the C input derived from direct data used to implement RothC simulation

	Management practices	Tier 1 C input stock change factor	C input Tier 3 (t C ha^{-1} a^{-1})			
			Site 1	Site 2	Site 3a	Site 3b
Winter wheat before change	Straw removed from field + digestate addition	Medium 1.00 *Representative for annual cropping with cereals where all crop residues are returned to the field. If residues are removed, then supplemental organic matter (e.g., manure) is added. Also, it requires mineral fertilization or N-fixing crop in rotation.*	2.22	2.24		
Winter wheat after change	Straw incorporated in soil + manure addition	High with manure 1.44 (Error ±13 %) *Represents significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.*	4.02	4.67		
Peach orchard before change	Pruning residues burned, chemical weed control (site 3a), and tillage (site 3b)	Low 0.95 (Error ±13 %) *Low residue return occurs when there is due to removal of residues (via collection or burning), frequent bare fallowing, production of crops yielding low residues (e.g., vegetables, tobacco, cotton), no mineral fertilization, or N-fixing crops.*			1.8	1.8
Peach orchard after change	Pruning residues incorporated in soil, mechanical weed control, no tillage, compost addition	High without manure 1.04 (Error ±13 %) *Represents significantly greater crop residue inputs over medium C input cropping systems due to additional practices, such as production of high-residue-yielding crops, use of green manures, cover crops, improved vegetated fallows, irrigation, frequent use of perennial grasses in annual crop rotations, but without manure applied*			5.8	6.8

change, expressed as CO_2 removed from atmosphere, decreases, since SOC change is always faster during the first years after disturbance. This aspect has already been highlighted in Petersen et al. (2013), where they suggested using a 100-year time horizon when simulating SOC change for CFP studies, based on a 100-year GWP calculation. However, it is difficult to elaborate predictions in such a long term, as many factors characterizing the agricultural sector (e.g., land use, cropping systems, and management regimes) are usually defined by highly volatile framework conditions (e.g., consumer demand, economic trends, societal transformation, and public policy). For agricultural land use decision-making, even 20-year continuous land use of the same kind is not common and LUC should be considered at a more reasonable time horizon. Furthermore, when changing the cultivation system each year, the effect of management change on the SOC content is not stable and the uncertainty of the results is very high. In order to more consistently compare Tier 1 and Tier 3 methods, the yearly SOC change value derived from 20-year RothC simulation has been used and included into CFP of the examined case studies (Fig. 2).

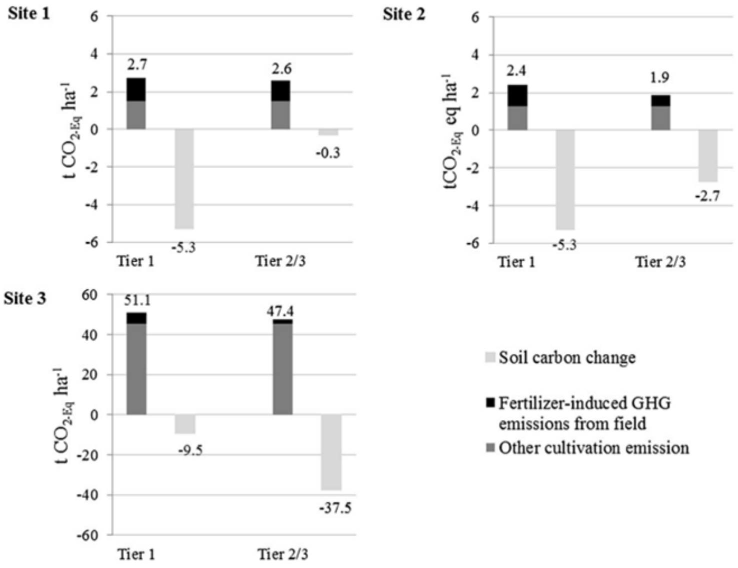
Figure 2 shows the CFPs of sites 1, 2, and 3a and the relative contribution of the three different GHG emission categories. The CO_2 removals from SOC change are reported separately as prescribed by ISO 14067 (2013), because of the temporary character of CO_2 storage in soil. For sites 1 and 2, the CFP represents the sum of all GHG emissions and removals during a 1-year crop cycle, while for the site 3a CFP, the entire 15-year peach orchard life cycle was taken into account, with the last 8 years of management regime shifted to sustainable practices. For CFP calculation of annual crops, the whole crop rotation and the crop rotation-related effects should be taken into consideration as stated by Brankatschk and Finkbeiner (2015). Especially, crop residues can have a great influence on the crop rotation effects, since crop residues remaining on the field affect the subsequent crop through influencing the physical, chemical, and biological soil properties and improving the soil fertility. The nutrients (N, P, K)

Table 4 Results of SOC change, expressed as CO_2 removed from atmosphere, calculated with different time horizons and different Tier approaches for the experimental sites

Experimental site	Assessment approach	Time horizon (years)	SOC change at equilibrium (t C ha^{-1})	SOC change (t CO_2 ha^{-1} a^{-1})
1	Tier 3 RothC	1		−1.13
		20		−0.33
		50		−0.26
		100	5.18	−0.19
	Tier 1	20	28.8 (±14.7)	−5.29
2	Tier 3 RothC	1		−7.80
		20		−2.74
		50		−1.87
		100	38.15	−1.40
	Tier 1	20	28.8 (±14.7)	−5.29
3a	Tier 3 RothC	20		2.99
		50		2.63
		100	55,2	2.03
	Tier 1	20	7.4 (±12.7)	−1.35
3b	Tier 3 RothC	7		−9.91
		20		−5.36
		50		−2.94
		100	43.87	−1.61
	Tier 1	20	7.4 (±12.7)	−1.35

remaining in crop residues on field can be used by the subsequent crop and can result in a reduced fertilizer dose for the subsequent crop. This problem can be accounted in the CFP of the subsequent crop in two ways: allocating the respective environmental burdens to the subsequent crop or a credit can be given for the current crop if a reduced fertilizer dose is recommended for the subsequent crop. So far, there is no agreement about a uniform approach on how to include the effects of the crop rotation in the CFP calculation of an annual crop (Brankatschk and Finkbeiner 2015). We tried to include the crop rotation effect for the winter wheat crops by using the real crop cultivation data provided by the researchers from the experimental sites. The amount of farming operating material for each crop applied at field was calculated in advance in consideration of the local pedo-climatic conditions, the characteristics of the previous crop (overall fertilization strategy

Fig. 2 Comparison of CFP calculated using the Tier 1 and Tier 2/3 approach for the three case studies (for sites 1 and 2, mean values from two cultivation years at each site, site 3 values are totaled up over 15 years). SOC change is calculated in a 20 years' time horizon



for the crop rotation), and the amount of nutrients available in the soil (provided by the soil samples). Furthermore, the real obtained yield and nutrient content at each site were used to calculate the amount of SOC added to the field through crop residues and digestate.

For site 1, the choice of either Tier 1 or Tier 3 for SOC change estimation is a relevant decision, as SOC change calculated with Tier 1 corresponds to 194 % of all other CFP emissions (the agro-ecosystem is a C sink), while the Tier 3 estimate amounts to approximately 13 % of all other emissions. For site 2, the Tier level selected for SOC change estimation is less crucial, as in both cases, the agro-ecosystem is considered to be a C sink, but the benefit calculated by Tier 3 is lower (145 against 221 % of all other CFP emissions offset with Tier 1). In site 3a, the use of the Tier 3 method resulted in a more realistic value of SOC change than Tier 1. During 8 years of sustainable management practices, 81 % of all other CFP emissions can be offset through soil C storage, compared to only 19 % estimated with Tier 1. Pursuing a sustainable management regime, the Tier 3 simulation reveals that the subsequent peach orchard life cycle would be a C sink, storing 152 % of the emissions from agricultural operations and field emissions from fertilization in the soil.

For the annual crops, field emissions from fertilizer application are an important factor, accounting for almost 50 % of the emissions calculated using Tier 1 for sites 1 and 2. In contrast, for the perennial peach crop, emissions from fertilizer application contribute around 10 % (Fig. 2). In all case studies, the Tier 2 estimates of fertilizer-induced field emissions are lower than the Tier 1 estimate (−9 % for wheat at site 1, −46 % for wheat at site 2, and −65 % for peach at site 3) and within the uncertainty range of ∼−70 to +325 % reported for the default global emission factor from Tier 1. The consequence of using a higher Tier (Bouwman et al. 2002b) to calculate field GHG emissions from fertilizer application is a CFP reduction of 4 % for wheat production at site 1, 21 % for wheat production at site 2, and 7 % for peach production at site 3a. As the yield from annual crops is strictly dependent on nutrient availability and weather conditions during a relatively short cultivation period, the fertilizer management system is often more intensive for the short annual crop cycle than for perennial crops. Consequently, the fertilizer management system has a larger influence on overall field emissions for annual crops than for perennial crops, which feature considerably lower fertilizer input throughout their entire life cycle.

As reported in the IPCC (2006a) guidelines, the global default values (Tier 1) are, in some cases, adequate to determine fertilizer-induced field emissions—as confirmed by our wheat case study (site 1). However, in most cases, these factors should be specified based on environmental conditions (climate and soil characteristics) as well as on crop management conditions (fertilizer type, fertilizer application method, and rate) as in our second wheat (site 2) and our peach (site 3) case study.

To evaluate these findings, we compared the Tier 1 and Tier 2 estimates for N_2O and NH_3 emissions from the two winter wheat case studies with field-measured GHG emissions (Fig. 3). For both sites and both gases, the Tier 1 and 2 calculations overestimated the measured fluxes. However, for NH_3-N emissions, Tier 2 estimates only deviate 1 and 10 % from measured data of site 1 and site 2, respectively. In contrast, Tier 1 calculated NH_3-N emissions are 87 and 168 % higher than measured emissions for site 1 and site 2, respectively. Tier 2 estimates of fertilizer-induced N_2O-N field emissions are less accurate than estimates for NH_3-N, but more accurate than Tier 1 estimates. As Firestone and Davidson (1989) have stated, the microbial processes of denitrification and nitrification are the dominant sources of gaseous N emissions from agricultural soil systems. Many factors associated with crop, soil, water, climate, and fertilizer management can influence soil turnover processes at all levels, e.g., organic matter decomposition, denitrification, and nitrification. Consequently, the heterogeneity of soil and weather conditions hamper a sufficiently accurate representation of N_2O, NO, and NH_3 emissions from a field using a model. As presumed, the Tier 2 estimates of fertilizer-induced N_2O-N and NH_3-N field emissions were closer to the measurements than the Tier 1 estimations. Especially, the NH_3-N field emission estimates were very close to the measurements results. Most NH_3-N emissions on field arise from organic fertilizer application, but the modeling approach from Bouwman et al. (2002a) does not distinguish between different organic fertilizer types, but the used KTBL (2009) calculation method for organic fertilizer takes the fertilizer type, the temperature during application of the organic fertilizer, and the application method into account. Therefore, through combining the two modeling approaches (for mineral fertilizer Bouwman et al. (2002a) and for organic fertilizer KTBL (2009)), the accuracy of the modeling results could be increased.

Comparing modeling data with measurements can be problematical since measured data and modeled data have also a risk of uncertainty. As Bouwman et al. (2002c) pointed out in their study, the amount of N_2O and NO emissions is influenced by the measurement technique, the length of measurement period, and the frequency of measurements per day. For N_2O emissions are longer measurement periods (>300 days) and intensive measurements (≥1 per day) better to detect the fertilization effect on the N_2O emissions. However, for NO emission, no significant differences in measurement frequency classes could be found. The frequency of measurement and continuity is a sensitive factor to detect the fertilization effect on the N_2O emissions. In our case, N_2O measurements were conducted one to two times per month with higher resolution following fertilization events; therefore, they are not continuous and include a risk of uncertainty. To reduce this uncertainty, the N_2O fluxes arising in the periods between the measurements were calculated using linear regression analysis as

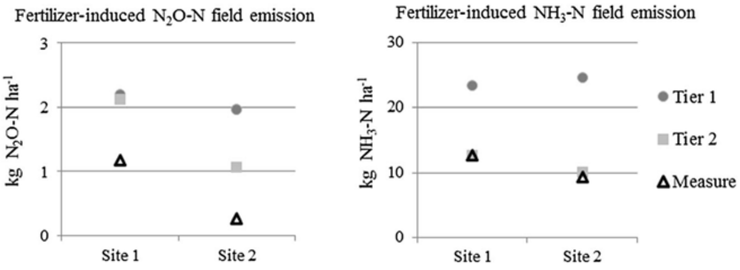


Fig. 3 Comparison of fertilizer-induced N_2O-N and NH_3-N emissions on field calculated using Tier 1 and 2 approach and measured data, mean values from two wheat cultivation periods at each site

explained in the Sect. 2.1. Ammonia volatilization was measured for 2 to 5 days immediately following fertilization. On both sites (1 and 2), the experimental length exceeded the 300 days and, correspondingly, our measurement period implying a low risk of uncertainty. The considered time frame for data collection can influence the N_2O emission result. The emissions that occur during mineralization of organic matter after harvest can be charged to the harvested crop or to the subsequent crop. Both modeling approaches (Tiers 1 and 2) are based on the same dataset of measurements, with a determined level of uncertainty (Bouwman et al. 2002a, b). However, the Tier 1 modeling approach only considers the amount of N applied and is more suitable for global- or national-scale calculation where the variability of environmental- and management-related factors is not appreciable for the different regions (IPCC 2006a). Since the Tier 2 modeling approach introduces more parameters to account for the heterogeneity of local pedo-climatic and management conditions, it is more suitable to represent field emissions at farm or project scale.

Gabrielle et al. (2006) also compared different modeling approaches for N_2O emission calculation from winter wheat on regional scale. We come to the same conclusion as Gabrielle et al. (2006) that in the case of fertilizer-induced field emissions, a higher Tier approach with a focus on the aforementioned regulating factors, especially regional environmental conditions, could therefore be used to adequately detect mitigation potentials. As Fig. 3 shows, our suggested Tier 2 approach can be a good solution to estimate fertilizer-induced field NH_3-N emissions, as it takes these regional environmental and management conditions into account. However, the results for fertilizer-induced field N_2O-N emissions modeling with the different Tier approaches were not convincing; therefore, we recommend to continue testing at more sites and with more crops to confirm our hypothesis.

4 Conclusions

The choice of the methodological approach (Tier level) can considerably affect the CFP of agricultural products. Therefore, sufficient transparency is required to inform relevant parties about possible error and shortcomings introduced by the selected method when applied to a case study. In this paper, we identified appropriate, readily available, assessment methods at the Tier 2 and Tier 3 level with medium efforts for stakeholders and explored the consequences of these methodological choices on the CFPs of annual and perennial crops for field GHG emissions from crop cultivation.

Only few site-specific data are needed to apply these higher Tier approaches, which can be used to improve the accuracy of the estimate of land-based GHG emissions from fertilization and soil C change, thus supporting the assessment of the agricultural mitigation potential and the development of GHG reduction plans at farm level.

The results for fertilizer-induced field emission calculation were consistent among the three case studies: using the higher Tier (Tier 2) led to lower estimated field emissions from fertilization at two sites and to almost equal emissions at one site compared to results obtained with the Tier 1 approach and to a more reliable estimate in agreement with field measurements. Based on our results, we suggest the following recommendations: For annual crops, a higher Tier approach is particularly important when estimating fertilizer-induced field emissions, whereas for perennial crops, it has a minor impact on the CFP. However, we cannot draw general conclusions on the efficacy of default emission factors for annual and perennial crops from this limited amount of data; therefore, further studies are needed to confirm our findings.

Regarding soil C stock change, important differences were found between results calculated with Tier 1 and Tier 3 methodologies. Using the Tier 1 approach can lead to wrong estimates due to equivocal interpretation of the carbon input stock change factor (qualitative description of the amount of organic material entered to soil) and to the lack of specification of local pedo-climatic conditions. Tier 3 RothC simulations can constitute a valid alternative, as local primary data about climate, soil features, and carbon input can be entered in the model; RothC simulation of SOC change after the modification of a crop management routine showed more reliable results when tested against available measurements than Tier 1 estimates. A more frequent SOC monitoring campaign would be useful to further test the model's performance and calibrate it to orchards' features. The present study has underlined the relevance of SOC change from crop management change on

CFP of perennial crops, which cannot be always adequately represented using a Tier 1 approach. Concerning annual crops, crop rotations were not included in the RothC simulation, as SOC change after land use change (crop change) was not included in the scope of the assessment. However, the influence of SOC change on CFP of 1-year crop cycle could be strongly related to the long-term SOC dynamic, subsequent to crop choice and to the management regime, which determine the amount of organic residues returned to soil. Thus, for annual crops, a simulation approach is also advisable to evaluate SOC change as the default Tier 1 does not allow to represent the change of different crops in the rotation. Further investigation efforts are needed in this direction. Similarly to what was done in this paper for *default carbon input level stock change factors*, it would be interesting to assess how the *default land use stock change factors* (long term cultivated, paddy rice, perennial crops, set aside) of Tier 1 method influence the performance of SOC change estimate with respect to higher Tier approaches.

The outcomes of the present paper suggest that it is necessary to foster more awareness and consensus within LCA practitioners and policy-makers about the importance of including regional field emissions into CFP of agricultural products, as it can considerably affect the results of the analysis. Moreover, it is recommendable to use modeling approaches for field emissions' estimate, taking into account local pedoclimatic and crop management conditions, because this can significantly improve the reliability of GHG accounting for agriculture at farm level.

The higher-tiered methodologies for the calculation of field emissions from fertilization and SOC change require little additional effort compared with default Tier 1 methods, and thus, their practical application is advisable. However, the development of user-friendly, crop-specific tools underpinning these modeling approaches could more efficiently increase the usefulness of CFP for agricultural sustainability assessment at farm and regional landscape level.

Acknowledgments The authors want to express their gratitude to the participants of the following research projects who provided the observed data used for the CFP calculations: (i) "Development and comparison of optimized cropping systems for the agricultural production of energy crops" (FKZ 22013008), funded by the German Federal Ministry of Food and Agriculture through the Agency of Renewable Resources (FNR); (ii) "Innovation for Quality and Sustainability of fruit and vegetable production (IQuaSoPO)," funded by Measure 124 of the Rural Development Program 2007–2013 of Basilicata Region (Italy); and (iii) the joint research project "Potentials for the mitigation of climate-relevant greenhouse gas emissions from energy crop cultivation for biogas production" (FKZ 22021008), funded by the German Federal Ministry of Food and Agriculture through the Agency of Renewable Resources (FNR) e.V. We would especially like to thank Achim Seidel, Gawan Heintze, and Madlen Pohl for their contribution of data on field NH_3 and N_2O emissions and Anne-Katrin Prescher for reviewing the manuscript.

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3 Paper 2

Do greenhouse gas emission calculations from energy crop cultivation reflect actual agricultural management practices? – A review of carbon footprint calculators

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Published in:

Renewable and Sustainable Energy Reviews (2016) 67:461-476

Submitted: 18 December 2015; accepted: 9 September 2016; published online: 17 September 2016

Renewable and Sustainable Energy Reviews 67 (2017) 461–476

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Do greenhouse gas emission calculations from energy crop cultivation reflect actual agricultural management practices? – A review of carbon footprint calculators

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ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form
4 May 2016
Accepted 9 September 2016

Keywords:
Crop rotation
Carbon Footprint
Crop management
Energy crops
Life Cycle Assessment
Greenhouse gas emissions

ABSTRACT

A wide range of calculators have been developed to assess the greenhouse gas (GHG) emissions of agricultural products, including biomass for bioenergy production. However, these calculators often fail in their ability to take into account the differences in pedoclimatic conditions, agricultural management practices and characteristics of perennial crops and crop rotations. As a result, the predictions of GHG emissions by these calculators are characterized by a high level of uncertainty, and calculators may fail in their ability to detect mitigation options along the production chain. The aim of this study was to analyze the available calculators for calculating GHG emissions from energy crop cultivation based on Carbon Footprint (CFP) approaches according to the goal and scope of the calculator, the methodology used to account for GHG emissions from energy crop cultivation, energy crop cultivation management practices and the ability to model crop rotation. Out of 44 environmental assessment calculators for agricultural products, we identified 18 calculators which are capable of assessing GHG emissions from energy crop cultivation. These calculators differ in their goal and scope and which farming operations related to crop management are taken into account; this makes it difficult to compare and interpret the results from these CFP assessments. Only seven calculators out of 18 can calculate GHG emissions from energy crop rotations. At the moment, none of these calculators are able to consider actual effects from energy crops in rotation in the context of nutrient shifts, reductions in the use of agricultural operating needs, or the sequence and composition of crop rotations. However, by expanding the system boundaries of the CFP study, by taking the whole energy crop rotation and local agricultural management practices into account, the opportunity to identify more GHG mitigation options increases.

Contents

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http://dx.doi.org/10.1016/j.rser.2016.09.059
1364-0321/

1. Introduction

Human influence on climate change was again confirmed by the latest report from the Intergovernmental Panel on Climate Change (IPCC) [1]. Anthropogenic greenhouse gas (GHG) emissions from fossil fuel combustion and industrial processes contributed about 78% to the total increase of GHGs in the atmosphere over the last 40 years [1]. Furthermore, the Agriculture, Forestry and Other Land Use sector (AFOLU) accounted for about a quarter of anthropogenic GHG emissions [1]. In response to this, a growing number of governments have begun introducing renewable energy policies in an effort to reduce GHG emissions by replacing non-renewable fossil fuels with renewable energy sources. The European Commission has committed itself to increase the proportion of renewable energy to 20% of the overall share of the energy consumption and to 10% of transportation-related energy consumption by 2020 [2]. In 2008, 12.9% of the total global primary energy supply had already originated from renewable energy sources, of which bioenergy contributed the dominant share (80%) [3]. This implies that the production and use of biomass to generate power, heat and fuel has significantly increased in recent years [4].

Biomass for the supply of energy is traditionally obtained from fuelwood. However, in the last decade, the use of crop residues and dedicated energy crops delivering the demanded biomass increased. Energy crops are agricultural crops solely cultivated for energy-related use. Several food crops (e.g. maize or sugar beet) can also be grown as energy crops if they have high yields and, preferably, a low demand for agrochemical inputs [5].

Energy generation from energy crops has an almost-closed CO_2 cycle (in which the combustion of biomass releases the same amount of CO_2 as was captured by the crop during growth). However, it is not carbon neutral over its whole production chain, since GHG emission occurs during the production stage, e.g. through production of fertilizer, pesticides, farming machinery or fuel combustion from machinery used [5]. Agricultural management practices have a considerable effect on the amount of GHG emissions from energy crop production and, correspondingly, on the entire biomass energy production chain [6]. Consequently, agriculture, including energy crop cultivation, holds significant potential for reducing GHG emissions [7].

However, appropriate assessment tools are required to identify the GHG emission benefit of bioenergy compared to its fossil alternatives. The most widely used approach is the Life Cycle Assessment (LCA) defined by ISO Standards 14040 [8] and 14044 [9,10].

LCA is defined as a method for compiling and evaluating all inputs, outputs and the potential environmental impact of a production system throughout its life cycle. It enables the user to measure and quantify the environmental impacts of a product. Furthermore, it helps to identify hot spots where the most significant impacts occur, giving the user the opportunity to develop strategies for improving the product's environmental performance [8].

In addition to the LCA guidelines, the Carbon Footprint (CFP) defined by ISO Standard 14067 [11] provides requirements and guidelines for the quantification and communication of GHG emissions in a production chain. The CFP is a specific method within the LCA approach and summarizes all GHG emissions and removals occurring within the established product system boundaries, expressed as CO_2 equivalents. There are a considerable number of tools working with the CFP approach for calculating the GHG emissions from agricultural products [12,13]. An overview of currently available tools for quantifying GHG emissions at landscape scale from AFOLU was provided by Denef et al. [13]. They divided those tools into three categories: (1) calculators, (2) protocols and guidelines, and (3) process-based models. Based on these results a review of these tools was conducted by Colomb et al. [14,12] to evaluate the methodological differences between these tools, to promote transparency and to provide guidance for the user to choose the most appropriate tool. As distinct from Colomb et al. [14], our review focuses only on calculators, including web-based and software-based calculation tools, which are able to quantify GHG emissions from energy crop cultivation at farm scale. For this subset we provide an extended analysis of the complex crop cultivation system, including an evaluation of the calculators for their ability to take energy crop production specific characteristics, crop rotation effects and farm specific management practices into account.

CFP calculators are used by farmers, agricultural suppliers and scientists to identify the potential for GHG mitigation in their local agricultural production chains [15]. In order to be able to detect these GHG emission mitigation potentials, however, calculators should account for local agricultural management practices on the farm and especially for energy crop specifications by taking into account differences in pedoclimatic conditions, farming practices, farming technologies [16], the characteristics of perennial crops [17], and crop rotations (sequence and composition of crops) [18]. Diversification of crop rotation patterns is one option for GHG emission reduction in cropping systems [19], but CFP studies from crop cultivation typically only take into account one vegetation period of one single crop [18]. Accordingly, as agriculture systems are highly complex, not all underlying material flows can be quantified when the assessment is limited to such a short time period. As result, calculation systems leave out crop rotation effects, including all interactions between the previous crop and the assessed crop, such as nutrient shifts, reduction in the use of agricultural operating needs, different intensity and the timing of farming activities [18]. Furthermore, CFP studies frequently fail to adequately consider the specifics of energy crop cultivation, such as differences in the timing of sowing and harvesting dates, the allocation of byproducts (e.g. the production of digestate and its reuse as fertilizer), and cultivation management (e.g. increased fuel use for the whole plant harvest, tillage frequency, and fertilizer quantities) [5,20].

There are various case studies that use the CFP approach to assess the GHG emissions of biomass energy production. Cherubini and Strømman [20] presented an overview of these case studies and an assessment of the key methodological issues. They pointed out that there are wide ranges and uncertainties in bioenergy CFP case studies due to differences in methodological assumptions (e.g. different reference systems, the database used, functional units, and allocation procedures) and the many variables involved in this calculation (e.g. selection of system boundaries, including land use change and accounting for field emissions from different fertilizer types and crop residues). Furthermore, some of these key parameters regarding agricultural processes are still not well understood and depend heavily on local and climate conditions [21].

The aim of this paper is to review currently available calculators for their ability to quantify GHG emissions from energy crop cultivation by taking into account the specific features of energy crop production and local management practices (as explained above). Following Buytaert et al. [22], who note that LCA is the most suitable assessment tool to assess emissions from bioenergy production systems, we focused our review on calculators that are based on the specifications of the LCA approach for GHG emission assessment, the CFP. Additionally, for CFP studies focusing on agricultural processes, the system boundary can be restricted to "cradle to farm gate" instead of "cradle to grave" to avoid complications of a full CFP study [23]. Following the recommendation of Audsley et al. [23], we set the system boundaries of our study at the farm gate ending with crop harvest, but including byproducts such as organic fertilizers (e.g. digestate, manure, slurry). Our analysis of the calculators is based on four criteria: (1) the goal and scope of the calculator, (2) the methodology used to account for GHG emissions from energy crop cultivation, (3) energy crop cultivation management and (4) the ability to model crop rotation.

2. Materials and methods

The review process was performed in three steps: first, we identified calculators which account for GHG emissions of agricultural products. Out of these, in the second step, we identified the calculators which could account for GHG emissions from energy crop cultivation. In the third step, we analyzed and compared the resulting calculators regarding to the four criteria described in Table 2.

2.1. Material: identifying GHG calculators for energy crop cultivation

Our search for calculators was carried out in English and German and covered only published information, which includes peer-reviewed literature, reports, calculator descriptions and websites. A systematic database search of peer-reviewed articles was conducted using the electronic Web of Science. All analyses were conducted between January and November 2014. The following thematic search terms were used: energy crops AND review, LCA AND agriculture, environmental impact AND bioenergy, Carbon Footprint AND energy crops, LCA AND modeling AND bioenergy. The composite terms were placed inside quotation marks, and an asterisk was used at the end of each term to capture all possible extensions and variations of a particular word. The documents were considered relevant if they matched at least one of the topical search terms in their titles, abstracts or keywords and were published in the last 25 years. After identifying the relevant papers, we used references and citations from these papers to search for cited reports, websites and models. In two cases we consulted the software developer directly for further information.

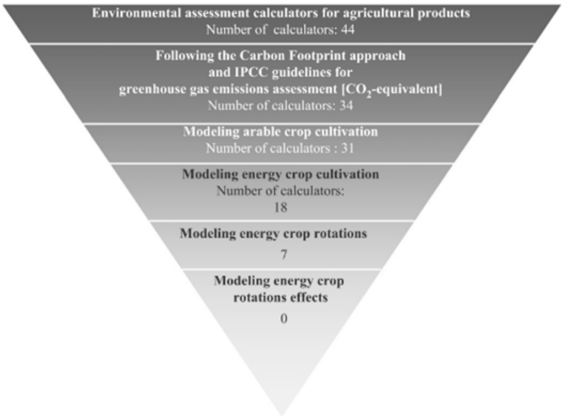

Fig. 1. Selection process for GHG emission calculators for energy crop cultivation.

Calculators that were developed exclusively for internal use by companies, consultancies or scientists for a very specific product were not included in our review. In the end, we identified 44 environmental assessment calculators for agricultural products. An overview of these 44 calculators, including their specific properties (user interface, method, GHG indicator, availability, target user group and literature source) is provided in Table S1 (supplementary material).

Fig. 1 depicts our selection process. Methodologies for governmental certifications of bioenergy sustainability often use CFP methodology [24,25] and the guidelines of the IPCC for AFOLU [26] to assess GHG emissions from biomass production [24,25]. Therefore, we selected all calculators out of the 44 earlier identified calculators which were able to calculate GHG emissions from crop cultivation (focusing on all processes occurring from "cradle to farm gate") following this methodology and these guidelines. The result is that all GHG emissions occurring during the production process are aggregated into one single impact category of "climate change" by using the category indicator the Global Warming Potential (GWP) or CML 2001 [7,27]. Calculators following other environmental assessment methods as described by Payraudeau and van der Werf [28] were excluded, as well as calculators designed to model detailed soil-plant-atmosphere processes on farms. Adopting these criteria in our selecting process, we identified 34 calculators matching these criteria.

From the remaining 34, we selected all calculators that were able to model GHG emissions from arable crop cultivation. Calculators modeling only horticultural crops and calculators working only with fixed datasets for crop cultivation, without the possibility to modify the inputs and outputs or cultivation processes, were excluded. This resulted in 31 suitable calculators.

Finally, from the remaining 31 we selected all calculators that were capable of calculating GHG emissions from energy crop cultivation. Since several arable crops for food, feed or fiber production can also be grown as energy crops, our analysis included calculators designed for GHG emission assessment from arable crop cultivation; while these are not exclusively designed for energy crops, they nevertheless are capable of assessing GHG emissions from energy crop cultivation as well. Calculators modeling crops without any specification of crop type or only with broad crop categories (e.g. general cropping system, rice fields) without a category for energy crops were excluded. Eighteen calculators were identified that fulfill the requirements (Table 1).

Thirteen of the calculators are freely available and can be downloaded directly from their website or by contacting the developer. We tested these calculators to determine their features,

Table 1
Overview of the 18 selected calculators for GHG emissions from energy crop cultivation.

Name	Full title	Developed by	Reference
Agri-LCI models	Agricultural Life Cycle Inventory models	Cranfield University, UK	http://www.cranfield.ac.uk/about/people-and-resources/schools-and-departments/school-of-applied-sciences/groups-institutes-and-centres/cwsi-software/CWSI-AgriLCA-download.html? ref=161050, accessed: 25.09.2014
BioGrace	Biofuel Greenhouse Gas Emissions in Europe	Agency NL, IFEU, BIO IS	http://www.biograce.net/content/ghgcalculationtools/recognisedtool, accessed: 29.10.2014
CAPRI	Common Agricultural Policy Regionalized Impact analysis	University of Bonn	http://www.capri-model.org, accessed:11.11.2014
CFF	Farm Carbon Calculator	Farm Carbon Cutting Toolkit	http://www.cffcarboncalculator.org.uk, accessed: 29.10.2014
COMET FARM	Whole Farm And Ranch Carbon And Greenhouse Gas Accounting System.	United States Department of Agriculture, Colorado State University	http://www.cometvr.colostate.edu, accessed: 26.09.2014
CFT	Cool Farm Tool	Cool Farm Alliance	http://www.coolfarmtool.org/CftExcel, accessed: 15.01.2015;[54]
C-Plan	Carbon Footprint Calculator	CPLAN 2014 (Scottish Farmer)	http://www2.cplan.org.uk, accessed: 12.11.2014
FarmGAS	FarmGAS Calculator And Financial Tool	Australian Farm Institute	http://calculator.farminstitute.org.au, accessed: 12.11.2014
FSGGEC	Farm System Greenhouse Gas Emissions Calculator	Michigan State University	http://surf.kbs.msu.edu, accessed: 13.11.2014
GaBi	Product Sustainability Solution	PE International	http://www.gabi-software.com, accessed: 22.01.2014
GEMIS	Global Emission Model Integrated Systems	International Institute for Sustainability Analysis and Strategy	http://www.iinas.org/news-de.html, accessed: 21.02.2014
HGCA 1	Biofuel Greenhouse Gas Calculator	Agriculture and Horticulture Development Board	http://www.hgca.com/tools/biofuel-greenhouse-gas-calculator.aspx, accessed: 14.08.2014
HGCA 2	Carbon Footprinting Decision Support Tool	Agriculture and Horticulture Development Board	http://www.hgca.com/tools/carbon-footprinting-decision-support-tool.aspx, accessed: 14.08.2014
IFSC	Illinois Farm Sustainability Calculator	University of Illinois	https://ideals.illinois.edu/handle/2142/13458, accessed: 15.08.2014
openLCA	Open Source LCA Software	GreenDelta	http://www.openlca.org, accessed: 14.09.2014
SALCA	Swiss Agricultural Life Cycle Assessment	AGROSCOPE	http://www.agroscope.admin.ch/oekobilanzen/01199/index.html?lang=de, accessed: 22.01.2014
SimaPro	Sustainable Performances Of Products And Services	Pré	http://www.pre-sustainability.com/software, accessed: 21.02.2014
Umberto	LCA And Environmental Product Declaration Software	ifu Hamburg	http://www.umberto.de/en, accessed: 21.02.2014

inputs and outputs, functionality and operability. For all 18 calculators, their methodological and practical aspects were obtained from published information, including peer-reviewed literature, reports and calculator descriptions on the websites, plus the results from our calculator tests.

Before analyzing them in the third step of our review, we screened them for their ability to assess GHG emissions from energy crop rotations and their effects. Seven of these 18 calculators were capable of modeling energy crops in rotation, but none of these calculators could assess energy-crop rotation effects like interactions between crops such as nutrient management or green manuring.

2.2. Method: analytical framework for analyzing GHG calculators for energy crop cultivation

The CFP methodology defines four phases to assess GHG emissions along the production chain: (1) the goal and scope definition phase, (2) the inventory analysis phase, (3) the impact assessment phase and (4) the interpretation phase [11]. The first phase defines the general framework of the CFP study. The data collection for each process is carried out in the second phase, and this data is summarized into one CFP result in the third phase. In the final CFP phase, the results from the first three phases are evaluated in light of their completeness and sensitivity; on this basis, researchers form their conclusions, including any limitations of the study and finally give recommendations. The adoption of these phases in GHG emission calculators is essential for the calculated result and therefore for the applicability and utilization of the results. As the first three CFP phases are particularly relevant for the design and development of the calculator and for the results of the CFP study, we focused on the first three phases in our study.

We chose the following four criteria for the comparison of the selected calculators: (1) the goal and scope of the calculator, (2) the methodology used to account for GHG emissions from energy crop cultivation, (3) energy crop cultivation management and (4) the ability to model crop rotation. These criteria were assigned to the first three CFP phases, and indicators and variables related to these CFP phases were identified (Table 2). The importance and relevance of each criterion (including CFP phases, indicators and variables) are described in detail in the following paragraphs.

2.2.1. Goal and scope

The following indicators should be considered and clearly described in the first CFP phase: the goal of the study, the system boundary, the allocation method and the functional unit [11]. By defining these indicators, the limits of the processes included in each calculator as well as the working plan of the entire CFP study can be defined.

When characterizing the goal of CFP studies, the intended application and audience as well as the reason for the study has to be defined [8]. GHG emission assessment of crop production can be undertaken for various reasons. Colomb et al. [14] divided these reasons into four categories: raising awareness, reporting, project evaluation and product assessment. Calculators whose goal is *raising awareness* often have an educational purpose by giving information about climate change in crop cultivation and are often used by farmers and farming consultants. Calculators in the second category, *reporting,* assess GHG emissions at the farm level (used by farmers) or landscape level (used by policy-makers) to compare results with other farms or countries and to help propose GHG mitigation options. The third category, *project evaluation,* includes calculators assessing the GHG emissions of a project or a policy, often used by policy-makers, NGOs, technicians or consultants comparing different projects (e.g. different management systems, agricultural innovations). The fourth category, *product*

Table 2
Assignment of the four criteria for analyzing the 18 selected GHG emissions calculators from energy crop cultivation to the CFP phases and their related indicators and variables.

Criteria	CFP phase	Indicator	Variables
Goal and scope of the calculator	Goal and scope definition	Goal of the calculator	-Raising awareness -Reporting -Project evaluation -Product assessment
		System boundaries	-Process definition: "cradle to grave" or "cradle to farm gate" -Calculation scale: global, national or farm level -Time horizon: one year or multiple years
		Allocation method	-Expanding and substituting other products -Specific indicator -Avoid allocation
		Functional unit	-Per unit area -Per unit product -Per emission category -Per farm
Methodology used to account for GHG emissions from energy crop cultivation	Goal and scope definition	Data requirements, assumptions and quality requirements	-Calculation pathway: Tier 1, 2 or 3 -Country specific (calculation method)
	Inventory analysis	Kind of database used	-E.g. Ecoinvent, RED, IPCC, Agri-Footprint LCI database
	Impact assessment	Impact category "Climate Change"	-Global warming potential for 20, 100 or 500 years
Energy crop cultivation management	Inventory analysis	Indirect GHG emissions (caused by the manufacture of agricultural farming operating needs)	-Including: fertilizer, pesticides, building materials, seeding material, energy, fuel or machinery -Distinguish among pesticides -Distinguish among fertilizer
		Direct GHG emissions (induced by farming processes)	-Distinguish among: mineral fertilizer types -Including: organic fertilizer (digestate) -Distinguish among: organic fertilizer types -Including: crop residues -Including: fuel combustion -Distinguish among: tillage types -Including: land use change
		Calibrated energy crops	-Energy crop species -Including: perennial crop -Including: undersowing
Ability to model crop rotations	Inventory analysis	Crop rotation effect	-Including: catch crops or green manure -Including interaction between previous crop and assessed crop: nutrient management, timing of farming activities

assessment, covers calculators used by private businesses for assessing GHG emissions from agricultural production chains to compare different production systems and to provide GHG reduction plans.

The system boundary defines processes, inputs and outputs of the production system to be included in the inventory analysis [8]. The CFP study may be performed for the complete production chain "from cradle to grave" to the end product – e.g. biodiesel from oilseed rape, or just for the first product in the production chain, "from cradle to farm gate" – e.g. rapeseed cultivation. If the objective of the study is to evaluate GHG emissions from the cultivation process, the post farm gate processes can be neglected in the assessment. However, for determining the global impact up to consumption, all processes "from cradle to grave" (including post-farm gate processes) should be considered in the assessment [17]. Depending on the goal of the calculator, the scale of the assessment can range from the global level, to the national, regional or individual farm level, or even down to individual farming processes.

The time scale is another important factor in the system boundary consideration. CFP can be carried out for the whole life cycle of one crop, which could be less than one year for annual crops or more than one year for perennial crops. It is essential to define the time scale for each CFP and describe the findings in the CFP report in order to make it comparable to other CFP studies. Annual crops are typically assessed for one vegetation period from seedbed preparation to harvesting. The influence of the previous crop on the assessed crop is often outside the system boundary of typical CFP studies. For perennial crops, the system boundaries can be set either to one single production year or to the entire life cycle, from crop establishment to the final harvesting period. Further reflections on this complex issue of modeling crop rotations and the effects it has on single crops, will be discussed in Section 2.2.3.

Allocation issues occur when a single process delivers more than one product or service (multifunctional process). Energy crop cultivation and processing of biomass can lead to multiple outputs, e.g. oil and oilseed meal from oilseed crushing, or biogas and digestate from anaerobic biomass digestion. There are three different methods available to allocate the processes emissions to different products [29]. The first allocation method expands the system boundary (until the use of the byproduct is included) and then applies the substitution method. The second method divides the emissions of the entire system among the different byproducts by using a specific indicator (either a physical indicator, e.g. weight or energy content, or a socioeconomic indicator, e.g. market value). The third allocation method ignores the allocation process and allocates all emissions to the main product or avoids allocations by using a suitable fictional unit. The chosen allocation method is extremely important for bioenergy systems, due to its large impact on the final CFP result [21].

The functional unit should be consistent with the goal and scope of the CFP study and provide a reference unit for all life cycle flows and indicators, allowing the comparison between systems [9]. The results from CFP studies from energy crop production can be expressed as kg of CO_2 equivalent per unit area; per unit product; per emission category or per farm.

2.2.2. Methodology used to account for GHG emissions from energy crop cultivation

Defining the data requirements, assumptions and quality requirements of the data is part of the first CFP phase and is influenced by the goal of the calculator and the goal of the CFP study correspondingly. The IPCC provides three calculation pathways, called Tiers, in the AFOLU guidelines to account for land-based GHG emissions [26]. The Tiers differ in their degree of complexity: Tier 1 is the least accurate methodology, though the simplest to use, as it provides equations and global default values; Tier 2 may use the same methodological approaches as Tier 1, but requires specific regional data and emission factors, while Tier 3 level methodologies are based on actual measurements or model simulations. Using a higher Tier generally improves the accuracy of the inventory analysis and reduces uncertainty, but requires a higher amount and quality of input data. Making sure that the chosen GHG emissions calculation pathway (Tier) corresponds to the geographical coverage of the calculator is very important [14]. Global or national calculators use the Tier 1 approach, in which only a small amount of input data is required and global or country average emission factors are used. Calculators using the Tier 2 approach often focus on a regional application, and pedoclimatic and management data is needed. Using the Tier 3 approach for assessing the GHG emissions enables the calculator to obtain farm-specific results in different timeframes (day, month and/or year). However, this requires specific measurements or complex pedoclimatic and management input data, which is often too time-consuming to obtain. Furthermore, calculators using the Tier 3 approach are locally restricted or focus on a specific product or emission processes; this could be unfeasible for most CFP studies. The results of the GHG calculator and the integrated calculation pathway can only be as precise and reliable as the input data used to compute these results.

Various LCA databases are available, providing datasets from agriculture, energy supply, transportation, biofuels and biomaterials, bulk and special chemicals, construction and packaging materials, basic and precious metals, and metal processing, as well as waste treatment. These datasets integrated in the calculators enable users to calculate their production chain by simply combining the single production steps which are provided in a kit of modules from the chosen database. All datasets are representative of previously completed LCA study results. The result of a CFP study largely depends on which database is used.

In the third CFP phase, the impact categories and category indicators are selected consistent with the goal of the study. The collected emission data from the inventory analysis are assigned to the selected impact category [9]. In our review, we focused on calculators following the IPCC guidelines [26] and using the impact category "climate change" with the category indicator GWP [7,27]. The GWP can be calculated over a specific time interval: 20, 100 or 500 years, and aggregates all emitted GHG into one unit (kg of CO_2 equivalent per functional unit), which makes it easier to compare GHG emissions from different products.

2.2.3. Energy crop cultivation management

The production of biomass from energy crops requires multiple steps: tillage, sowing, fertilization, use of pesticides, and harvest. GHGs are emitted from each farming operation. However, agricultural croplands that are intensively managed offer many opportunities for reducing GHG emissions through changes in agronomic practices [7]. The IPCC [26] recommends taking into account all indirect and direct emissions caused by farming operations when calculating the CFP of crop cultivation. Indirect emissions occurring during the production of all inputs (agricultural operating needs such as seeds, fertilizer, pesticides, agricultural machinery, fuel, building materials and energy) and have often been considered by using combined emission factors expressed in CO_2 equivalent from available databases. Indirect emissions from the production of agricultural operating needs can have a significant impact on the CFP results [23]; fertilizer production in particular is responsible for high GHG emissions [30]. Therefore, distinguishing between fertilizer types used in agricultural production can have a great impact on the CFP results [30]. The production of pesticides is less GHG emission intensive, but the distinction between different types can affect the CFP result as well.

Direct GHG emissions occur on the field through the application of crop residues and fertilizer (organic and mineral). According to the IPCC guidelines for AFOLU [26], CO_2, N_2O and CH_4 should be considered for direct emissions and NH_3 and NO_x for indirect emissions when estimating anthropogenic GHG released during crop cultivation. CO_2 emissions result from liming and urea application. Nitrous oxide (N_2O) emissions from managed soils arise from anthropogenic nitrogen input, such as mineral and organic fertilizer and crop residues, including N_2O through two indirect emissions pathways. The first indirect N_2O pathway is nitrogen volatilization, which occurs for example when NH_3 and NO_x are deposited onto soil and water. Leaching and runoff of nitrogen from fertilizer application is the second pathway for indirect N_2O emissions. Both indirect emissions pathways lead to further processes in which N_2O emissions occur. The type of fertilizer applied on the field affects the direct and indirect GHG emissions caused by the fertilizer [31]. This can be seen in a simple form, by distinguishing between mineral and organic fertilizer in general, but also in a more advanced distinction as seen between mineral and organic fertilizer types. The use of digestate as an organic fertilizer to substitute for mineral fertilizer is one option for reducing GHG emissions [32] by eliminating the GHG emissions from mineral fertilizer production. However, digestate application increases diesel consumption and correspondingly GHG emissions [33]. Consequently, the possibility of distinguishing between fertilizer types could be beneficial for the CFP of energy crop cultivation.

From crop residues remaining on the field, GHG emissions occur through the process of nitrification and denitrification, and should be included in the CFP calculations. The amount of nitrogen added to the field annually through crop residues (above-ground and below-ground) including nitrogen-fixing crops, is related to crop type, yield, residual nitrogen content, ratio of below-ground and above-ground biomass and the crop management system (what is left on the field, e.g. straw, stubble) [26].

CO_2, CH_4 and N_2O and other air pollutants (e.g. CO, NO_x) are emitted during fuel combustion [34]. The amount of fuel used for each cropping system as a function of machinery operation for tilling, drilling, seeding and harvest is related to machinery performance (technical standard) and the type of machinery used, soil type, and harvest yield, as well as crop management (e.g. the tillage system, the amount and type of fertilizer and pesticides applied) [35].

CO_2 emissions can occur through changes in soil organic carbon (SOC) stock changes caused by changes in the land use and management regime, called a Land Use Change (LUC). According to ISO 14067 [11], GHG emissions through LUC should be integrated, but documented separately in CFP studies.

The choice of crop can have a high impact on GHG emissions from the whole production system as well as on N_2O and NO emissions from fertilized fields [31]. Therefore, a parameter addressing the type of energy crop should be included in GHG emission calculators. A wide range of species can be used as energy crops, but the intensity of crop management depends on the species selected. Energy crop production management is in many ways similar to conventional food crop management. Crops with rapid growth, a high yield of usable biomass, an ability to grow under adverse weather and poor soil conditions, and with a high resistance against pests and diseases are favored as energy crops [36]. Sometimes, energy crops can have different crop management requirements than food crops [36], especially if the selected species has not traditionally been grown in the area (e.g. *Sorghum* in Central Europe) or if perennial crops are used instead of annuals (e.g. *Miscanthus sinensis, Silphium perfoliatum*). If food crops are grown as energy crops, alternative genotypes less suited for food production but with lower input requirements may be used [37]. However, biomass yield still depends on climate and soil conditions, fertilizer supply, and the timing of sowing and harvesting [38].

Perennial crops can have several benefits compared to annual crops. The inputs of a perennial cropping system are lower because the crop only has to be established once and the long-living roots can interact with the ecosystem, which can be beneficial to the nutrient balance of the soil [36]. When describing the crop management of perennial crops, the whole life cycle should be taken into account, since the agricultural performance of the crop correlates with the age of the plants. During crop establishment and at the end of the crop cycle, productivity is lower than in the years between these two phases. Consequently, the CFP of perennial crops may be underestimated when assessing only a single productive cultivation year and ignoring the other cultivation stages. Hence, the inclusion of detailed inventories of agricultural management at each stage of perennial crop cultivation would improve CFP calculation and the reliability of the assessment results [17]. Integrating undersowing crops (sowing a secondary crop underneath the main crop) into crop management may also have a positive influence on the CFP result [39].

2.2.4. *Ability to model crop rotation*

Energy crops can be included in traditional food crop rotations or can be grown in self-contained rotations. In general, crop rotation improves soil fertility (by enhancing soil structure, reducing soil erosion and maintaining sufficient content of soil organic matter), nutrient use efficiency (reduced and demand-oriented fertilizer use), and biodiversity (improved crop diversity). Crop rotation also tends to reduce the input of crop protection agents and increase crop yields [37]. The system boundaries in agricultural CFP are typically set at one vegetation period of one single crop [18]. However, as agriculture systems are highly complex, often not all underlying material flows can be quantified when the assessment is limited to such a short time period. Including all interactions (crop rotation effects) between the previous crop and the assessed crop in the CFP was recommended as a possible solution by Brankatschk and Finkbeiner [18]. When looking at only one vegetation period, it can be difficult to consider the exact nutrient supply, since each crop uses different amounts of nutrients and leaves different residue nutrients in the field. Another effect of crop rotations can be the improvement of phytosanitary conditions by reducing the pressure of disease and infestation by parasites. Therefore, the previous crop can affect nutrient and pesticide management for subsequent crops. By switching crops in a crop rotation, the intensity and timing of farming activities can be influenced, since the soil structure and texture are influenced. Crop residues remaining on the field or the introduction of green manure crops or catch crops in the crop rotation can have a major impact on the subsequent crop and on the crop rotation as a whole by affecting the soil properties and fertility, and correspondingly the achievable yield [18,19]. Today's CFP studies typically assess each crop independently if crop rotations are assessed, but by doing so they lose the ability to reflect the effects of crop rotation itself [18]. For this reason, the whole crop rotation should be assessed in CFP of energy crop cultivation in order to assess all effects related to crop rotation. This includes the consideration of all shifts of inputs in the crop rotation from one crop to the subsequent crop; otherwise the previous crops within the crop rotation carry the GHG emission burden from the following crops.

3. Results

3.1. *Goal and scope of the GHG assessment calculators*

Not all 18 identified calculators have assessment of GHG emissions from energy crop cultivation as their only goal, with a target audience of farmers or private companies. However, all of them included a possibility for GHG assessment from energy crop cultivation in their goal and scope definition. Nevertheless, the objective of each calculator and user group varies (Table 3). C-Plan and Farm GAS (both web-based) were mainly designed to raise awareness among farmers, consultants, students and land managers. They are both focused on giving an initial overview of farm-related GHG emissions and the impact of farm management decisions on GHG emissions.

BioGrace, CFF, COMET-FARM, FSGGEC, HGCA 1 and IFSC have the purpose of reporting accurate GHG emissions for subsequent comparisons between farms or countries. BioGrace and HGCA 1 are both based on Microsoft Excel, and were developed for the purpose of calculating the entire CFP ("from cradle to grave") of biofuel production from biomass. Both calculators were designed for politicians or consultants to support decision-making and to design national GHG reduction programs, and for farmers to see how changes in management practices could affect the overall GHG emissions of the resulting biofuel production. CFF, COMET-FARM and FSGGEC are web-based calculators developed to support farmers to estimate the CFP of their farm or single products with a focus on carbon sequestration and crop management. IFSC addresses the same topic, but is Excel-based. All four calculators have the goal of identifying mitigation options of GHG emissions on the farm and to report the CFP results voluntarily to national GHG emission reports or for CFP labeling and for comparing CFPs from similar products.

Only one of the 18 calculators under review, CAPRI, was developed for the purpose of project evaluation. CAPRI is a multi-purpose modeling system software for EU agriculture developed for policy-makers and scientists to analyze research questions in relation to specific agricultural policies [40].

Nine out of 18 calculators were developed for product assessment. Four of them (GaBi, openLCA, SimaPro and Umberto) are software solutions and were originally developed to assess the life cycle from industrial products. These tools were designed to be used by scientists, companies or policy-makers to assess the potential environmental burdens of a product in its production, use and disposal, and to detect mitigation options in the production chain. Agri-LCI models, CFT and HGCA 2 (all Excel-based) and SALCA (software solution) were developed for farmers, companies and policy-makers to assess the LCA from agricultural products and different management systems and to derive recommendations from these results for GHG reduction. GEMIS is a life cycle calculating software program developed for companies and policy-makers to model energy, material and transportation flows.

All 18 calculators under study include the assessment of GHG emission from crop cultivation "from cradle to farm gate" in their system boundaries, but only eight of them (BioGrace, GaBi, GEMIS, HGCA 1, openLCA, SALCA, SimaPro and Umberto) are able to extend the system boundary to the end of the life cycle of the assessed production chain (Table 3). Despite the similar system boundary of "cradle to farm gate", each calculator includes

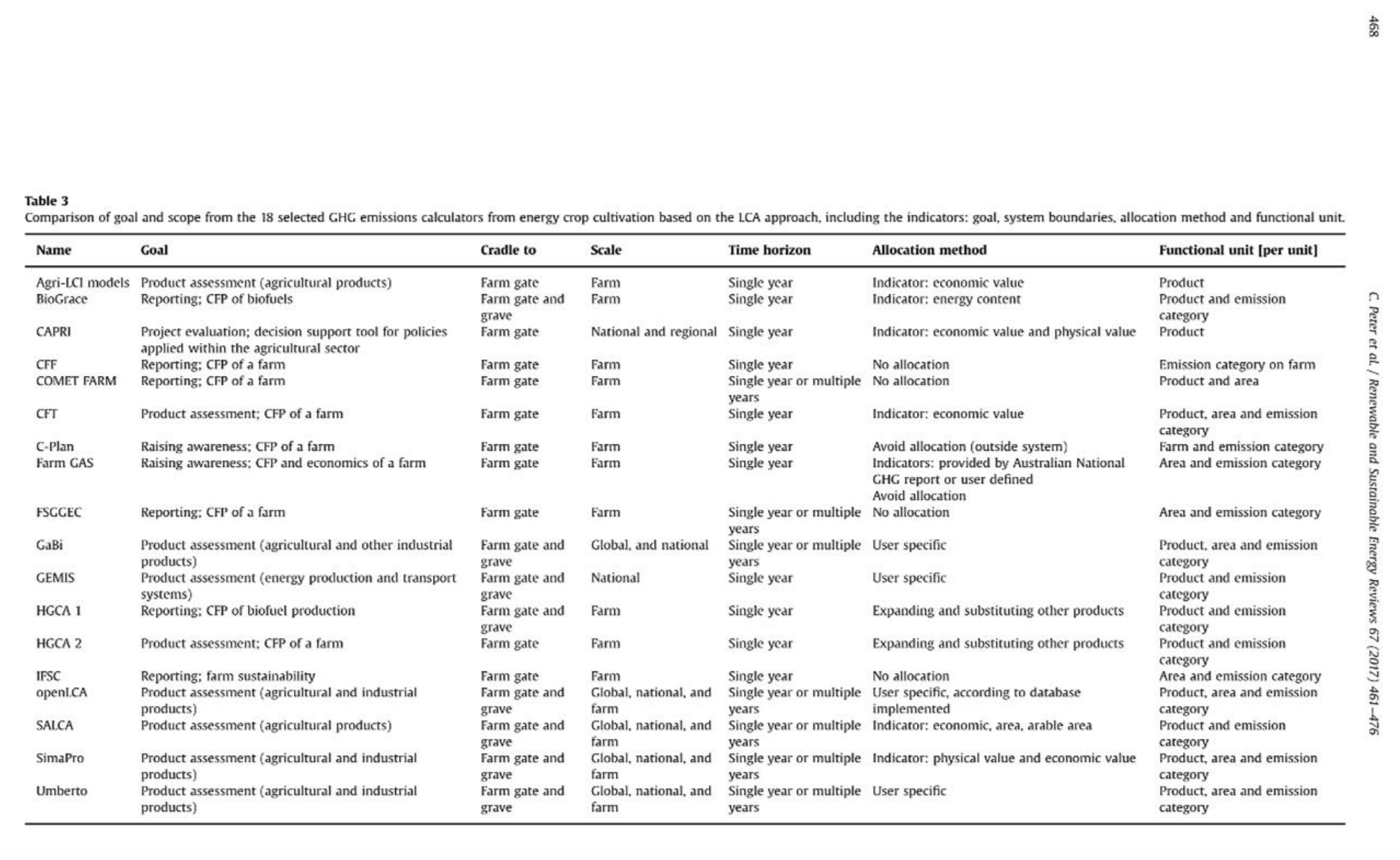

Table 3
Comparison of goal and scope from the 18 selected GHG emissions calculators from energy crop cultivation based on the LCA approach, including the indicators: goal, system boundaries, allocation method and functional unit.

Name	Goal	Cradle to	Scale	Time horizon	Allocation method	Functional unit [per unit]
Agri-LCI models	Product assessment (agricultural products)	Farm gate	Farm	Single year	Indicator: economic value	Product
BioGrace	Reporting; CFP of biofuels	Farm gate and grave	Farm	Single year	Indicator: energy content	Product and emission category
CAPRI	Project evaluation; decision support tool for policies applied within the agricultural sector	Farm gate	National and regional	Single year	Indicator: economic value and physical value	Product
CFF	Reporting; CFP of a farm	Farm gate	Farm	Single year	No allocation	Emission category on farm
COMET FARM	Reporting; CFP of a farm	Farm gate	Farm	Single year or multiple years	No allocation	Product and area
CFT	Product assessment; CFP of a farm	Farm gate	Farm	Single year	Indicator: economic value	Product, area and emission category
C-Plan	Raising awareness; CFP of a farm	Farm gate	Farm	Single year	Avoid allocation (outside system)	Farm and emission category
Farm GAS	Raising awareness; CFP and economics of a farm	Farm gate	Farm	Single year	Indicators: provided by Australian National GHG report or user defined Avoid allocation	Area and emission category
FSGGEC	Reporting; CFP of a farm	Farm gate	Farm	Single year or multiple years	No allocation	Area and emission category
GaBi	Product assessment (agricultural and other industrial products)	Farm gate and grave	Global, and national	Single year or multiple years	User specific	Product, area and emission category
GEMIS	Product assessment (energy production and transport systems)	Farm gate and grave	National	Single year	User specific	Product and emission category
HGCA 1	Reporting; CFP of biofuel production	Farm gate and grave	Farm	Single year	Expanding and substituting other products	Product and emission category
HGCA 2	Product assessment; CFP of a farm	Farm gate	Farm	Single year	Expanding and substituting other products	Product and emission category
IFSC	Reporting; farm sustainability	Farm gate	Farm	Single year	No allocation	Area and emission category
openLCA	Product assessment (agricultural and industrial products)	Farm gate and grave	Global, national, and farm	Single year or multiple years	User specific, according to database implemented	Product, area and emission category
SALCA	Product assessment (agricultural products)	Farm gate and grave	Global, national, and farm	Single year or multiple years	Indicator: economic, area, arable area	Product and emission category
SimaPro	Product assessment (agricultural and industrial products)	Farm gate and grave	Global, national, and farm	Single year or multiple years	Indicator: physical value and economic value	Product, area and emission category
Umberto	Product assessment (agricultural and industrial products)	Farm gate and grave	Global, national, and farm	Single year or multiple years	User specific	Product, area and emission category

Table 4
Comparison of methodology used from the 18 selected calculators to account for GHG emissions from energy crop cultivation, including the indicators: calculation pathway (Tier), country specialization, database used and time horizon for the GWP assessment.

Name	Tier	Country	Database, data source	GWP [years]
Agri-LCI models	1,2	England, Wales	Ecoinvent, UK Inventory Report, DEFRA and MAFF publications, farm production databases, IPCC	100
BioGrace	1	EU	RED[a]; JEC[b] consortium, IPCC	100
CAPRI	1,2	EU, Norway, Western Balkans and Turkey	Data from: EUROSTAT, FAOSTAT, OECD, FADN	100
CFF	1	UK	UK DEFRA, IPCC	100
COMET FARM	1,2,3	USA	DAYCENT, IPCC	100
CFT	1,2	Global	Ecoinvent, ASABE, IPCC	100
C-Plan	1	UK	IPCC, UK National Inventory	100
Farm GAS	1,2	Australia	Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks	100
FSGGEC	1,2,3	USA	IPCC, SOCRATES soil carbon change model	100
GaBi	1,2,3	Global	GaBi Database, Ecoinvent, US LCI	20, 100, 500
GEMIS	1	Germany	RED[a], IPCC	100
HGCA 1	1,2	UK	IPCC, DEFRA, UK specific emission factors	100
HGCA 2	1,2	UK	IPCC, DEFRA, UK specific emission factors	100
IFSC	1,2	Illinois, USA	IPCC, Literature, COMET-VR soil carbon model	100
openLCA	1,2,3	Global	Ecoinvent, ELCD, GaBi Databases, LCA Food, NEEDS, ProBAS	20, 100, 500
SALCA	1,2,3	EU, Switzerland	SALCA LCI Database	20, 100, 500
SimaPro	1,2,3	Global	Ecoinvent, ELCD, LCA Food DK, US LCI, Agri-Footprint LCI database, US Input Output library, Swiss Input Output Database	20, 100, 500
Umberto	1,2,3	Global	Ecoinvent	20, 100, 500

[a] Renewable Energy Directive.
[b] European Commission Joint Research Center.

different direct and indirect GHG emissions sources related to crop cultivation (Tables 5, 6).

OpenLCA, SimaPro, SALCA and Umberto offer assessment of GHG emissions at the global, national and farm scale, GaBi on the global and the national scale, GEMIS at the national level, and CAPRI at the national and regional scale. The other 11 calculators were only developed to assess the GHG emissions at the farm scale.

In 11 of 18 calculators, the time horizon for GHG emission assessment was limited to one crop vegetation period (one year) only. However, seven calculators can extend the assessment to multiple crop cultivation periods.

Different allocation methods are used by the 18 calculators to allocate the GHG emissions to co-products. HGCA 1 and 2 expand the system boundaries and substitute the byproducts with other products already included in the CFP study. Six calculators share the system's emissions among byproducts by using specific indicators. Three of them use only one indicator for allocation: Agri-LCI models and CFT use economic indicators; energy content is used by BioGrace. Sometimes in a multifunctional production process it is impossible to find one appropriate indicator which works for all byproducts. As a result, two indicators (physical and economic, as used by CAPRI and SimaPro) or three indicators (economic information, area and arable area as SALCA offers) can be used for allocation. CFF, COMET FARM, C-PLAN, FSGGEC and IFSC avoid using an allocation method and either allocate all emissions to the main product or choose a suitable functional unit by which the byproduct is outside the system boundary. The other calculators provide all allocation methods and the user can choose a suitable method according to the goals defined for the particular CFP study.

Table 3 provides an overview of the functional units used by the calculators to report the CFP results. COMET FARM, CFT, GaBi, openLCA, SimaPro and Umberto provide results per unit product and per unit area. All calculators except the Agri-LCI models, CAPRI and COMET FARM provide the GHG emissions separately for each emission category in addition to the total result. IFSC and COMET FARM provide the results in imperial units, whereas all the other calculators are metric.

3.2. Methodology used to account for GHG emissions from energy crop cultivation

The amount of data required by each calculator depends on the processes, activities and sources included in the calculator and on the GHG emission calculation pathway (Tier) used. The calculators are classified into different Tiers in Table 5 in order to distinguish their degree of complexity of integrated methodology to account for land-based GHG emissions. In seven out of 18 calculators, all three Tiers were combined into one approach, e.g. COMET FARM and FSGGEC. In GaBi, openLCA, SALCA, SimaPro and Umberto, own more detailed data can be integrated as well. Seventeen out of 18 calculators not only use the IPCC guidelines [26], but mix different assessment methodologies. However, the assessment methodologies chosen are always on the same complexity level as the Tier methodology applied in the calculator. BioGrace, CFF and C-Plan use the Tier 1 approach with global or national default values. Seven of the 18 calculators use Tier 1 and Tier 2 approaches for GHG emission calculation and can be modified with country-specific emission values. Calculators including the Tier 2 approach focus on regional application, and pedoclimatic and management data are required. COMET FARM and FSGGEC provide a country map, with climate and soil data, where the user can locate their farm and run the dynamic process-based crop–soil–atmosphere models. The Tier 3 approach requires measurements or high-resolution input data for model simulation, and is locally restricted. Seven calculators use Tier 3 approach methods, but only to calculate some processes included in the CFP that are crucial for the result of the CFP; they calculate other processes using approaches of lower complexity.

When choosing a GHG emission calculator, it is important to know for which region or country it was developed, and consequently which GHG emission default values were implemented. Only CFT, GaBi, openLCA, SimaPro and Umberto can be used worldwide. All the other reviewed calculators were calibrated for specific countries.

Six out of the 18 calculators under review use the Ecoinvent Database [41] and other agricultural and product databases (Table 4). The Ecoinvent Database provides around 10,000 datasets from agriculture, energy supply, transportation, biofuels, biomaterials and other industrial processes [41]. The datasets integrated in the models enable users to calculate their production chain by simply combining the individual production steps, which are provided in a kit of modules from the Ecoinvent Database. If a specific crop or production step is not available, it is possible to modify an existing dataset or create a dataset from scratch (e.g. new energy crops). For most modules, global, European or national mean values are available.

SALCA uses its own GHG assessment concept for agriculture. This covers LCA methods adapted to the agri-food chain, such as GHG emission calculators, and the SALCA life cycle inventory database, based on the Ecoinvent Database [42]. OpenLCA is an open-source software program into which freely and commercially available databases can be integrated. The methodological approach of this calculator is equivalent to GaBi, SimaPro and Umberto, and the same databases can be integrated. In a similar way to other software, it works like a kit, in which the individual production steps are provided as freely combinable modules. The general methodology of the other calculators is based on global, European or national guidelines (e.g. IPCC and RED) which provide GHG emission default factors for different cultivation-related GHG sources. Furthermore, datasets from literature are used to assess specific indirect and direct agricultural GHG emissions. COMET FARM integrated the dynamic agro-ecosystem model DayCent (the official U.S. National Greenhouse Gas Inventory model) to estimate emissions on the field and through LUC. IFSC uses the COMET-VR soil carbon model from COMET FARM.

Regarding GWP, the calculators GaBi, openLCA, SALCA, SimaPro and Umberto can determine GWP for 20, 100 and 500 years, and the user can choose the preferred indicator. All other calculators only provide GWP for 100 years (Table 4).

3.3. Energy crop cultivation management

As mentioned above, the selected system boundaries can significantly affect the processes, activities and sources included in each calculator as well as the amount and quality of the input data required. Table 5 gives an overview of the included indirect emissions arising from farming processes for each calculator. In two calculators (COMET FARM, FarmGas), indirect emissions from the production of operating resources (e.g. machinery, pesticides and fertilizer) are omitted. In contrast, in eight out of 18 calculators, GHG emissions for the production of all agriculturally related inputs are embedded in the assessment (CAPRI, CFF, GaBI, GEMIS, openLCA, SALCA, SimaPro and Umberto). This group consists of calculators in which a large amount of datasets is provided, allowing the user to decide which indirect emissions should be included in the CFP. In GEMIS and CFF, indirect emissions from the production of agricultural inputs are included in the calculators; in CFF, the user can influence the values by modifying the amount of inputs. The remaining calculators provide indirect emissions from production for only a limited number of farming inputs – sometimes only one. Twelve out of 18 calculators include indirect emissions from manufactured pesticides. However, only seven can distinguish among types of pesticides by dividing pesticides into categories: herbicides, insecticides, fungicides and lubricants. Furthermore, with GaBi, openLCA, SALCA, SimaPro and Umberto, the user can calculate the CFP of the individual pesticides by aggregating the GHG emissions of the pesticide ingredients provided by the database included in these calculators. The other five calculators include pesticide production by aggregating emissions from pesticide use in one category; they do not distinguish between types of pesticides. Fourteen out of 18 calculators include indirect emissions from manufactured mineral fertilizer, but only 12 out of these 14 can distinguish among types of mineral fertilizers. They all provide a different number of fertilizer types. BioGrace, for example, only distinguishes among mineral fertilizer ingredients (N, CaO, K_2O and P_2O_5) while CFT provides 35 different types of mineral fertilizer, and the user can add new types or edit existing ones.

Table 5
Comparison of energy crop cultivation management related indirect GHG emissions from the 18 selected calculators regarding indirect emissions from the manufacture of agricultural operating needs, and the possibility of distinguishing among different types of pesticides and fertilizer (+ =yes; – = no).

Name	Included operating needs (emissions from manufacturing)	Distinguish among types of	
		Pesticides	Fertilizer
Agri-LCI models	Fertilizer, building materials, fuel	–	–
BioGrace	Fertilizer, pesticides, seeding materials, energy	–	+
CAPRI	All agricultural related inputs	+	+
CFF	All agricultural related inputs	+	+
COMET FARM	No indirect emissions from input production	–	–
CFT	Fertilizer, pesticides, energy, fuel	–	+
C-Plan	Energy	–	–
Farm GAS	No indirect emissions from input production	–	–
FSGGEC	Fertilizer	–	–
GaBi	All agricultural related inputs	+	+
GEMIS	All agricultural related inputs	–	+
HGCA 1	Fertilizer, pesticides	–	+
HGCA 2	Fertilizer, pesticides	–	+
IFSC	Energy	–	–
openLCA	All agricultural related inputs	+	+
SALCA	All agricultural related inputs	+	+
SimaPro	All agricultural related inputs	+	+
Umberto	All agricultural related inputs	+	+

Table 6 gives an overview of the included direct GHG emissions arising from farming processes for each calculator. C-Plan and FSGGEC do not distinguish among mineral fertilizer types; they only take the amount of N fertilizer (sum of N in kg) applied on the field into account. The other 16 calculators can distinguish among mineral fertilizers to a different degree of accuracy. With the exception of FSGGEC, all calculators included organic fertilizer in their assessment; 13 calculators can even distinguish among different types of organic fertilizers. Regarding digestate, only nine calculators take this particular organic fertilizer into account. However, they cannot distinguish among application methods (manure chisel plow, drag shoe, drag hose or incorporated in one hour after application) to account for the GHG emission arising from different digestate applications. Other than Agri-LCI models, COMET FARM and C-Plan, all calculators of the 18 include direct GHG emissions from crop residues applied on the field.

Through the use of machinery during energy crop cultivation, GHG emissions arise from fuel combustion. All calculators take this into account except COMET FARM and Farm GAS. Fourteen calculators can even distinguish among different types of tillage. Agri-LCI models and COMET FARM use categories (e.g. reduced tillage, plow-based, direct drilling) to account for different crop management systems and the amount of diesel used, respectively. In the other 12 calculators, it is possible to calculate the amount of diesel used by selecting each crop management step within the calculator (e.g. CFT provides a list of management steps) or by adding the actual amount of diesel used (e.g. BioGrace).

Thirteen out of the 18 calculators account for GHG emissions from LUC, but not all calculators document these results separately and some just account for emissions through land use change and not through management change. However, CAPRI, COMET FARM, FSGGEC GaBi, IFSC, open LCA, SALCA, SimaPro and Umberto all feature integrated process-dynamic models to determine

Table 6
Comparison of energy crop cultivation management related direct GHG emissions from the 18 selected calculators regarding the included emissions arising from the application of organic fertilizer, crop residues, fuel combustion from machinery use, and emission occurring after land use change. Furthermore, if the calculator distinguishes among different types of mineral and organic fertilizer use and tillage (+ =yes; − = no).

Name	Distinguish among types of			Including			
	Mineral fertilizer	Organic fertilizer	Tillage	Organic fertilizer (digestate)	Crop residues	LUC	Fuel combustion
Agri-LCI models	−	−	+	+ (−)	−	+	+
BioGrace	+	−	−	+ (−)	+	+	+
CAPRI	+	+	+	+ (+)	+	+	+
CFF	+	+	−	+ (−)	+	+	+
COMET FARM	+	+	+	+ (−)	−	−	−
CFT	+	+	+	+ (−)	+	+	+
C-Plan	−	−	−	+ (−)	−	+	+
Farm GAS	−	−	−	+ (−)	+	−	−
FSGGEC	−	−	+	− (−)	+	+	+
GaBi	+	+	+	+ (+)	+	+	+
GEMIS	+	+	+	+ (+)	+	−	+
HGCA 1	+	+	+	+ (+)	+	−	+
HGCA 2	+	+	+	+ (+)	+	−	+
IFSC	+	+	+	+ (-)	+	+	+
openLCA	+	+	+	+ (+)	+	+	+
SALCA	+	+	+	+ (+)	+	+	+
SimaPro	+	+	+	+ (+)	+	+	+
Umberto	+	+	+	+ (+)	+	+	+

emissions from soil carbon change through management changes.

Only BioGrace, HGCA 1 and GEMIS were originally designed to calculate GHG emissions from energy crop cultivation, but the calibration is limited to traditional energy crops for bioenergy production. However, the other 15 calculators provide datasets and calibrations for energy crops in addition to food crops, and also provide the possibility to modify or add crops. An overview of the calibrated energy crops in the calculators under study is given in Table 7. If the category "other" is selected on the calculator, other energy crops can be calculated without a specific calibration for this crop.

Datasets from energy crop cultivation are included in CAPRI, GaBi, openLCA, SALCA, SimaPro and Umberto, but they are limited to the traditional energy crops as shown in Table 7. Previously unconsidered energy crop species, such as *Silphium perfoliatum*, could be added by users by modifying existing datasets or creating their own.

Perennial crops are omitted in most calculators or integrated as an annual average whenever it is impossible to distinguish among the different stages of cultivation. CFT, GaBi, openLCA, SALCA, SimaPro and Umberto can calculate the GHG emissions from perennial crop cultivation. However, the user has to check if the full life cycle (from the establishment to the end of the crop productivity) of the perennial crop is considered. Undersowing crops were not addressed in any of the 18 calculators under review.

3.4. Ability to model crop rotation

Seven (COMET FARM, FSGGEC, GaBi, openLCA, SALCA, SimaPro and Umberto) of the 18 identified GHG emissions calculators for energy crop cultivation based on the CFP approach can calculate energy crop rotations. For crop rotation modeling with GaBi, openLCA, SALCA, SimaPro and Umberto, the existing modules (datasets) from crop cultivation can be combined, e.g. three years of maize cultivation can be calculated by using the same maize cultivation module three times. Within the single modules, the management system can be changed by the user. With COMET FARM, it is possible to calculate GHG emissions on a farm for a longer period. The user can enter management data on an annual basis, which can cause problems if the cultivation period spans over two calendar years (e.g. winter crops). FSGGEC offers a simple type of crop rotation calculation to the user: for each year, a single crop can be cultivated and calculated at Tier 1 or 2 level. The result is a very simple CFP where only a few GHG emission sources are taken into account. COMET FARM is the only calculator which has catch crops integrated.

It is difficult in all seven calculators to assess crop rotation effects, such as shift of nutrients or reduced farming activities and inputs. Most of these calculators generate their crop modules as single annual crops, which makes it difficult to display and to determine the effects of the crops on each other.

4. Discussion

4.1. Goals of GHG assessment calculators

The most important stakeholders for biomass cultivation in bioenergy production are farmers, energy industries, politicians and NGOs. All of them require information about GHG emissions and calculators to assess this information for their own purposes. None of the calculators discussed here can meet the needs of all target groups, but many calculators are available with varying levels of complexity and target different goals and user groups. Raising awareness is the goal of C-Plan and Farm GAS. These calculators require little time and knowledge of GHG emissions and climate change. They can be used without training and need only small amounts of input data to estimate GHG emissions. The results are displayed as simple graphics and guide the user toward identifying mitigation opportunities. However, they are not usually designed to assess changes in management and to take into account alternative and more sustainable management practices.

Results from calculators designed for reporting can be used as the reporting basis for the certification of sustainable biofuel production and for the verification of compliance with sustainability criteria for biofuels of the Renewable Energy Directive and the Fuel Directive [2]. BioGrace, for example, was developed to harmonize the different European calculators and calculation methods for GHG emissions from biofuel production, which is necessary to comply with the Renewable Energy Directive and Fuel Quality Directive [43]. The calculation scheme (calculation rules, default values) of BioGrace is often used in combination with other national calculators (national default values and legal

Table 7
Overview of calibrated energy crops in 18 calculators of GHG emissions from energy crop cultivation.

Name	Alfalfa (*Medicago sativa*)	Barley (*Hordeum vulgare*)	Grass (*Poaceae*)	Legumes (*Fabaceae*)	Maize (*Zea mays*)	Millet	Miscanthus (*Miscanthus sinensis*)	Oil Seed Rape (*Brassica napus*)	Palm (*Arecaceae*)	Perennial Grass	Rey (*Secale cereale*)	Sorghum	Soya bean (*Glycine max*)	Sugar cane (*Saccharum officinarum*)	Sugar beet (*Beta vulgaris*)	Sunflower (*Helianthus annuus*)	Switchgrass (*Panicum virgatum*)	Triticale (*X triticosecale*)	Wheat (*Triticum aestivum L*)	Other
Agri-LCI models		+			+			+					+					+	+	
BioGrace					+			+	+				+	+	+	+			+	
CAPRI								+ +	+				+			+			+	+
CFF		+		+	+			+			+		+		+			+	+	
COMET FARM	+	+	+	+	+	+							+	+	+	+			+	
CFT	+	+		+	+					+	+	+							+	+
C-Plan		+			+			+			+				+			+		+
Farm GAS		+			+	+		+				+						+	+	+
FSGGEC					+								+				+		+	+
GaBi			+		+			+	+	+			+			+			+	+
GEMIS			+		+			+	+					+					+	
HGCA 1								+											+	
HGCA 2								+			+							+	+	
IFSC		+		+	+		+	+			+	+	+			+		+	+	
openLCA			+		+			+	+				+			+				+
SALCA			+		+			+	+	+			+			+			+	+
SimaPro			+		+			+	+	+			+			+			+	+
Umberto			+		+			+	+	+			+			+			+	+

frameworks) for reporting the national specific GHG emissions from biofuel production, e.g. $ENZO_2$ in Germany. The calculators in this group are either available as an Excel document, in which case calculation functions, emission values and intermediate results can easily be reproduced, or have a web-based user interface where modification can only be rendered manually via input data.

Calculators designed for product assessment are well suited for revealing the relationship between different production levels. The software-based calculators are in general more time consuming and require a basic knowledge of agronomy and basic computer skills. Standard values for energy crops are available and different scenarios can be calculated by the user with only a small amount of input data. However, these standard modules only contain global or national mean values, and have to be modified by the user for regional calculations. In order to model new energy crops, datasets from farm operations, machinery, and mineral and organic fertilizers (including digestate) are available in the integrated databases. However, the user must pay particular attention to the inclusion of field emissions and also to which Tier is used to calculate these emissions.

The goals of a CFP study should always correspond to the goals of the chosen calculator and to the defined target user groups, otherwise the results of the study could be misinterpreted. At the very least, the calculator chosen should be in the same purpose category as defined by Colomb et al. [14]. The user should bear in mind that it is difficult to draw a meaningful comparison of results across similar production chain studies using different calculators with different goals, as these goals affect the system boundaries and the calculation approaches used.

All 18 investigated calculators can calculate the GHG emissions from "cradle to farm gate", and these results can be integrated in further CFP of bioenergy production chains. The defined system boundary affects the processes, activities and sources included in each calculator. System boundaries in CFP studies from agricultural production systems vary greatly within and among the same production chains [17]. Significant differences in GHG emission results can occur from the same dataset of one bioenergy production chain, depending on the calculator used [55]. The results show that it is crucial which farming processes are integrated in the calculator, which calculation pathway and allocation method is used, and if the whole cropping cycle (e.g. perennial crops) or crop rotation is included [44].

Various crop cultivation CFP studies have been based on secondary data from statistics or literature. Input data based on global or national statistics can be used to assess the GHG emissions from typical cropping systems at the global or national level, but not to assess the influence of regional pedoclimatic conditions and specific management practices on GHG emissions [17]. Therefore, the user should identify the type of available input data and the assessment goal and scale for the CFP study before choosing the calculator and the calculation scale, respectively.

The allocation of GHG emissions among the individual byproducts of energy crop cultivation, as well as the subsequent use of the byproduct's burdens in other production cycles, are major methodological challenges. The inaccuracy of the CFP results can increase with each allocation step performed in one LCA, and the results are fundamentally affected by the choice of allocation method [45]. Six of the calculators in the analysis share the emissions of the system among the different co-products by using a specific indicator as recommended by ISO Standard 14067 [11]. Physical indicators (e.g. weight or energy content) appear to be most scientifically accurate, as they use physical principles instead of societal values, but economic indicators reflect the driver of the process through product demand. However, market prices can differ among countries and can lead to different CFP results [20]. Expansion of the system boundary can help to foresee the effects on GHG emissions through changes induced by substituting products. The integrated allocation method should always be transparent for the user of the calculator and in compliance with the intended purpose of the CFP study.

According to the scope of the study, the user should select the functional unit carefully, because different functional units can lead to contradictory interpretations of the results. Calculators can provide the results in two ways: for the assessed process, or as result of a comparison of two scenarios (baseline vs. end of project). Calculators providing the GHG emissions separately for each emission category have a greater potential for identifying mitigation options. Users should pay attention if the GHG emissions are reported in CO_2 equivalents or as individual GHGs, e.g. N_2O, CH_4, and CO_2, or as N_2O-N, CH_4-C and CO_2-C. The simplest reporting unit for energy crop GHG emissions assessment is by area. However, this unit is not suitable for reporting GHG emissions in the context of renewable energy sustainability, and cannot be included in the calculation pathways for biofuels or bioenergy. In CFP from bioenergy, connecting the GHG emissions to the product is more appropriate. However, this includes several units which are associated with production (kg product, MJ product) and several outputs (main product e.g. kg grain and byproduct e.g. kg straw). For bioenergy-oriented crop cultivation, results should always be related in some way to the next production phase in the production chain.

4.2. Methodology used to account for GHG emissions from energy crop cultivation and management

GHG emissions from crop cultivation depend on local conditions [23]. Therefore, the results from the CFP can be improved by using one of the 14 calculators which take into account national or regional climate and soil conditions.

Datasets from different databases representing the same process can result in different emission factors (emission assessments) affecting the comparison of CFP studies with datasets from different databases. Consequently, for similar inputs (e.g. fertilizer production), emission factors from the same database should be used to quantify different types of inputs (e.g. fertilizer types).

In addition to the GWP based on the IPCC guidelines [26], GaBi, SALCA, SimaPro and Umberto are able to calculate the GHG emissions for other impact assessment methodologies as well (e.g. ReCiPe, Impact 2002+, Eco-Indicator 99, CML, TRACI and IPCC). Furthermore, these calculators offer the possibility of extending the LCA with other impact categories provided, such as acidification, eutrophication, aquatic and terrestrial ecotoxicity, human toxicity, land use and/or ozone depletion. Regardless of the calculator chosen, the user should bear in mind that it is difficult to draw a meaningful comparison of results across similar production chain studies using different time horizons in terms of the GWP for 20, 100 or 500 years or using different impact assessment methodologies to translate life cycle flows to the same impact category impact.

Cultivation of energy crops differs from that of conventional food crops in some aspects which may significantly influence the GHG emissions and their estimation. LCA methodologies have been recently adopted for agricultural products to account better for location characteristics and differences in farming practices, focusing on annual crops [17]. The amount of GHG emissions from energy crop cultivation can be controlled by the choice of crop type, fertilizer, pesticides and machine management and by the design of crop rotations [46].

Indirect emissions from on-farm operations (e.g. machinery use) have a significant impact on the CFP results [23]. However, emissions from production of the agricultural operating needs (e.g. seeds, pesticides, fertilizer, machinery, fuel) are sometimes ignored or only partly addressed by the calculators. Since each calculator accounts for different GHG emission sources, potential users of these calculators need to check which key sources (e.g. production of fertilizer, pesticides, machinery or seeding materials) are covered by the calculator in order to derive mitigation options for their investigated production chain from the results. Furthermore, differences in crop cultivation management can be better detected if the calculator distinguishes among type of fertilizer and pesticides used for crop cultivation, since it has a significant impact on the whole CFP – especially the amount and form of nitrogen (e.g. NH_4-N, NO_3-N, urea-N) of the fertilizer used [30]. Optimizing crop management and nutrient use efficiency by adjusting the use of nitrogen fertilizer according to the crop's needs can directly reduce GHG emissions on the field and also indirectly through reduced fertilizer manufacture [46].

Direct GHG emissions, especially N_2O emissions from managed soils, have a significant impact on the CFP result [47]. However, the calculation of land-based GHG emissions from energy crop cultivation is the stage where the calculators differ most, since different calculation pathways are applied. The methodology used to calculate N_2O emissions from N-fertilization is the main contributor to the derivation among calculator results [44]. In most CFPs, the Tier 1 approach [26] is used to calculate N_2O emissions from managed crops. This approach uses a default emission factor of 1% of nitrogen added to the soil assuming that 1% from mineral and organic fertilizer and crop residues is lost as N_2O to the atmosphere. Using this method, no distinction is made between fertilizer types, crop types or soil characteristics. Calculators following the Tier 2 approach [26] often use the approach from Bouwman et al. [31]. This approach takes into account different regional conditions as well as different crops and fertilizer types (mineral and organic). COMET FARM is the only calculator that adopts the Tier 3 approach and uses the dynamic agro-ecosystem model DayCent to calculate field emissions. Fifteen out of the 18 investigated calculators take into account GHG emissions from crop residues, calculating these GHG emissions according to the Tier 1 approach (as described above). The accuracy of this calculation method can be improved by including crop residues management in the calculation such as the amount of straw left on the field (e.g. HGCA 1 and HGCA2), the quantity of crop residues or the amount of stubble burnt (e.g. Farm GAS) and by using the real nitrogen content of the above-ground biomass (grain and straw) to calculate the nitrogen content of the above-ground and below-ground biomass (this can be integrated by the user in GaBi, open LCA, SALCA, SimaPro and Umberto). Consequently, before choosing one of these calculators, the user should check which nitrogen sources are considered in the calculator and which Tier approach is used, and decide if these are sufficient for their specific goal.

The amount of NH_3 emissions induced by organic fertilizers (i.e. slurry and manure, digestate, poultry manure) depends on the fertilizer type, the fertilizer application rate and method, the daily temperature and a binary variable indicating whether the fertilizer was incorporated within one hour [48]. Seventeen of the investigated calculators can distinguish among types of organic fertilizer. Calculators using the Tier 2 approach of Bouwman et al. [31] for calculating GHG emissions from organic fertilizer application take into account different application methods (e.g. CFT). However, none of these calculators take into account the daily temperature or incorporation time. The properties of digestate are different from conventional organic fertilizer (slurry ore manure) and are affected by the anaerobic, microbial fermentation process and by the substances used in the process [49]. During the production, storage and application of digestate, CH_4, NH_3 and CO_2 emissions can occur [50]. Through organic fertilizer production and storage management as well as the application method, the amount of GHG emissions can be influenced and should be included in the consideration of CFP calculations.

LUC should be included in the CFP assessment, but should be reported separately in the results (ISO 14067). However, some calculators exclude LUC for practical reasons since the methodology used to detect LUC is very complex. Models like RothC [51] (Tier 3 level) can calculate the SOC change on a monthly and regional basis, but also require a lot of input data. Using the Tier 1 approach [26] is less complex, because global emission factors (CO_2 emissions occurring over a period of 20 years) and reference native soil carbon content, depending on soil type and climate region, are provided. It is very important to consider the period of time over which emissions occur, since calculators that do not account for time are unable to calculate LUC-induced emissions [14]. Generally, with a longer time horizon, the yearly rate of SOC change decreases, since SOC change is always faster during the first years after disturbance. This aspect has already been highlighted in Petersen et al. [52], where the authors suggested using a 100-year time horizon when simulating SOC change for CFP studies, based on a 100-year GWP calculation. However, a 100-year time horizon conflicts with the confidence time of many other factors characterizing the agricultural sector (e.g. land use, cropping systems, management regimes) as their defining framework conditions (e.g. consumer demand, economic trends, societal transformation, public policy) are highly volatile and it is difficult to elaborate predictions in the longer term. For agricultural land use decision-making, 20 years should be considered as a more reasonable time horizon, which is why it has been used to include SOC change into CFP according to the Tier 1 approach. However, when changing the cultivation system each year, the effect of management change on the SOC content is not stable and may be disregarded when calculating the CFP from annual crops [26].

In CFP calculation, different tillage systems are accounted for through the different amount of resources used [35]. New technologies and crop cultivation methods have been shown to reduce the direct fossil fuel (diesel) consumption. Diesel consumption is either modeled by the calculator or the user can include the real amount of diesel used. Using mean values for diesel consumption estimates can overestimate the amount of diesel consumption by 47% [35]. Taking real diesel consumption data from the farm is always the most precise way for GHG emission calculations. However, if this data is not available, using diesel consumption models which distinguish among farming operations (tillage, seeding, fertilizing and harvesting) and considering the soil characteristic (e.g. CFT) may be a good alternative to simply dividing the results among tillage systems in general (categories as, e.g. reduced tillage, no tillage) or making no distinction whatsoever.

Not all calculators in this study were designed for specific energy crop calculations. Most calculators are calibrated for a small number of crops and it is not possible to integrate new ones. Furthermore, characteristics related to energy crop cultivation, e.g. digestate application on the field and whole plant harvest, are often ignored or insufficiently considered.

New cropping management systems, such as undersowing, were not considered in any of the calculators under review. Not only does undersowing offer benefits for reducing GHG emissions by minimizing the farming operations required, thus saving fuel, weeds may be replaced by the undersowing crop and the second crop will be further ahead than if it were sown after the primary crop was harvested [39].

The GHG assessment of perennial cropping systems is complex, since it is sometimes impossible to gather data for the whole cropping cycle [53]. Perennial cropping systems are insufficiently considered in the available GHG assessment methods and calculators. As previously mentioned, the crop type is a driving factor for N_2O emissions, but in most approaches perennial crops are not represented and can only be classified as “other crops” or “grass”

[54] or representative data for proper calibration of the models is lacking [17]. Hence, more research on perennial cropping systems and their field emissions is needed. The whole cropping cycle and detailed inventories of agricultural management at each stage of perennial crop cultivation should be included in order to improve the CFP calculation and the reliability of the assessment results [17]. Including the specific characteristics of energy crop type, cultivation management and new cropping management, e.g. undersowing, in GHG emission accounting calculators can reduce the uncertainty in GHG emission assessment and can help users to detect GHG mitigation options in the cultivation process. But to carry out this concept, a high amount of input data with high quality requirements and specific high Tier level GHG emission calculation pathways are necessary.

4.3. Ability to model crop rotation

Seven of the 18 investigated calculators are able to calculate energy crop rotations, but none of these cover the consequences of optimizing the management, sequence and composition of crop rotations. Most of these calculators generate their crop modules as single annual crops, which makes it difficult to display and to determine the effects of the crops on each other. For this reason, it seems challenging for the user to have to evaluate new energy crops and their effect at a specific position in the crop rotation and to model crop rotation effects, such as savings in operating resources (e.g. fertilizer, machinery use) and effects on yield. Neglecting nutrient shifts from one crop to the subsequent crop leads to free-rider situations for crops that consume nutrients left by preceding crops [18]. Consequently, the amount of GHG emissions of the subsequent crop decreases, since the crop does not get charged for its true nutrient and fertilizer consumption. This points out the need to include the effects of crop rotation in CFP. Diverse crop rotations (including the use of catch crops or green manure) can help to reduce the CFP [19]. Expanding the systems' boundaries to consider the whole crop rotation could improve the CFP calculations, because in this way all crops (and thus the effects between them) are included in the CFP. However, most energy crop cultivation CFP studies are performed for one single crop and therefore for a specific product. Hence, the effort for including the whole crop rotation is often too high for users. For this reason, new LCA approaches to account for crop rotation effects in single crop cultivation assessment should be developed, such as the agricultural allocation approach developed by Brankatschk and Finkbeiner [18], and integrated in the existing calculator.

5. Conclusion

In this paper, we identified 18 calculators for GHG emissions for energy crop cultivation that followed the CFP guidelines [11] and adopted the IPCC approaches [26] for calculating emissions from managed soils. However, using the same calculation guidelines does not guarantee the same accuracy of results across all calculators.

Each calculator addresses different goals and user groups, and consequently has individual advantages and disadvantages. This is why users have to work out for themselves the balance between efficiency (time and input data) and accuracy (desired output) when deciding which calculator to use.

The integrated methodology and default emission factors given by the calculator as well as the amount of farming processes included in an assessment correspond to the level of input data required. The main limitations in the assessment of energy crop cultivation management are the failure to account for LUC and to distinguish among fertilizer types including digestate, the lack of distinction among tillage types, and the lack of parametrization of many energy crops in the calculators. Furthermore, the impact on the CFP result by using regional GHG emission assessment methodologies is often overlooked. The ability of the calculators to detect GHG mitigation options through improvements in cultivation management is therefore limited. The methodologies used and the farming operations included in any study have a significant impact on the CFP results, thus emphasizing why CFP results should be carefully interpreted. Differences in integrated methodology and accuracy in energy crop cultivation management accounting make any comparison of results from current calculators virtually impossible.

Only seven calculators are capable of calculating GHG emissions from perennial crops and from energy crops in rotation. This may be due to both a lack of methodological guidance to account for crop rotations (or an entire life cycle of a perennial crop, respectively) and a lack of focus on the agronomical specifics of crop rotations systems. Expanding the system boundaries of a CFP by taking into account the whole energy crop rotation increases the likelihood of identifying GHG mitigation options. However, currently, no reviewed calculator can process the effects from energy crops in rotation as nutrient shifts, reduction in use of agricultural operating needs, sequence and composition of crop rotations as well as integration of catch crops of green manuring. To overcome this shortcoming, existing calculators should be extended by integrating energy crop rotations, or new calculators and methods need to be created.

Acknowledgments

The authors wish to express their gratitude to the members of the project "Development and comparison of optimized cropping systems for the agricultural production of energy crops" (FKZ 22013008), funded by the German Federal Ministry of Food, Agriculture and Consumer Protection through the Agency for Renewable Resources (FNR).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2016.09.059.

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4 Paper 3

The MiLA tool: Modeling greenhouse gas emissions and cumulative energy demand of energy crop cultivation in rotation

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Published in:

Agricultural Systems (2017) 152:67-79

Submitted: 22 September 2016; accepted: 7. December 2016; published online: 28. December 2016

Agricultural Systems 152 (2017) 67–79

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

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ARTICLE INFO

Article history:
Received 22 September 2016
Received in revised form 12 December 2016
Accepted 17 December 2016
Available online xxxx

Keywords:
Carbon footprint
Biogas production
Farm-focused
Crop rotation effects
Life Cycle Assessment

ABSTRACT

Crop rotations are part of current agricultural practice, since they and their effects can contribute to a sustainable agricultural cropping system. However, in current Life Cycle Assessment (LCA) studies, crop rotation effects are insufficiently considered, since these effects are difficult to measure. LCA studies from crop production typically take only one vegetation period into account. As a result, the consideration of how the assessed crop is influenced by the previous crop (crop rotation effects) including: (1) nutrient carryover, (2) reduction in operational requirements and (3) different intensity and timing of farming activities, is outside of the system boundary. However, ignoring these effects may lead to incorrect interpretation of LCA results and consequently to poor agricultural management as well as poor policy decisions. A new LCA tool called the "Model for integrative Life Cycle Assessment in Agriculture (MiLA)" is presented in this work. MiLA has been developed to assess GHG emissions and cumulative energy demands (CED) of cropping systems by taking the characteristics of crop cultivation in rotation into account. This tool enables the user to analyze cropping systems at farm level in order to identify GHG mitigation options and energy-efficient cropping systems. The tool was applied to a case study, including two crop rotations in two different regions in Germany with the goal of demonstrating the effectiveness of this tool on LCA results. Results show that including crop rotation effects can influence the GHG emission result of the individual crop by −34% up to +99% and the CED by −16 up to +89%. Expanding the system boundary by taking the whole crop rotation into account as well as providing the results based on different functional units improves LCA of energy crop production and helps those making the assessment to draw a more realistic picture of the interactions between crops while increasing the reliability of the LCA results.

1. Introduction

The use of biomass for energy production has been promoted as an environmentally friendly and energy-efficient way for heat, electricity and fuel production compared to fossil fuels. It is assumed, that the well-considered expansion of bioenergy production can improve the sustainability of energy generation by reducing greenhouse gas (GHG) emissions and by helping to secure energy supply (European Commission, 2009). However, a rush into bioenergy production can cause serious environmental concerns, especially when energy crops (EC) are used for bioenergy production, as in case of Germany where increased maize-based biomethane production has caused a specialization in maize in short rotations, up to the point of monocultures (Koçar and Civaş, 2013). These practices result in less diversified crop rotation (CR, the sequence of crops grown on the same field), which in turn can generate potential environmental problems such as soil damage through soil erosion or soil compaction, or an increased risk of nutrient leaching (European Environment Agency, 2007).

Although the energy production from ECs has been promoted as "GHG emission neutral" regarding the almost-closed CO_2 cycle, in which the combustion of biomass releases the same amount of CO_2 that was assimilated during crop growth, the GHG emissions originating from the production and use of fertilizers, pesticides, and farming machinery for EC cultivation need to be considered as well (Cherubini et al., 2009). Consequently, crop management has a major impact on the amount of GHG emissions from EC cultivation and correspondingly on the entire bioenergy production chain (Blengini et al., 2011; Davis et al., 2013). As the demand for arable land for food, feed, chemical, and energy production increases, it is important to prioritize EC production

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http://dx.doi.org/10.1016/j.agsy.2016.12.008

systems that are the most energy efficient with regard to the land area used and potential for high GHG emission reduction relative to fossil fuels (Börjesson and Mattiasson, 2008). As a result, there is a growing demand for farmers, driven by political and societal pressures, to implement sustainable cropping systems in the context of energy efficiency and GHG mitigation options.

1.1. Approaches to sustainable crop management assessment

In order to cope with the challenges of sustainable crop management, assessment tools are needed to detect GHG mitigation options and energy efficient systems. The most widely used approach is Life Cycle Assessment (LCA), defined by ISO Standards 14044 and 14044 (Buratti and Fantozzi, 2010; ISO 14040, 2006; ISO 14044, 2006). LCA is defined as a method for compiling and evaluating all inputs, outputs, and the potential environmental impact of a production system throughout its life cycle. It enables the user to measure and quantify the environmental impacts of a product. Furthermore, it helps to identify hot spots where the most significant impacts occur, enabling the user to develop strategies for improving the product's environmental performance (ISO 14040, 2006).

There are a considerable number of tools available working with the LCA approach to calculate GHG emissions from agricultural products (Colomb et al., 2012, 2013; Denef et al., 2012). These tools differ in terms of system boundary (processes included), scales (area and time) and methods used to calculate emissions during crop cultivation. Most tools designed for EC assessment, e.g. *BioGrace* (BioGrace, 2015) or the *Biomass Carbon Calculator* (BCC, 2015), use GHG emission assessment methods and default values on a global or national scale, which limits their ability to consider the site-specific and complex nature of GHG emissions from EC cultivation. As an alternative approach, complex process-based ecosystem models such as RothC (Coleman et al., 1997) can be applied to calculate the soil emissions at field level. However, these models require a large amount of detailed input information (e.g. climate, soil, and management data) with a fine resolution (e.g. daily values) and their implementation is often so complex that the use of such models for LCA studies is often impracticable (Peter et al., 2016).

The *Cool Farm Tool* developed by Hillier et al. (2011) is a multivariate empirical farm-scale tool which takes climate conditions and crop management into account and can detect management-relevant GHG emissions with little effort regarding data requirements and usability. This tool was mainly designed for cash crop and livestock modeling of one crop per year, but ECs can be calculated as well. However, the limitation of the calculated time period (one year) and amount of crops (one crop) can increase the modeling uncertainty, since agricultural systems are highly complex and not all underlying material flows can be quantified when the assessment is limited to such a short time period (Brankatschk and Finkbeiner, 2015).

Unfortunately, ECs have special characteristics that make it difficult to use these assessment tools. Either the tool is not specific enough to capture farm-level analysis, or it does not take into account aspects of cultivation and plant type specific to ECs, or it is limited in scope with respect to CR practices.

ECs are agricultural crops solely cultivated for energy-related use. Several food crops (e.g. maize or sugar beet) can also be grown as ECs if they produce high yields and, preferably, have a low demand for agrochemical inputs (Cherubini et al., 2009). EC cultivation can differ in comparison to traditional crops in terms of sowing and harvesting dates, cultivation management, e.g. increased fuel use for the whole plant harvest, tillage frequency, and fertilizer quantities as well as the use of by-products, such as digestate (Cherubini et al., 2009; Rehl et al., 2012). These special characteristics of EC cultivation can significantly influence the LCA results and should be considered.

LCA studies also must adequately address the nature of perennial crops. Perennial crops can have several benefits compared to annual crops; for example, the inputs of a perennial cropping system are lower, since the crop only has to be established once to support multiple years of harvest (López-Bellido et al., 2014). In LCA studies of perennial crops, the system boundaries are either set to one single production year or to the entire life cycle, from crop establishment to the final harvesting period. When describing the crop management of perennial crops, the whole life cycle should be taken into account, since the agricultural performance of the crop correlates with the age of the plants. During crop establishment and at the end of the crop cycle, productivity is lower than in the years between these two phases. Consequently, the LCA results of perennial crops may be underestimated when assessing a single cultivation year and ignoring the other cultivation stages. Hence, the inclusion of detailed inventories of agricultural management at each stage of perennial crop cultivation would improve LCA calculation and the reliability of the assessment results (Bessou et al., 2013a).

CR design influences the cultivation management, e.g. the use of fertilizer and pesticides, the length of cultivation period of the individual crop, and crop yield (methane potential) which consequently has an impact on LCA results (Brankatschk and Finkbeiner, 2015). LCA studies from annual EC (Alluvione et al., 2011; Börjesson et al., 2015; Börjesson and Tufvesson, 2011) typically take only one vegetation period from seedbed preparation to harvesting into account. The influence of the previous crop on the assessed crop (CR effect) is often outside the system boundary. As a result, calculation systems disregards CR effects such as: (1) nutrient carryover, (2) reduction in the use of agricultural operating needs and (3) different intensity and timing of farming activities. When looking at one vegetation period, it can be difficult to evaluate the exact nutrient supply, since each crop uses different amounts and sources of nutrients, including decomposing residues of the preceding crop. Good farming practice uses an optimal fertilization plan including mineral and organic fertilizer, crop residues, and green manuring crops to provide the soil with an optimal nutrient amount and balance (Brankatschk and Finkbeiner, 2015). Fertilization plans for the basic nutrients e.g. P_2O_5, K_2O, MgO and $CaCO_3$ are often designed for a time period of two to four years, where the fertilizer is not regularly applied each year. Crop residues remaining on the field and the introduction of green manure crops in the CR can have a major impact on the subsequent crops by affecting soil properties including nutrient content and fertility, and correspondingly the achievable yield (Nemecek et al., 2015). Green manuring crops increase the soil N availability, once the biomass mineralizes, and decrease the fertilization needs of the subsequent crops (Tribouillois et al., 2015). By disregarding CR fertilization plans and the nutrient uptake efficiency of each crop, the carryover of nutrients from one crop to the subsequent crop are neglected; this leads to a free-rider situation for crops that consume nutrients which were applied to and left over by preceding crops. Consequently, the amount of GHG emissions and cumulative energy demand (CED) of the subsequent crop appears artificially low, since the crop does not get charged for its true nutrient and fertilizer consumption (Brankatschk and Finkbeiner, 2015).

LCA approaches also must more accurately take into account the wide range of CR techniques. CR design and the diversification of CR patterns offer options to reduce GHG emissions and CED in agricultural cropping systems (Nemecek et al., 2015), including the integration of undersowing crops (sowing a secondary crop underneath the growing main crop). Undersowing has some benefits as minimizing the farming operations required, e.g. saving fuel and usage of pesticides, since weeds may be suppressed by the undersowing crop, and the second crop will be further ahead in growth than if it were sown after the primary crop was harvested (Merker et al., 2010). However, no agreement has yet been achieved about whether and how CR effects are to be included in LCA via a uniform approach, even though these effects can have a strong influence on the total LCA result of each single crop in the rotation as described above.

1.2. Aims and objective

Currently available LCA-based tools to assess emissions of agricultural products can account for differences in local agricultural management practices, pedoclimatic conditions, farming practices, and farming technologies (Bessou et al., 2013b); however, all are lacking in the consideration of the characteristics of perennial crops (Bessou et al., 2013a) and CRs (Brankatschk and Finkbeiner, 2015). To overcome this limitation, we developed a LCA tool called the "Model for integrative Life Cycle Assessment in Agriculture" (MiLA) for assessing GHG emissions and CED of agricultural cropping systems including ECs. MiLA is based on the farm-scale approach of the Cool Farm Tool (Hillier et al., 2011) and was expanded to account for the specific characteristics of annual and perennial EC cultivation in rotation. This tool – which requires a moderate level of effort regarding data quantity and usability – enables the user (1) to assess and analyze cropping systems at farm level, (2) to identify GHG mitigation options and the most energy-efficient cropping systems available for their farm and region, and (3) to identify management options which would have a positive impact on both GHG emissions and CED. The objectives of this paper are to:

(1) describe the tool and the methods used for integrating CR effects into LCA calculations and
(2) demonstrate the performance of this approach on LCA results by applying the tool to a case study including two CRs containing perennial and annual crops in two different regions in Germany.

2. Tool description

MiLA is a Microsoft Excel® 2010 based, multivariate empirical tool available in the English and German language. It is designed to estimate the GHG emissions and CED from EC cultivation in rotation using the LCA approach defined by ISO Standards 14040 (2006) and 14044 (2006). It takes into account the impacts of farm-specific pedoclimatic conditions, crop management characteristics, and CR effects on the GHG emissions and CED from each individual modeled crop. The tool can be used by farmers, private businesses, and scientists to assess GHG emissions and CED of crop cultivation at farm scale and to compare different cultivation systems, crops, and CR in order to provide GHG and energy reduction plans and to increase the crop diversity on field and hence environmental sustainability.

2.1. Background

MiLA was developed within a national joint research project called "Development and comparison of optimized cropping systems for the agricultural production of ECs under varying site conditions in Germany" (the EVA project, Glemnitz et al., 2015). The aim of the EVA project was to test CRs for EC production under varying environmental conditions in Germany to provide suitable agricultural alternatives to the dominant cultivation of maize as an EC. Several plot experiments were carried out on eight experimental stations across Germany, run by regional agricultural authorities. The experimental sites differed in their main agricultural profile and regional geomorphological and bioclimatic conditions. On each site, several four-year CRs were established as randomized plot experiments. The entire experiment was replicated four times in parallel in the following starting years: 2005, 2006, 2009, and 2010. Description of the sites, measured parameters, design of the CRs and initial results of the indicator assessment can be obtained from Glemnitz et al. (2015). EC-specific characteristics regarding, e.g. crop nutrient contents and biogas generation potential were analyzed in the EVA project, and the datasets derived from this were integrated in MiLA.

2.2. Methodological basis

2.2.1. System boundary

MiLA was developed to assess the GHG emissions and CED at farm scale, or for larger areas that nonetheless share pedoclimatic conditions. For each crop calculation, a field size of 10 hectare (ha) and a field-to-farm distance of 5 km were default values. The system boundaries were set from cradle to farm gate, starting with the production of all farming inputs (e.g. fertilizer) and ending with the harvest of the crop or transportation and ensilage of the biomass, including all indirect and direct GHG emissions and CED related to the crop cultivation (Fig. 1). The biogas plant, including the production of biogas, is outside the system boundary. However, the modeled results can be used for further LCA studies of bioenergy or food production chains (cradle to grave). The modeling approach takes into account different local agricultural management practices specific to EC cultivation, different pedoclimatic conditions, the farming technologies used, and the design of the CR as these factors have a significant impact on the LCA results in the tool (Fig. 1).

2.2.2. Functional units

MiLA focuses on two different aspects: (1) the agricultural process of EC cultivation in rotation and (2) the methane yield which could be theoretically achieved from the harvested biomass fermented in a biogas plant. Consequently, the modeled LCA results are based on three different functional units. The first functional unit is area-based according to ha, for the purposes of comparing food crops and ECs as well as for questions of land-use efficiency. The second functional unit is product-based according to kilogram (kg) of dry matter (DM) of the crop in case this value is needed in further LCA studies of bioenergy or food production chains. The third functional unit is also product-based, but according to Mega Joules (MJ) of methane production potential; this means it is independent of the type of biogas plant and any subsequent production steps used for bioenergy or biofuel production. The output of cash crops included in CR is set to 0 MJ. To calculate the methane production potential of a cash crop would be misleading, since this energy output is always smaller than using the same crop as an EC (whole plant harvest).

2.2.3. Allocation process

Background datasets detailing the production of farming operating material, e.g. fertilizer, were taken from the Ecoinvent database, version 3.1 (Weidema et al., 2013). This database provides datasets for the same product calculated with different allocation methods. We chose the LCA attributional approach, in which burdens are attributed proportionally to specific processes and the system model divides multi-output activities by specific indicators, such as physical or economic characteristics, and mass. Byproducts of treatment processes are considered to be part of the waste-producing system and are allocated together.

Straw as a byproduct can occur when cash crops are harvested. Since MiLA focuses on ECs, we considered this byproduct to be outside the system boundary. However, GHG emissions and CED from straw harvesting can be calculated with MiLA as well as the GHG emissions arising from crop residues if the straw is left on field and incorporated.

Fermentation of biomass in biogas plants results in the main product biogas as well as digestate as byproduct. Even though this production step is outside of the system boundary, MiLA calculates the theoretically obtained methane yield from the harvested biomass and the theoretical digestate yield. Therefore, it is possible for the user to integrate this data into further calculations following their own allocation method. Digestate is a waste product from the biogas production chain, but this waste can be reused as organic fertilizer for crop production. From the moment when digestate leaves the first production chain (biogas production) by transporting it to another farm or storage in a digestate tank, the purpose of the treatment changes from waste disposal to organic fertilizer use, and the digestate thus becomes a "new" product. Consequently, all GHG emissions and CED occurring during storage and transportation should be allocated to the digestate. As a result, MiLA accounts for GHG emissions and energy consumption from the production of organic fertilizer (including manure and slurry from husbandry systems) that occurs during storage and transportation, but not for the upstream biogas or livestock production chains.

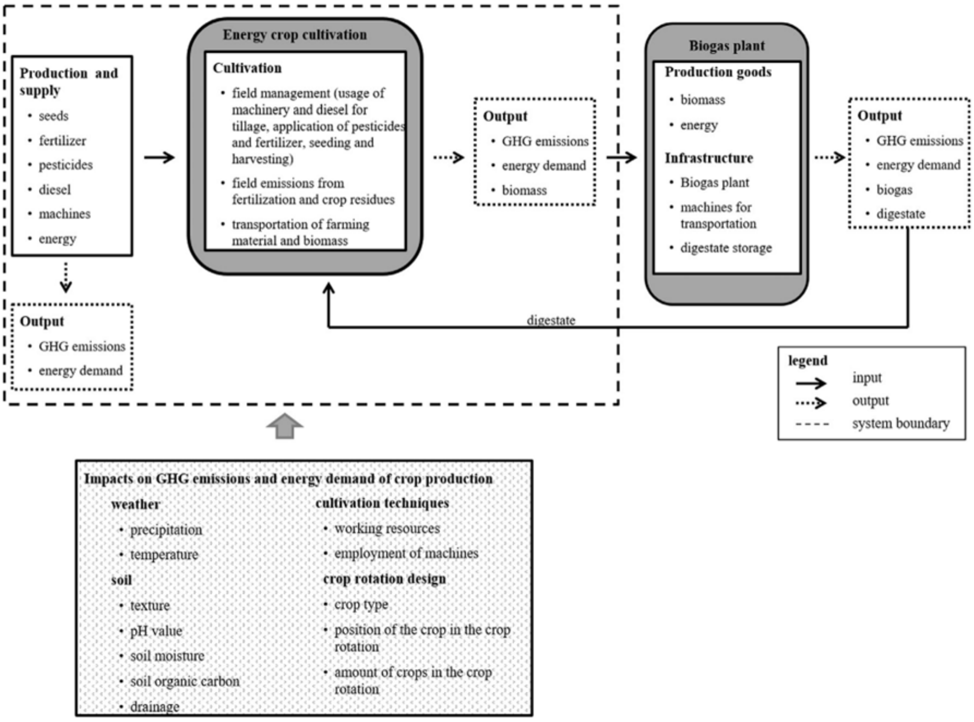


Fig. 1. System boundary and impact factors on GHG emissions and CED of EC production integrated in MiLA.

2.2.4. Indicators

LCA comprises a wide range of impact categories (e.g. resource depletion, ozone depletion, human toxicity, acidification of water and soil, eutrophication of surface water, erosion potential) to assess the sustainability of a product. However, in the context of promoting biogas production from ECs by experts and politicians, the key driver was the potential for GHG emission and CED reduction relative to fossil fuels (Dressler et al., 2012). Therefore, the tool focuses on the impact categories of "climate change" and "CED." All GHG emissions that occur during the production process are aggregated into one single impact category of "climate change" by using the category indicator of "Global Warming Potential (GWP)" for a 100-year time frame following the IPCC, 2013 guideline (Myhre et al., 2013). This guideline specifies characterization factors of $CO_2 = 1$, $CH_4 = 34$; $N_2O = 298$, to calculate the GWP expressed as kg CO_2 equivalent (eq) per unit.

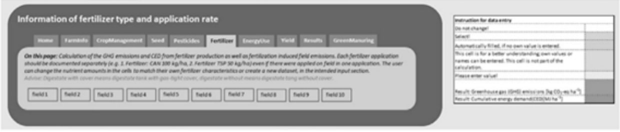
CED comprises the total use of primary energy that is required during the production of the crop (VDI 4600, 1997). The corresponding lower heating value was used to characterize the primary energy amount from different inputs. Furthermore, with help of the CED, it is possible to estimate the energy efficiency and the energy balance of the crop production. Energy efficiency or energy return on investment (EROI) is the ratio between the sum of produced energy (output in MJ methane yield) and the CED (input in MJ) to produce this yield. If the ratio (output/input) is less than one, more energy was needed than produced, but if the ratio is higher than one, the product is an energy source. Energy balance is calculated by subtracting the energy output from the energy input and is used to analyze and verify the transformation and use of energy resources of a production chain in detail.

2.3. Description of tool components

The following sections describe the user interface, integrated databases and calculation approaches of MiLA.

2.3.1. User interface

MiLA consists of multiple sub-modules that calculate GHG emissions and CED according to different aspects of crop production. The tool separates the parameter inputs and presentation of results into ten different worksheets: one sheet presents general information about MiLA, seven sheets are used for data input with presentation of initial results, and two sheets present and summarize results – one with main results and the other with an assessment of the effect of green manuring crops. On each worksheet there is a navigation bar (Fig. 2) that included a short summary about the content of the worksheet as well as switch



Information of fertilizer type and application rate

On this page: Calculation of the GHG emissions and CED from fertilizer production as well as fertilization induced field emissions. Each fertilizer application should be documented separately (e.g. 1. Fertilizer: CAN 100 kg/ha, 2. Fertilizer TSP 50 kg/ha) even if there were applied on field in one application. The user can change the nutrient amounts in the cells to match their own fertilizer characteristics or create a new dataset, in the intended input section.

Advise: Digestate with cover means digestate tank with gas-tight cover, digestate without means digestate tang without cover.

Instruction for data entry
Do not change!
Select!
Automatically filled, if no own value is entered.
This cell is for a better understanding, own values or names can be entered. This cell is not part of the calculation.
Please enter value!
Result: Greenhouse gas (GHG) emissions [kg CO_2-eq ha^{-1}]
Result: Cumulative energy demand(CED)[MJ ha^{-1}]

Fig. 2. Navigation bar and legend in the MiLA tool (originally in color).

areas to navigate between elements on this worksheet and other worksheets more easily.

2.3.2. Site description and crop rotation

MiLA allows the specification of different pedoclimatic conditions by using factor classes or values describing soil (texture, soil organic carbon content (SOC), density and pH value) and climate (climate zone) conditions. These parameters have an impact on the diesel amount and fertilizer induced field emission calculations. The tool also provides options to specify the CR design, including crop type, usage of the crop (e.g. grain for food, whole crop for energy or feed, green manuring crop) and position in the CR (e.g. main crop, catch crop, secondary crop in a double cropping system).

2.3.3. Field operations

MiLA encompasses all agricultural operations for crop cultivation on farm from tillage to ensilage of the biomass. To assess the amount of diesel different operations require, MiLA uses an online database named "Feldarbeitsrechner" developed by KTBL (2015). The diesel amount provided by the database is dependent on the following parameters: machinery type (including operating width and performance of the machinery), soil type and quantity of farming inputs. The amount of diesel of tillage operations depends on the soil texture (fine, medium or coarse) and diesel consumption for harvest operations depends on the amount of biomass harvested. The calculation of CO_2, CH_4 and N_2O emissions from diesel combustion are based on IPCC (2006a). To calculate the primary energy amount of diesel combustion, the lower heating value from diesel provided by the Renewable Energy Directive (RED) (European Commission, 2009) is used.

GHG emissions and CED related to the production of diesel and machinery used for agricultural operations were taken from the Ecoinvent database v. 3.1. The database provides six classes of agricultural equipment: tractors, harvesters, trailers, agricultural machinery in general (e.g. seeders, cultivators, and self-loading trailers), agricultural machinery for tillage (e.g. plows, harrows, and rollers) and slurry tanks (e.g. vacuum tankers and pump tankers).

The LCA inventory takes into account all resources used and emissions occurring during the production, maintenance, and disposal of agricultural machinery (Nemecek and Kägi, 2007). The functional unit is 1 kg of machinery over the entire lifetime. The amount of machinery (AM) needed for each farming operation can be assessed by multiplying the weight of the machinery used by the operation time for each operation and dividing the result by the lifetime (maximum working hours or ha) of the machinery (Nemecek and Kägi, 2007) (Eq. (1), WU = working unit).

$$\mathrm{AM}\left[\frac{\mathrm{kg}}{\mathrm{WU}}\right] = \mathrm{Weight}\,[\mathrm{kg}] * \frac{\mathrm{Operation\ time}\left[\frac{\mathrm{h\ or\ ha}}{\mathrm{WU}}\right]}{\mathrm{Lifetime}\,[\mathrm{h\ or\ ha}]} \quad (1)$$

Information regarding the weight of the machinery used was collected from the producers' websites; information regarding functional life of each machine is taken from the KTBL (2009b) data collection, and the operation time per field operation is from the KTBL "Feldarbeitsrechner" (KTBL, 2015).

To calculate the CED and GHG emissions for each machine used, AM is multiplied by the value from the Ecoinvent database for the corresponding agricultural machinery category. In MiLA, the GHG emissions (or CED) of each field operation is calculated from the production of diesel and machinery as well as from diesel combustion during operation on the field.

2.3.4. Production of farming material

GHG emissions and CED related to the production of farming material used (e.g. seed, pesticides and fertilizer) are also taken from the Ecoinvent database v. 3.1 focusing on datasets representative of Germany or – if unavailable – for Europe. The functional unit is 1 kg of product. The database did not offer information for every crop type included in MiLA. To solve this lack of information, new datasets were created for the missing crops by either using datasets of related crops or – in the case of seed mixtures – combining the datasets of the crop types included in the mixture corresponding to the mixture shares.

In the Ecoinvent database, pesticides are only represented by one averaged dataset named "pesticides unspecific". This dataset was determined from the arithmetic mean of all inputs and outputs of 78 different pesticides. However, there are many different pesticides with different modes of action and ingredients available on the market, and these lead to different amounts of GHG emissions and CED during production. In order to take the characteristics of individual pesticides into account, we created a list of 770 common pesticides used in Europe and integrated it into MiLA. These pesticides were calculated by aggregating the GHG emissions and CED of the pesticide ingredients which were provided by the Ecoinvent database. In cases where no dataset from the pesticide ingredients is available, the aforementioned "pesticides unspecific" dataset is used.

MiLA integrates a catalog of 107 European common fertilizers, providing the shares of their ingredients and values for GHG emissions and CED during their production. The data of 88 mineral fertilizers is taken from the Ecoinvent database v. 3.1. The data of 19 organic fertilizers including animal manure and slurry as well as digestate is taken from other literature (as described in Supplement S1). In the literature, GHG emissions have been calculated using GWP values for 100 years based on reports from IPCC, 1997 or , 2007 (IPCC, 1997; IPCC, 2007); since our tool uses GWP values provided by the IPCC, 2013 guidelines (IPCC, 2013), we re-calculated the GHG emission values in accordance with the data provided in the literature. An overview of the organic fertilizers including nutrient content and value for GHG emission arising during the organic fertilizer production is given in Supplement S1. In MiLA, only GHG emissions occurring during storage of the organic fertilizer are considered; emissions from the upstream biogas or livestock production chains are excluded. We assume that no GHG emissions occur during storage of digestate if the storage tank is covered gastight (Clemens et al., 2006; Liebetrau et al., 2010).

During the storage of organic fertilizer, normally no energy (in form of electricity, heat, or fuel combustion) is required and the CED from production of organic fertilizer would be zero. However, in order to be comparable with the mineral fertilizer datasets, the energy consumed during the construction of the infrastructure (building) was included. To estimate CED values of digestate and slurry, the datasets for the construction of liquid-manure storage tanks (taken from the Ecoinvent database) are used.

2.3.5. Fertilizer and crop residue-induced field emissions

GHG emissions on the field occur after crop residue and fertilizer (organic and mineral) application. According to IPCC (2006b) guidelines, CO_2, N_2O, and CH_4 should be considered for direct and indirect emissions when estimating anthropogenic GHG emissions released during crop cultivation. Indirect N_2O emissions take place via two pathways. The first is volatilization of N as NH_3 and NO_x and their deposition onto soil and water. The second is defined as the leaching and runoff of N from fertilizer application and crop residues. The IPCC (2006b) Tier 1 method was used to calculate indirect N_2O-N emissions from leaching and runoff. The amount of indirect emissions can be converted to N_2O-N by multiplying the NO-N and NH_3-N emission by the default value 0.01 (IPCC, 2006b). N_2O-N emissions are converted to N_2O by multiplying the kg of N_2O-N by 44/28 (the ratio of molecular weight of N and N_2O).

N emissions from agricultural soil systems are influenced by many factors such as crop, soil, water, climate, and fertilizer management (Firestone and Davidson, 1989). The modeling approach of Bouwman et al. (2002c) was chosen to determine direct N_2O-N and indirect NO-N emissions on the field induced by fertilizer application, while the approach of Bouwman et al. (2002b) was applied for NH_3-N volatilization. Both approaches have been validated on a large global dataset from measured agricultural field emissions (Bouwman et al., 2002a, 2002b). The multivariate empirical model of Bouwman et al. (2002c) classifies the parameters influencing N_2O and NO emissions into specific categories for each factor. For N_2O, the significant parameters are fertilizer type and application rate, crop type, soil texture, SOC, soil drainage, soil pH, and climate type, but only data regarding fertilizer type and application rate, SOC, and soil drainage are needed to calculate NO emissions. The approach for NH_3 emissions (Bouwman et al., 2002b) is similar to the Bouwman et al. (2002c) approach, but the significant parameters are fertilizer type, fertilizer application rate and method, crop type, soil texture, soil cation exchange capacity (CEC), soil pH, and climate type. MiLA incorporates a more detailed approach by KTBL (2009a) to calculate NH_3 emissions caused by organic fertilizer applications, with NH_3 volatilization depending on fertilizer type, fertilizer application rate and method, daily temperature, and a binary variable indicating whether the fertilizer was incorporated within one hour (Peter et al., 2016).

For the calculation of N_2O and N_2 emissions resulting from crop residues, the methodological approach described in the German national GHG emission agricultural inventory report (Rösemann et al., 2015), which is based on the IPCC Tier 1 method (IPCC, 2006b), is used. Crop residue is defined as plant matter from crop production that is not used as a product and left on the field, e.g. straw, leaf litter, and stalks. Emissions are calculated proportionally to the amounts of N stored in the aboveground and belowground biomass. The emissions from the decomposition of crop residues are calculated as described by Rösemann et al. (2015), with the integration of crop-specific datasets that were compiled through the EVA project: the N content from aboveground biomass was determined from crop yield analysis conducted in the course of the EVA project as well. The estimated values were specified for each crop type according to different DM contents, crop product harvested, position in the CR, growth stages of the crop (German BBCH scale Meier, 2001) and for perennial crop first cut or subsequent cuts. Supplement S2 provides additional detail on the calculation approach.

CO_2 emissions can occur through SOC stock changes caused by changes in land-use and management practices. According to ISO 14067 (2013), GHG emissions through land-use change should be integrated into LCA studies but documented separately. In MiLA, the GHG emissions caused by land-use change were excluded based on the assumption that only arable areas would be used for crop cultivation which had the same land use before.

CO_2 emissions resulting from the application of urea and liming are calculated based on Tier 1 IPCC (2006a) factors: for limestone 0.12, dolomite 0.13 and urea 0.20.

2.3.6. Electricity used on the farm

On farms, electricity is used for heating, lighting, and various other things. In MiLA, the user can enter the shares of the fuel mix for electricity generation for the given region manually, or use the provided default values for Germany from 2014 to calculate the emissions from electricity use on the farm. However, the use of the integrated sub-module "Electricity on farm" is optional to the user, since its outcome has a rather minor impact on the total LCA results.

2.3.7. Crop yields and calculated methane yields

Crop yield is assessed for the main product, byproduct(s), and each cut. This input data is needed (1) to calculate the emissions from crop residues left on field, (2) to estimate the possible methane and digestate yield and (3) to assess product-based results. The GHG emission calculation method from crop residues is explained in Section 2.3.5. Biomass-specific methane yields of different ECs are based on results from batch anaerobic digestion tests performed in the course of the EVA project (Herrmann et al., 2016). Therefore, coherent EVA datasets (instead of data from literature) are applied in the tool for determining methane yields per ha. MiLA also gives a list of default values for the calculation of biomass-specific methane yields per ha. These are classified by crop type, DM content of the silage, position in the CR, growth stages of the crop; for perennial crops, there are also classification values for the first cut or subsequent cuts. In order to calculate the methane yield it is first necessary to calculate biomass losses on the field, during storage and withdrawal from the silo. MiLA provides default values for DM losses of ensilage biomass based on DM content of the biomass according to Jeroch et al. (1993). The digestate yield is calculated using the mass balance (silage yield after fermentation [kg fresh matter] − ($CO_2 + CH_4$ biogas yield [kg]; ($CO_2 + CH_4$ biogas yield [kg]) = (methane yield ∗ 0.72) + (biogas yield − methane yield) ∗ 1.98)).

2.3.8. Crop rotation effects

MiLA considers CR effects such as nutrient carryover from one crop to the subsequent crops. Before that, the user has to choose the number of crops following in the CR for which the nutrients applied via basic fertilizers or green manuring crops are available. Emissions and CED arising during the production of these fertilizers as well as fertilization-induced emissions from soil are then divided according to the specified number of crops, including the crop where the fertilizer was applied. For cover crops used for green manuring, GHG emissions and CED from the entire cultivation process are divided according to the number of crops that benefit from the nutrients supplied.

MiLA also provides the possibility to take undersowing crops into account. In order to include undersown crops, the user needs to specify the secondary (undersown) crop as its own crop in the CR. The "crop management" sub-model supports an agricultural operation "undersowing (free of charge)," with no environmental burdens counted. All other environmental burdens occurring during the cultivation and harvest of the undersown crop are attributed to this crop and declared in the results.

All cultivation phases of perennial crops can be modeled. The user can decide if the life cycle phases of establishment, main productive phase, and end of life phase are modeled as single crops in the CR according to cultivation years, or as one crop including all life cycle phases.

2.3.9. Presentation of results and graphs

Each worksheet calculates and depicts initial partial results from each cultivation process. These results are summarized in one worksheet called "ResultsGraphs," either in tables (numbers) or in graphics. MiLA calculates each result for all impact categories and functional units, as a total for the CR as well as separately for each crop or for each field. In addition to the CED, energy balance and EROI are also calculated. A separate worksheet called "GreenManuringEffect" shows results accounting for green manuring crops in the CR and compares them to the previously estimated results for each crop.

2.4. Tool usability, quality management, and restrictions

MiLA provides a great deal of sample data to simplify the data entry and different default values in cases where no specific value is available, e.g. N content and raw ash content of the crop; these default values are based on data derived from EVA project results. Furthermore, default information in MiLA can be overwritten if the user has more detailed information available.

MiLA checks the user's data entries for known pesticides or fertilizers. If the entered element is unknown to MiLA, e.g. due to misspelling, the respective unit cell indicates this error by showing a "#NV" value. All further calculations for this crop will be interrupted at this point.

The tool allows the analysis of up to ten plots with different soil conditions including one CR per plot and up to eight crops per CR. The user can decide how many years a given CR encompasses and can specify the number and type of crops that are included. In order to compare different CRs, the same time scale (growing years) should be used. If the farm has more than ten fields or crops per CR, a copy of the tool can be saved separately and the remaining crops can be entered in the copy.

3. Case study

3.1. Description

Data from EVA project experimental trials was used to create a case study and test the performance of MiLA. The case study includes the cultivation of two CR including annual and perennial crops at two different sites (Site 1 in central Germany (S1) and Site 2 in southwestern Germany (S2)). The sites' characteristics are presented in Table 1, including the site-specific data needed to use MiLA.

Two CRs – one including double cropping systems and a green manuring crop (CR 01) and a second one including perennial alfalfa-grass (CR 02, Table 2) – were selected to demonstrate the range of functions of MiLA. The perennial alfalfa-grass was sown as a secondary crop underneath the main crop barley. The barley was harvested in autumn and the alfalfa-grass remained on the field. In the same year and in the following two years, biomass from the alfalfa-grass could also be harvested. Both cropping systems were rain-fed and mineral-fertilized. Site-specific rates of N fertilization were calculated based on field-sampled soil mineral N content in springtime and crop-specific target values from the official recommendation system, which reflects expected crop N uptake during the season. The last crop in the CR was a cash crop, and both grain and straw were harvested.

3.2. Results from the case study

MiLA was used to calculate GHG emissions and CED for the two CRs included in the case study. Table 3 summarizes all data inputs and outputs related to CR management for each crop and site calculated by MiLA after configuring site conditions and CR design, including all management steps. The amount of diesel used to cultivate each crop is one of the outputs provided by the tool. Tillage on S1 entails shallower tillage such as harrowing, in contrast to the plowing on S2. This results in lower diesel amounts used for tillage on S1. The application rate is summarized according to fertilizer type in the table, but when using MiLA each fertilizer application step was taken into account separately (e.g. same fertilizer type application on different days). Methane and energy yield as well as N content of crop residues are outputs of MiLA.

Table 1
Site description of the two experimental sites in Germany (soil data was taken from the first 30 cm of the soil profile).
Source: analyses from the EVA project.

	S1	S2
Name	Dornburg (Thuringia)	Ettlingen (Baden-Wuerttemberg)
Geographical location	51° 00′ N 11° 39′ E	48° 55′ N 8° 24′ E
Average annual temperature [°C][a]	8.3	10.2
Precipitation [mm][a]	584	791
Risk of leaching[b]	No	No
Soil value[c]	65	75
Soil type[d]	Luvisol	Regosol
Soil texture (class[e])	Silty clayey loam (medium)	Sandy silt (medium)
Clay content [%]	23.3	0.2
Silt content [%]	73.5	71.1
pH value	6.2	7.1
Bulk density (g/cm^3)	1.5	1.4
SOC (%)	1.03	0.7
Humus[f]	1.77	1.2
Soil drainage[g]	Good	Good

[a] 30-year average (1961–1990).
[b] risk of leaching regions when the sum of rain in rainy season − potential evaporation > soil water holding capacity then "yes," otherwise "no".
[c] soil rating value (max. 120 points).
[d] according to FAO classification.
[e] soil texture classes based on Bouwman et al. (2002c).
[f] SOC *1,72 (Ad-hoc-AG Boden, 2005).
[g] soil drainage class based on Bouwman et al. (2002c).

3.2.1. GHG emissions

Comparing the GHG emissions from both sites reveals differences between the two CRs and between the same CR at the different sites (Fig. 3, GHG emissions per ha). At both sites, GHG emissions per ha from CR 01 are higher than from CR 02. The emissions resulting from the cultivation of both CRs are always higher at S1 than at S2. At S1, fewer GHG emissions appear during machinery use (including diesel combustion), since less diesel was used for the crop cultivation as a result of shallow tillage compared to plowing at S2 and fewer field passages for fertilizer application. Fertilizer management differs on the sites according to the nutrients applied, as Table 3 indicates. N fertilizer application is nearly the same at both sites, but S2 had higher levels of P and K fertilizer, and lower amounts of $CaCO_3$. However, GHG emissions from fertilizer application (including production and field emissions) are higher at S1 for both CRs than at S2. At S1, more DM biomass was produced in the total CR. As a result, more crop residues were left on the field, resulting in higher GHG emissions arising from the decomposition of residues.

Fig. 3 also shows the result for the functional unit of "kg CO_2-eq GJ^{-1} energy yield." At S1, more GHG emissions per product occur from CR 01 than from CR 02, in contrast to S2. When choosing the functional unit of "kg CO_2-eq t^{-1} DM yield," the same tendencies emerge. More GHG were emitted during the cultivation of CR 01 (178.1 kg CO_2-eq t^{-1} DM) compared to CR 02 (152.9 kg CO_2-eq t^{-1} DM) at S1, but at S2 it is the opposite (CR 01 = 152.1 kg CO_2-eq t^{-1} DM and CR 02 = 163.8 kg CO_2-eq t^{-1} DM).

3.2.2. Cumulative energy demand, energy yield, and energy balance

At both sites, CR 01 has a higher CED than CR 02 (Fig. 4). In contrast to the indicator of GHG emissions per ha, the CED is lower at S1 for both CR productions. The calculated energy yield from CR 01 is higher than from CR 02 at both sites. At S2, the energy yield of CR01 is higher than at S1, which compensates for the higher CED. As a result, the energy balance at S2 is higher than at S1, although the aggregate DM yield of CR 01 is the same at both sites (63.1 t DM). However, the DM yield from maize and sorghum (C_4 crops with the highest methane yield potential in Germany) was higher at S2. This might be due to the fact that this site has better growing conditions (2 °C higher average annual temperature and 200 mm higher yearly precipitation). On the other hand, S1 has better growing conditions for cereals. Therefore, the DM yield was higher for wheat and triticale than at S2. Since cereals have a lower methane yield potential than maize and sorghum, the higher DM yield of the cereals in CR 01 at S1 cannot compensate for the lower maize and sorghum DM yield considering the overall methane yield per ha compared to S2. At S1, higher alfalfa-grass DM yield (CR 02) occurred compared to S2, resulting in a higher methane yield per ha. This can be explained by the fact that at S2, no N fertilizer was used during production, but at S1 130 kg N per ha was applied.

3.2.3. Crop rotation effects

Table 4 shows calculations of GHG emissions and CED for each crop in both CRs and sites with and without the inclusion of nutrient carryover from basic fertilization (included in MiLA). The calculated GHG emissions and CED attributed to each crop in the rotation differ if the crop will be charged only for its true nutrient consumption and carry no more environmental burdens than what is physically true. Consequently, the variation of the calculated result depends on the calculation methods used. Including the nutrient carryover altered the GHG emissions and CED assessment results of w. triticale by <1% but of alfalfa-grass in the establishment year at S2 by +99% (−34% in the second main production year) and CED by 89% (−0.4% in the second main production year). At S2 the CED of w. barley decreases by −16% when the nutrient carryover is included in the calculations but some crops were not influenced at all (e.g. w. wheat CR 01). If nutrient carryover from basic fertilization and green manuring is taken into account the calculated GHG emissions for w. wheat, in CR 01 the following crop after the

Table 2
Crop rotation descriptions.

Crop rotation	Year 1 2009	Year 2 2010	Year 3 2011	Year 4 2012
CR 01 including double cropping systems	**Winter barley**; **sorghum b. × s.**[a]	**Maize**	**Winter triticale**;*phacelia*	Winter wheat
CR 02 including perennial use of forage mixtures	**Summer barley undersown with alfalfa-grass**	**Alfalfa-grass**	**Alfalfa-grass**	Winter wheat

bold = biomass production, normal = cash crop production; *italic* = green manure.
[a] *Sorghum bicolor* × *Sorghum sudanense*.

green manuring crop phacelia, increased by +7% (S2) and +8% (S1) and for CED by +11% (S1) and +13% (S2), while the environmental burdens of the green manuring crop is zero.

4. Discussion

The Tier 1 methods (IPCC, 2006b) for GHG emission calculations from crop cultivation were designed for the assessment of national or global inventories. Tools such as BioGrace (BioGrace, 2015) or C-Plan (C-Plan, 2015) using this method are unable to explain variations at farm level, such as differences in pedoclimatic conditions or management practices (Hillier et al., 2011). MiLA was developed to provide farm-specific emission calculations while requiring only a moderate level of effort with respect to acquiring input data (in terms of quantity and quality) and use of the tool (with a minimum understanding of atmospheric and soil processes). Our case study results showed that MiLA allows for the consideration of variations at farm level such as pedoclimatic conditions and management practice. Nevertheless, the tool and the integrated methods exhibit some uncertainties and limits.

4.1. Regional variation and country-specific applicability

The heterogeneity of soil and weather conditions hamper a sufficiently accurate representation of N_2O, NO, and NH_3 field emissions when using a model. In MiLA, the used approach of Bouwman et al. (2002b, 2002c), only accounts for climate and soil variation through classifying each factor into specific categories. For the specification of climate conditions, for example, only two categories ("temperate" and "tropical") are used, although climate conditions can vary immensely within these groups. Nevertheless, climatic conditions during crop cultivation are indirectly included via the integration of crop yield as input in MiLA. Furthermore, the KTBL (2009a) approach was used to calculate the NH_3 field emissions since this approach differentiates between organic fertilizer types and takes into account the temperature during application of the fertilizer as well as the application method. By combining the two modeling approaches (Bouwman et al., 2002b; KTBL, 2009a), MiLA is able to increase the accuracy of the modeling results compared to Tier 1 national calculation methods (IPCC, 2006b) as proved by Peter et al. (2016).

Fertilization plans for the CR are developed on the farm level according to the soil nutrient values of each field and to the soil fertility rating (German Agricultural Rating System for Soil Fertility (Bodenschätzung), the best value is 100) which is derived from soil type, origin and condition as well as climate and water availability (BodSchätzG, 2007). In the study, Site S2 has a higher soil fertility rating than S1, which indicates that S2 has a better nutrient storage capacity. Therefore, S2 requires less fertilizer to achieve the same yield as S1. The N fertilizer application rate was nearly the same at both sites, but differences in P, K, and $CaCO_3$ fertilizer application rates occurred between the sites. Though the production of N fertilizer is much more GHG emission intensive than P, K, and $CaCO_3$ fertilizers, the production of 1 kg PK fertilizer causes 99% more GHG emissions than 1 kg of $CaCO_3$ fertilizer (Weidema et al., 2013). However, in contrast to PK fertilizer, N and $CaCO_3$ fertilizers cause direct GHG emissions on the field. Since more $CaCO_3$ fertilizer was applied at S1, the GHG emissions from fertilizer application (including production and field emissions) are higher at S1 for both CRs than at S2. Not only did fertilizer management have an impact on GHG emissions arising from fertilizer application, but also the soil characteristics, e.g. 222 kg of calcium ammonium nitrate (CAN) with 27% N content applied at both sites for the same crop (barley), resulted in 237 kg CO_2 eq ha^{-1} at S1 and 211 kg CO_2 eq ha^{-1} at S2; this results in a difference of ~26 kg CO_2 eq ha^{-1}. S1 has a higher SOC and cation exchange capacity than S2 and these soil characteristics are two parameters that influence the N_2O and NH_3 emissions calculations based on the approach of Bouwman et al. (2002b, 2002c). Results demonstrate that site characteristics and applied crop management (e.g. choice of fertilizer type and amount) have a major influence on overall GHG emissions. MiLA takes these aspects into account, enabling the user to develop a better understanding of the GHG emission process and to reduce modeling uncertainties.

Further uncertainties can arise if the tool is applied outside of Europe, since the integrated dataset for production of farming goods is taken from the Ecoinvent database representative for Germany or for Europe. For example, the production of 1 kg N of CAN produces an average of 8.5 kg CO_2 eq kg^{-1} N (CED of 68.4 MJ kg^{-1} N) in Europe, but a worldwide average of 8.2 kg CO_2 eq kg^{-1} N (CED of 62.1 MJ kg^{-1} N) (Weidema et al., 2013). The amount of GHG emissions and CED for the production of fertilizer varies between countries, which may be due to the fact that each country has different infrastructure systems, transportation distances and fertilizer production techniques. The production and application of fertilizers is responsible for a significant amount of emissions and consequently has a significant impact on the total LCA result (Hasler et al., 2015). Therefore, using country-specific and up-to-date data can substantially decrease the model uncertainty. If the user has access to country-specific production data, this data can be entered into MiLA to further decrease the tool's uncertainty. If this data is not available, MiLA can still be used, as it provides many default values originating from an identical data source – the Ecoinvent database.

To assess the amount of diesel of different agricultural operations, MiLA utilizes datasets from the KTBL (2015) "Feldarbeitsrechner." This database uses average values from Germany, and in the tool we only provide datasets from one machine type used per agricultural operation which could lead to modeling uncertainties if different machines are used. However, MiLA provides the possibility to distinguish between different soil textures, which is also important in different countries and user can enter their own or a country-specific diesel demand in l ha^{-1} for each agricultural operation.

4.2. Crop rotation effects

As Brankatschk and Finkbeiner (2015) noted, CR effects in current LCA practice are insufficiently considered since it is difficult to quantify them. However, even though these effects are difficult to measure, CRs (and their effects) are part of current agricultural practice and they can contribute to a sustainable agricultural cropping system by increasing the diversification of CR patterns which can improve soil fertility, yield, and environmental soundness. Through the expansion of the system boundaries by taking the whole CR into account, CR effects such as nutrient carryover via basic fertilization or green manuring are automatically included in the LCA estimations. Typically, when single crops from the CR are calculated separately, these considerations are often

Table 3
Field trials: list of inputs and outputs from both CRs at both sites as calculated by MiLA.
Source: Authors' calculations using the MiLA tool.

	Unit	CR 01												CR 02									
		W. barley		Sorghum b. × s.[a]		Maize		W. triticale	Phacelia			W. wheat		S. barley	Alfalfa-grass			Alfalfa-grass		Alfalfa-grass		W. wheat	
		2009				2010		2011				2012		2009				2010		2011		2012	
		S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Agricultural operations																							
Tillage	l fuel ha^{-1}	3.4	46.0	3.4	15.1	7.0	27.0	26.6	11.8	11,9	10.0	4.0	15.2	35.4	36	–	–	–	–	–	–	43.5	15.2
Seeding	l fuel ha^{-1}	5.2	5.2	5.2	12.5	2.5	12.5	5.2	5.2	4.5	5.2	5.2	5.2	5.2	5.2	–	–	–	–	–	–	4.5	5.2
Fertilization	l fuel ha^{-1}	1.9	2.7	0.8	0,85	1.6	0.9	3.4	2.6	–	–	2.7	3.7	1.2	3.5	–	–	4.5	–	0.7	1.3	1.4	2.7
Application of pesticides	l fuel ha^{-1}	1.8	1.8	0.9	0.9	1.8	1.8	1.8	1.8	–	–	2.7	3.6	0.9	–	–	–	0.9	–	–	–	2.7	3.6
Harvest	l fuel ha^{-1}	50.3	53.7	43.4	57.08	64.6	64.4	50.4	37.4	9.0	9.0	28.7	26.9	43.4	47	18.2	18.7	162.5	242.3	150.7	134	29.4	26.9
Fertilizer application																							
Fertilizer type		CAN[b]	CAN[b] PK[g]	CAN[b]	Alzon[h]	CAN[b]	Alzon[h]	CAN[b] lime[c]	CAN[b] PK[g]	–	–	CAN[b] MS[e]: K60[f] TSP[d]	CAN[b] PK[g]	CAN[b]	CAN[b]; PK[g]	–	–	CAN[b], CC[j]	–	CAN[b]	PK[g]	CAN[b], TSP[d], K60[f]	CAN[b] PK[g]
Fertilizer application rate	kg ha^{-1}	490[b]	222[b], 1578[g]	291[b]	370[h]	589[b]	435[h]	422[b], 2612[c]	223[b], 806[g]	–	–	574[b], 21[e], 53[f], 126[d],	556[b], 300[g]	278[b]	574[b], 1739[g]	–	–	241[b], 4404[j]	–	241[b]	806[g]	481[b],139[d], 120[f]	744[b], 300[g]
Yield																							
Biomass yield	t DM[i] ha^{-1}	13.6	12.6	7.8	15.1	14.6	19.1	17.3	8.3	2.3	1.9	7.6 grain, 4.8 straw	6.1 grain; 3.8 straw	12.3	11.2	1.1	1.3	20.3	12.6	21.1	15.4	7.9 grain 3.7 straw	6.9 grain 4.9 straw
Methane yield	Nm^3 ha^{-1}	3808	3843	1963	3767	4024	5532	4792	2332	–	–	–	–	3318	3022	281	323	4549	2848	4740	3518	–	–
Energy yield	GJ ha^{-1}	137	125	71	136	145	199	173	84	–	–	–	–	119	109	10	12	164	103	171	127	–	–
N content of crop residues	kg N ha^{-1}	41.9	38.9	11.9	23.2	22.5	29.3	34.2	16.4s	36.5	30.6	25.7	20.4	37.9	34.6	10.7	10.7	36.6	27	47.1	33.3	26.7	21.9

[a] *Sorghum bicolor* × *Sorghum* sudanense.
[b] CAN = calcium ammonium nitrate (27% N content).
[c] burnt lime (66% Ca content).
[d] TSP = triple superphosphate (46% P_2O_5 content).
[e] MS = granulated magnesium sulfate (15% Mg content and 21% S content).
[f] K 60 = potash and magnesium fertilizer 60% K_2O.
[g] PK = compound PK with magnesium (12% P_2O_5, 19% K_2O and 5% Mg, 4% S).
[h] Alzon = urea fertilizer with nitrification inhibitor (46% N content).
[i] DM = dry matter.
[j] CC = calcium carbonate.

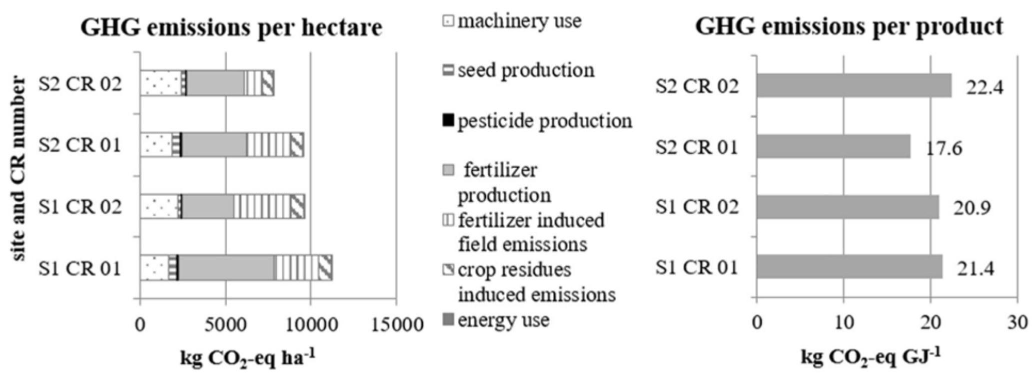


Fig. 3. Comparison of GHG emissions totaled over the whole CR per ha (left) divided into GHG emission categories, and the GHG emissions per product energy yield (right) at both sites.
Source: MiLA, based on authors' calculations.

omitted. In MiLA, these aspects are accounted for in the LCA calculations of single crops. The tool takes into account all inputs and outputs related to crop management from the whole CR on each field and thus includes inter-crop relationships. As the results show, the tool makes it possible to attribute the benefits of nutrients from basic fertilization left for the subsequent crops in the CR and hence only the nutrients consumed are apportioned to each crop.

In our case study, both CRs end with wheat as the last crop. In CR 02, GHG emissions and CED per t DM yield were less and the DM yields of wheat were higher than in CR 01 at both sites, which could be caused by the positive influence of the legume (alfalfa-grass) cultivated before wheat in CR 02. If a practitioner only compared the two wheat LCA results with each other, without the information of the crop management of the previous crops in the rotation, it is difficult to understand why a higher yield could be achieved by the wheat of CR 02 even though less fertilizer was applied. Furthermore, including all CR effects, the GHG emissions per ha from wheat in CR 02 is higher than in CR 01 on S1. The wheat benefits from the basic fertilizer applied to alfalfa-grass and nutrient carryover thus needs to be considered in order to assign GHG emissions to the crops consuming the nutrients – not only to the crop where the nutrients were applied. This example indicates the need to include interactions among crops of a CR in LCA studies. These effects can be also integrated into the LCA by including the whole CR if the aim of the study is to assess a single crop in the rotation (Brankatschk and Finkbeiner, 2015).

Modification of the system boundary is well known in LCA practice, but is not often used for agricultural systems. However, introducing the whole CR into an LCA study of a specific crop can cause problems regarding the different outputs (products) of the crops grown in the rotation; it is also much more difficult for those making LCA evaluations to handle the complexity of so many outputs. MiLA makes it possible to tackle these problems with a moderate amount of effort by including different functional units; this allows the assessment of the whole CR without using an additional allocation method.

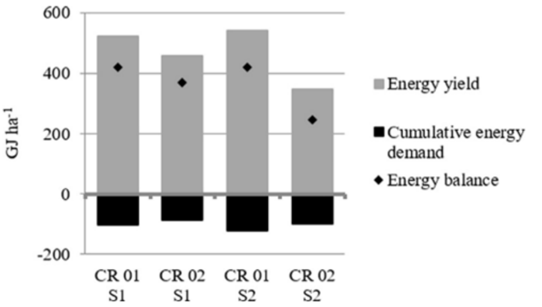


Fig. 4. Comparison of the energy yield, CED, and energy balance of CR 01 and CR 02 at both sites.
Source: MiLA, based on authors' calculations.

4.3. Perennial crops

The GHG assessment of perennial cropping systems is complex, since it is sometimes impossible to gather data for the whole cropping cycle. Therefore, most available GHG assessment methods and calculators insufficiently take perennial cropping systems into consideration (Bessou et al., 2011). Crop type is a driving factor for N_2O emissions on field, but in the approach of Bouwman et al. (2002c), perennial crops are not represented and can only be classified as "other crops" or "grass." This may be due to the fact that representative data for proper calibration of the models is lacking (Bessou et al., 2013a). The uncertainty regarding perennial crops can be reduced by taking the whole cropping cycle and detailed inventories of agricultural management at each stage of perennial crop cultivation into account (Bessou et al., 2013a). The benefit of modeling all perennial crop life cycle stages (as MiLA does) is that each stage can be evaluated separately for mitigation options and an average value per year can still be calculated.

The case study showed that perennial grasses included in CRs can have environmental benefits compared to CRs with only annual crops. GHG emissions and CED from CR 02 with perennial alfalfa grass were always lower at both sites than from CR 01. This is due to the fact that the perennial alfalfa grass was cultivated for 2.5 years; consequently, in this four-year CR, only three different crops were cultivated compared to six in CR 01. As a result, in CR 02 only three phases of tillage and sowing were required compared to six times for CR 01, resulting in lower GHG emissions and a CED reduction for CR 02. Another advantage is that the cultivated perennial crop left fewer residues on the field than the four annual crops cultivated in CR 01; moreover, alfalfa-grass is a legume with a low nitrogen demand, resulting in a decrease of GHG emissions from soil. One disadvantage of the perennial crop, however, is an increased amount of diesel for harvest since alfalfa-grass was harvested four to five times a year.

4.4. Land-use change

The influence of SOC change on the LCA result of annual crops could be strongly related to the long-term SOC dynamic, subsequent to crop choice and to the management regime, which determines the amount of organic residues returned to the soil. However, in the MiLA tool GHG emissions from SOC change are excluded, since at this moment to our knowledge no intermediate effort approaches exist to model these emissions for this short time period and at farm scale and the

Table 4
GHG emissions and CED from each crop in CR 01 and 02 at both sites calculated with the MiLA tool taking into account nutrient carryover from basic fertilization and green manuring and omitting this consideration.

			Nutrient carryover from basic fertilizer application and green manuring											
			Omitted				Included (only basic fertilizer)				Included (both)			
			GHG emissions [kg CO_2 eq ha^{-1}]		CED [GJ ha^{-1}]		GHG emissions [kg CO_2 eq ha^{-1}]		CED [GJ ha^{-1}]		GHG emissions [kg CO_2 eq ha^{-1}]		CED [GJ ha^{-1}]	
CR no.	Crop	Year	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
01	W. barley	2009	2390	1931	19.7	26.7	2390	1649	19.7	22.4	2390	1649	19.7	22.4
	Sorghum	2009	1311	1426	12.9	22.4	1311	1567	12.9	24.6	1311	1567	12.9	24.6
	Maize	2010	2509	1666	23.0	26.2	2509	1807	23.0	28.4	2509	1807	23.0	28.4
	W. triticale	2011	2125	1849	21.5	20.0	2121	1849	21.4	20.0	2121	1849	21.4	20.0
	Phacelia	2011	240	170	2.7	2.8	206	170	2.7	2.8	0	0	0.0	0.0
	W. wheat	2012	2629	2465	24.0	22.1	2631	2465	24.0	22.1	2837	2635	26.7	24.8
02	S. barley	2009	1703	2907	17.2	30.9	1703	2596	17.2	26.1	1703	2596	17.2	26.1
	Alfalfa-grass	2009	156	157	2.6	2.7	156	312	2.6	5.1	156	312	2.6	5.1
	Alfalfa-grass	2010	3719	1268	23.6	26.6	2421	1423	23.5	29.0	2421	1423	23.5	29.0
	Alfalfa-grass	2011	1728	998	21.1	18.1	2377	998	21.1	18.1	2377	998	21.1	18.1
	W. wheat	2012	2288	2428	23.4	21.7	2937	2428	23.5	21.7	2937	2428	23.5	21.7

bold = green manuring crop.

Tier 1 approach provided by the IPCC (2006b) insufficiently accounts for the SOC change from annual crops at farm scale (Peter et al., 2016).

4.5. Functional unit

As shown in the case study, calculations based on different functional units can lead to different outcomes. Therefore, MiLA includes different functional units to enable the user to choose the functional unit according to the LCA study goal. Each functional unit has its benefits. To compare crop cultivation systems from different production chains, e.g. food or bioenergy, the functional units of per ha and per t DM yield can be used. With these functional units, entire CRs can be compared, independent of the crops included and their end use. In contrast, it is difficult to evaluate the environmental impacts of a CR containing both energy and cash crops if the functional unit is based on energy yield of the methane yield per ha. It should be noted that changes in crop management can lead to changes in yield, so mitigation options may appear to be effective on an area-based functional unit, but may not be on a product-based functional unit (Hillier et al., 2012). Therefore, if the purpose of the study is to answer the question of relative land-use efficiency of different arable land uses, the functional unit should be expressed on a per hectare basis. Since arable land for crop production may become a limited commodity in the future, land should be used as efficiently as possible (Cherubini, 2010). If the purpose of the study is to compare EC as feedstock for biogas production, the result should be expressed on a per-unit output (e.g. energy yield) basis; to be independent from any further end use, t DM can be used as the output unit. Both functional units can be used to ascertain the production pathway that has the highest energy efficiency and GHG reduction potential (Cherubini et al., 2009) and allow a comparison with other feedstocks or fossil fuels when the results are integrated into a cradle-to-grave LCA study (Davis et al., 2013).

4.6. Allocation of digestate

The LCA approach offers different methods to allocate process emissions to different products (Benoist et al., 2012). The chosen allocation method has a major impact on the overall result of the LCA study, especially for organic fertilizers in EC production (Adams et al., 2015; Rehl et al., 2012). The UK Government Methodology and Biomass Carbon Calculator (BCC, 2015) assumed zero emissions associated with the production of organic fertilizer – i.e. the byproduct digestate (or manure) is considered a waste product with zero energy content and 100% of the emissions are allocated to the biogas (or animal) life cycle. The RED guidelines from the European Commission (2010) suggest allocating byproducts in proportion to their energy content (lower heating value). However, using the lower heating value of organic fertilizer does not accurately value its nutrient content; moreover slurry and digestate, particularly in liquid form, have a limited energy content (Adams et al., 2015). For these reasons, energy content is not an appropriate allocation method for organic fertilizers. Adams et al. (2015) suggested using a substitute approach by giving credit for the mineral fertilizer displaced by the organic fertilizer. Rehl et al. (2012) stated that the most logical allocation method is economic value. However, manure and digestate are not usually sold by farmers; therefore, it is difficult to determine prices. Moreover, market prices would differ among countries and this could lead to different LCA results, or it could be assumed that the market value is zero since byproducts are given away free of charge. Consequently, no environmental burdens arise during the production of organic fertilizer, but during storage and application on the field.

So far, there is no consensus about whether and how emissions during organic fertilizer production are to be included in LCA calculations of crop production. However, the most suitable allocation approach should be chosen based on the LCA study goals and appropriately documented in order to be able to compare studies calculated with the same approach. In MiLA, it is assumed that before manure and digestate become productive inputs for the crop life cycle, they were residues (byproducts) of the livestock and bioenergy life cycle. In order to avoid double counting, the environmental burdens emerging during storage and field application of the organic fertilizer are accounted for the crop cultivation process – where the emissions occur – and not in the upstream biogas or animal production chain. The Agri-footprint database (Blonk Agri Footprint BV, 2015) follows the same approach. This allocation approach is easy to apply since (1) less knowledge about the first production chain is needed, (2) the problem of double counting is prevented, and (3) the high uncertainty associated with other allocation methods is reduced.

4.7. Validity of the MiLA tool results in the context of other LCA study results

The comparison of this case study with other LCA studies is hampered by the fact that so far no comparable GHG emission and CED calculations from the same CRs have been published. Only a few LCA studies from CR have been presented (Hülsbergen et al., 2001; Nemecek et al., 2015), but they investigated different crop combinations which cannot be compared to our case study. However, results from single crop LCA studies are available that can be used to evaluate MiLA results. Hülsbergen et al. (2001) calculated an average energy input of 19.3 GJ ha^{-1} (varying between 10.1 and 23.3 GJ ha^{-1}) for w. wheat in a CR. Similarly, the CED of w. wheat in our results varied between 21.7 and 24.0 GJ ha^{-1}. In the report of Giuntoli et al. (2014) the GHG emissions from maize cultivation under varying conditions for electricity production from biogas ranged between 15.5 and 17 g CO_2-eq MJ^{-1} ha^{-1} and the energy input was 1.11 MJ MJ^{-1} ha^{-1} while in our case the GHG emission from maize cultivation varied between 17.5 (S1)–9.2 g CO_2-eq MJ^{-1} ha^{-1} (S2) and the energy input ranged between 0.8 (S1)–0.9 MJ MJ^{-1} (S2). Differences in calculation methods, system boundaries, input data and site characteristics may account for the deviations among the studies. Based on this assessment we assume that the MiLA tool is well-suited to calculate the GHG emissions and CED of EC cultivation in rotation.

5. Conclusion

Agriculture including EC production is a highly complex system influenced by farm-specific factors such as pedoclimatic conditions and crop management. In order to quantify all underlying material flows in the LCA of crop cultivation, reliable methods are needed. For the estimation of actual GHG emissions and CED from EC production in particular, it is essential to consider current crop management practices – including management practices specific to ECs as well as CRs and their effects. Existing LCA tools have a limited ability to fully reflect CR effects, such as nutrient carryover from basic fertilization and green manuring, as well as management-related effects such as reduced fertilizer and pesticide application, higher yields and improved soil fertility. To overcome these shortcomings, the MiLA tool was developed to integrate these aspects. CR effects have a significant impact on the LCA result of each individual crop in the CR. Expanding the system boundary by taking the entire CR into account as well as providing the results based on different functional units improves LCA accounting for EC production and supports the assessment of energy-efficient cropping systems and the development of GHG reduction plans at farm level. The tool is well-suited for product-specific LCAs for energy and food crops and helps users to draw a more realistic picture of the interactions between crops, thus increasing the reliability of the LCA results. This can be done with only a moderate level of effort regarding data quantity and usability. Even though the tool still contains modeling uncertainties regarding the approach to modeling CR effects as well as calculation methods and default values, it can be used by farmers, private businesses and researchers as a first step to understand the complexity of crop cultivation systems and the related environmental burdens as well as to identifying sustainable crop management systems. However, LCA assessment of EC cultivation should consider more than two indicators, ideally additional environmental indicators e.g. biodiversity, erosion potential, eutrophication as well as economic and social indicators, in order to assess most of the sustainability aspects. To close this gap, the MiLA tool could be extended with additional indicators or the presented new approach can be used to improve further sustainability indicators assessment in other models for assessing the regional impacts of EC systems. CR effects should also be included in national and global GHG emission agricultural inventory accountings for a better reflection of agricultural reality. However, the implementation of this approach on a larger scale, e.g. in German national GHG emissions agricultural inventory calculations, could be difficult since the required data is barely available at this level of resolution, and any modeling of such LCA results would be extremely complex and time-consuming. In order to include CR effects in larger-scale LCA assessments, a less data-intensive approach still needs to be developed.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2016.12.008.

Acknowledgements

The authors wish to express their gratitude to the members of the project “Development and comparison of optimized cropping systems for the agricultural production of energy crops” (FKZ 22013008), funded by the German Federal Ministry of Food, Agriculture and Consumer Protection through the Agency for Renewable Resources (FNR).

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5 Paper 4

Impact of energy crop rotation design on multiple aspects of resource efficiency

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Published in:

Chemical Engineering & Technologies (2017) 40:323-332

Submitted: 13 April 2016, accepted: 21 November 2016; published online: 23. December 2016

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Impact of Energy Crop Rotation Design on Multiple Aspects of Resource Efficiency

Biogas production can cause environmental problems due to a biased alignment of one energy crop used as a feedstock, e.g., maize in Germany. Diversification of crop rotations and resource-efficient management can be the key to sustainable crop management. Four crop rotations on eight sites across Germany were evaluated in terms of their resource efficiency (area use, energy, and economic efficiency) to derive options. Analysis revealed high variation in all indicators under review, with a high variance explanation by the interaction between crop rotation and regional characteristics. Furthermore, results indicate that high area-specific methane yields do not equate to high energy efficiency. Crop management adaptation is a useful tool for optimizing resource efficiency.

Keywords: Anaerobic digestion, Biogas production, Cropping system, Methane, Regional crop management

Received: April 13, 2016; *revised:* November 11, 2016; *accepted:* November 21, 2016

DOI: 10.1002/ceat.201600226

1 Introduction

A well-considered development of bioenergy production is assumed to improve the sustainability of energy generation by reducing greenhouse gas emissions and contributing to a secure energy supply [1]. However, the dynamic expansion of bioenergy production can cause environmental concerns, as in the case of maize-based bioethanol production in the USA, sugarcane bioethanol production in Brazil [2], or biogas production in Germany. Recently, arable land used for energy crop (EC) cultivation as biomass feedstock for anaerobic digestion amounted to over one million hectares (ha), representing approximately 8.3 % of the total arable land in Germany [3]. In addition to legal regulations, this trend has accelerated due to pressures for resource-efficient farming and specialization, encouraging maize cultivation in short rotations up to monoculture. Such practices result in diversification losses of crop rotation (CR), which can generate potential environmental damages [4]. Although the amended German Renewable Energy Sources Act [5] restricted the expansion of biogas plants fed with ECs by a reduction of the feed-in tariff system, approximately 7500 biogas plants installed in Germany [3] are under grandfathering and will run for the next 20 years, with sustained demand on crop biomass feedstock.

In general, long and diversely structured CR can improve soil fertility (by enhancing soil structure, reducing soil erosion, and maintaining sufficient content of soil organic matter), nutrient use efficiency (through reduced and demand-oriented fertilizer use), and biodiversity. Effective CR tends to reduce the input of crop protection agents and increase yields [6]. Thus, the benefits of diverse CRs along with improved resource-efficient management are key to sustainable EC management [7].

A large number of arable and novel crops (perennial, annual) can be grown as ECs. Crops with rapid growth, high yield of usable biomass, ability to grow under adverse weather and poor soil conditions, and with high resistance against pests and diseases are favored [8,9]. ECs may involve altered harvest and sowing dates, as well as pesticide and nutrient needs, compared with conventional food crops, and can be implemented in traditional food CRs or in self-contained CRs. However, establishing new cropping systems comprises agronomic, ecological, and economic uncertainties and risks for farmers. On the other hand, there is growing pressure on farmers to prove the sustainability of their EC system to society. Moreover, to meet future land demands for food, feed, chemicals, and energy, it is important to prioritize production systems that are resource-efficient with regard to land area used, energy requirements, and cost per unit of product [10]. Hence, there is a growing demand for scientific research and long-term experiments on EC systems to provide knowledge and advice for sustainable

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energy CR management. It is a central issue for biogas production pathways to use resource efficiency as a focal indicator to detect the most efficient production lines for the global energy supply, including sustainable EC systems.

Multiple aspect sustainability analysis of EC systems should be performed based on empirical data, e.g., data from a German joint research project called EVA (Site-Adapted Cropping Systems for Energy Crops) [11]. The focus of the project was on the development of economically successful, resource-efficient, and environmentally friendly EC production systems with special regard to CRs, with the aim of providing suitable agricultural alternatives to the dominant cultivation of maize for biogas production. This project has been carried out in eight different regions to evaluate different CRs for biomass production in extensive field trials. The aim of this paper is to evaluate four CRs on eight sites in terms of multiple relevant aspects of their resource efficiency (area use, energy, and economic efficiency) to derive options for sustainable EC management for biogas production. The analysis results are expected to be valid for energy cropping in Germany, as well as for other regions, at least in Europe.

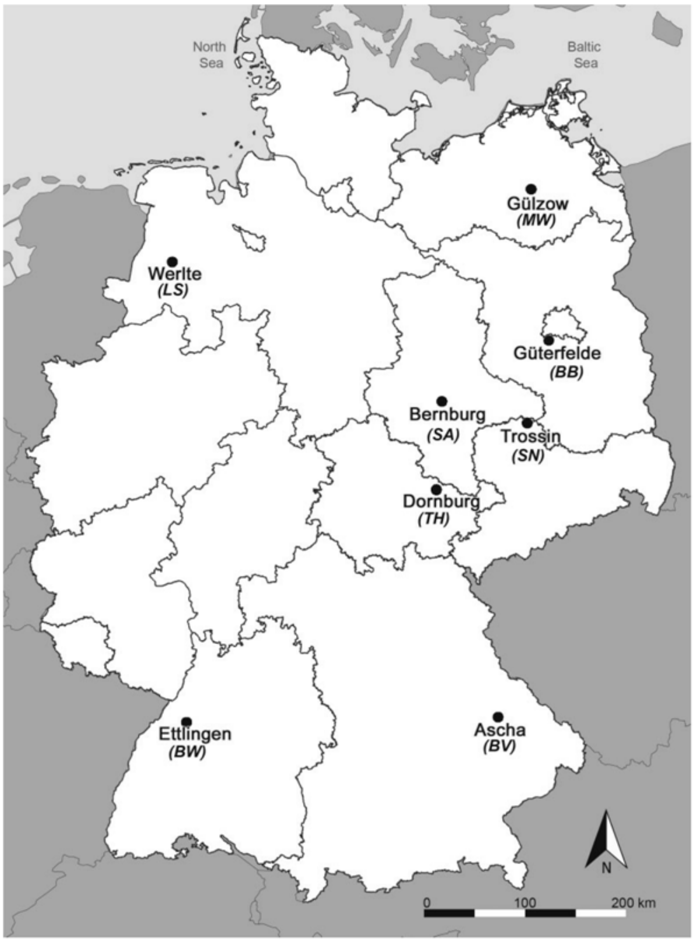

Figure 1. Location of EVA experiments in Germany.

2 Materials and Methods

2.1 Plot Experiments

The plot experiments were performed at eight sites across Germany run by regional authorities (Fig. 1). The sites differed in edaphic conditions and represented typical agricultural growing conditions of different arable regions (Tab. 1). At each site, the same five standard and four optimized regional-specific four-year energy CRs were established as a randomized plot experiment. The experiments were run with four replicated plots for each CR type, and the entire experiment was replicated four times in parallel starting in 2005, 2006, 2009, and 2010. For our analysis, we selected four standard CRs as follows: two management-intensive CRs (CR 01 and CR 02), including maize as the main crop and a sudangrass hybrid double-cropping system, one extensive perennial field forage CR (CR 04), and one mixed CR (CR 03) with 50 % ECs and 50 % cash crops (Tab. 2). All CRs included winter wheat as the final crop, to detect CR effects, except in Brandenburg and Saxony, where the final crop was winter rye. The perennial field forage CR varied among the sites according to the cultivated forage species mix: alfalfa/grass, alfalfa/clover/grass, or clover/grass. The management of particular crops was optimized according to the regional praxis. Thus, variation in crop management was mainly related to differences in precrops, seeding dates, and harvest targets (whole crop harvest, green manuring, grain harvest, and straw harvest).

2.2 Measured Parameters and Indicators Used

The sites were characterized by an extensive site investigation that described soil profiles and soil samplings up to 2 m depth with 6–8 replications. During the trial period, the following groups of parameters were observed: soil chemistry characteristics, weather, crop phenology, biomass accumulation, final yield and quality, specific methane yield of various ECs, crop diseases and pests, weed flora, and management practices. All investigations followed a uniform, standardized protocol.

To evaluate resource efficiency, three indicators were selected: area use efficiency, energy efficiency, and economic efficiency (Tab. 3). To avoid over-interpretation of individual aspects, the selected indicators were ranked equally and were not weighted.

Table 1. Site description of the EVA plot experiments.

Location name	Federal state	Climate precipitation [mm][a] and average annual temperature [°C]		Soils (FAO)[b]	Soil value[c]	Predominant crops[d]
Ascha (BV)	Bavaria	807	7.5	Stagnic Cambisol	47	wheat (w), potatoes, forage
Bernburg (SA)	Saxony-Anhalt	511	9.7	Chernosem	90	wheat (w), sugar beets, oilseed rape
Dornburg (TH)	Thuringia	584	8.3	Luvisol	65	wheat (w), barley (w), oilseed rape
Ettlingen (BW)	Baden-Wuerttemberg	771	10.3	Regosol	75	maize, wheat (w), barley (w)
Gülzow (MW)	Mecklenburg-Western Pomerania	560	8.9	Planosol	51	wheat (w), oilseed rape, barley (w)
Güterfelde (BB)	Brandenburg	570	8.9	Albeluvisol	29	rye (w), maize, potatoes
Trossin (SN)	Saxony	554	8.9	Gleyic Cambisol	31	wheat (w), maize, potatoes
Werlte (LS)	Lower Saxony	769	9.0	Stagnic Cambisol	40	maize, cereals (w)

[a]30 year average (1961–1990); [b]according to FAO classification; [c]soil rating value (max. 120 points); [d]data from official statistics; (w) = winter.

Table 2. EVA CR description.

CR	Year 1	Year 2	Year 3	Year 4
CR 01	winter barley[a], sudangrass hybrid [a]	maize[a]	winter triticale[a], phacelia[c]	winter wheat[b],[d]
CR 02	maize[a]	winter rye[a], sudangrass hybrid[a]	winter triticale[a], annual ryegrass[a]	winter wheat[b],[d]
CR 03	oats mixture[a]	winter triticale[a]	winter oilseed rape[b]	winter wheat[b],[d]
CR 04	summer barley[a], undersown by field forage[a]	field forage[a]	field forage[a]	winter wheat[b],[d]

[a]biomass production; [b]cash crop production, [c]cover crop; [d]in Brandenburg and Saxony winter rye instead of winter wheat.

Table 3. Overview of efficiency indicators, their focus, and literature source.

Indicator name	Focus	Source
area use efficiency [CH_4 yield Nm^3ha^{-1}]	methane yield per hectare	batch anaerobic digestion tests VDI 4630 [12]
energy efficiency (EROI) [output in MJ input MJ^{-1}]	efficiency of energy input	VDI 4600 [15], Ecoinvent [16] and KTBL [17] database
economic efficiency [$Nm^3€^{-1}ha^{-1}$]	methane yield per costs of production	KTBL [17] database and DLG [18]

2.2.1 Area Use Efficiency

Area use efficiency was determined by calculating potential methane yields from the harvested biomass of one ha, including only biomass from ECs. The given values were the total amounts of methane produced over the whole CR. Biomass-specific methane yields of whole crops grown in EVA CRs under different edaphic conditions were analyzed according to VDI 4630 under uniform conditions in batch anaerobic digestion tests [12]. The analysis contained samples from all eight sites of all five standard CRs and four regionally adopted CRs within all four replications. Based on these result datasets, the biomass-specific methane yields per ha were determined according to crop type, dry matter content of the silage, position in the CR, phenological development scale of the crop (German BBCH scale), and – for perennial crops – first cut or subsequent cuts [13]. To calculate the methane yield per ha, biomass losses on field and losses during storage in the silo must be calculated first; this study follows standard default values for DM losses of ensiled biomass based on Jeroch et al. [14].

2.2.2 Energy Efficiency

Energy efficiency, or energy return on investment (EROI), is the ratio between the sum of produced energy (output in MJ methane yield) and the cumulative energy demand (CED, input in MJ) to produce this yield. If the ratio (output/input) is less than one, more energy was required than the amount of energy produced, but if the ratio is greater than one, the product is an energy source. The amount of energy input (CED) comprised all primary energy required during production of the crop based on VDI 4600 guidelines [15]. The system boundaries were set from cradle to farm gate, starting with the production of all inputs and ending with the harvest of the crop and storage or ensilage of the biomass. For the calculation, a field size of 10 ha and a field-to-farm distance of 5 km was assumed. The project used datasets from the Ecoinvent database v.3.1 [16] to calculate CED related to the production (including raw material exploration, transportation, and production process ending with transportation to the regional storehouse) of the farming material (seeds, fertilizer, pesticides, agricultural machinery, fuel) by using datasets representative for Germany, or if not available, for Europe. The diesel amount for each field operation was taken from an online database, the "Feldarbeitsrechner", developed by KTBL [17]. Diesel consumption was dependent on the following parameters: machinery type used for field operations (including operating width and performance of the machinery), soil type, amount of seeds, fertilizer and pesticides applied, and crop yield harvested. The diesel demand for tillage operations was related to soil texture (fine, medium, and coarse), whereas harvest operations were related to the quantity of material harvested. Lower heating values were used as a characterization factor for the primary energy amount from different inputs, e.g., for diesel combustion, the value was provided by the Renewable Energy Sources Act [1]. The CED was then summed over the whole CR.

2.2.3 Economic Efficiency

Economic efficiency was calculated as methane yield per Euro per ha by taking into account the costs of all variables and the fixed costs of machinery and labor [18]. Labor requirements and diesel consumption were also taken from the KTBL [17] database, considering typical regional production methods. The methane yield per € production cost per ha was calculated by dividing the methane yield per ha by the total costs of all crops in the CR.

2.3 Statistical Data Analysis

Resource efficiency indicators were calculated for each single plot, i.e., each CR within each replication. Results for single crops, including cover crops, were summarized over the four-year CR. Statistical analyses were performed by using SPSS 19.0 [19]. Prior to analyses, variables were tested for normal distribution by using the Kolmogorov-Smirnov test. Data showed normal distribution; therefore, transformation was not required. The CR effects and variability of the efficiency indicators were analyzed by using generalized linear mixed models (GLMMs) [20], which accounted for nonindependent errors that might occur due to the hierarchically nested sampling design (here: regional sampling and site differences between experimental sites within the investigational regions). We tested the effects of CR and region as fixed categorical factors, with variability within fertilization (nitrogen (N) application rate), soil tillage (total tillage depth per CR), and labor requirements (the sum of working hours required for CR cultivation) as co-variates, influencing variability of the target variables at the micro level. The production and use of mineral N fertilizer was associated with high environmental burdens and costs. Consequently, N fertilization was one of the key factors that influenced the environmental impact and economic efficiency of CRs [7]. Within the same region, the N fertilization rate could vary widely between CRs; in particular, a high share of cereals in the CR could lead to a high N fertilization rate [7]. This also applied to the analyzed CR (Tab. 4); CR 01 and CR 02, including cereals and maize, required more N-fertilizer than CR 03 and CR 04 at all sites. CR 04, including perennial field forages with legumes, required very little N-fertilizer; however, this varied from site to site. Soil characteristics and CR design could influence the frequency and intensity of soil tillage during a CR. According to Nemecek et al. [7], some crops (e.g., pea and rapeseed) integrated in the CR improved the soil structure and, as a result, reduced the need for soil tillage. In the analyzed four CRs, CR 01 and CR 02, comprising six annual crops, required the most soil tillage and CR 04, comprising two annual and one perennial crop, the least (Tab. 4). Labor requirement was a key factor that influenced the economic efficiency, since it was related to cost-intensive machinery use and employment of labor. CR 03, comprising four annual crops, had the lowest labor requirement at all sites. The other CRs comprised more crops, resulting consequently in a higher labor requirement, since each crop needed to be planted and harvested. CR 04 comprised perennial field forage crop, which was harvested 3–4 times a year, resulting in an intensive labor requirement. From the output values, the significance of the model, coefficient of determination R^2, the significance of each single variable and their combinations, the estimated marginal means, and the means for construction of the homogenous subgroups, calculated by the Bonferroni test, were used for interpretation. In the second step, the variance explanation of the particular fixed factors and their interaction was analyzed by using covariance analysis and the Wald Z-test. Finally, variance explanation of the covariates was partitioned by applying "empty" GLMM runs without fixed factors by using the single covariates as random factors and subtracting their variance explanation from the overall variance explanation of the model with only regions and CR as underlying grouping variables (subjects) [21].

3 Results

3.1 Area Use Efficiency

The soil values of the experimental sites varied between 29 and 90 (German agricultural classification system for soil fertility, the best value is 120). The methane yields per ha showed a standard deviation of 38 % within the dataset under investigation; methane yields were strongly related to regional soil fertility values ($R^2 = 0.794$). The choice of CR among the four investigated types always accounted for a high standard deviation at the investigated sites (average 34.1 %), while the regional differences for a specific CR varied much less (average standard deviation = 26.1 %). Our results (Fig. 2) showed generic trends across sites: the superiority of CR 01 and 02 over CR 03 and 04, but also regional differences in the relative performance between CR 01 and 02 and between CR 03 and 04. On less fertile soils, CR 02 reached methane yields of at least the same lev-

Table 4. Overview of the three co-variates N-Fertilizer application rate, soil tillage, labor requirement of CR 01–04 by sites (average values, sum for four-year CR, marginal means over four rotations 2005–2013), and the number of field trial observations were the statistical analysis was based on.

		Location name							
Co-variates	**CR**	Ascha (BV)	Bernburg (SA)	Dornburg (TH)	Efftlingen (BW)	Gülzow (MW)	Güterfelde (BB)	Trossin (SN)	Werlte (LS)
N-Fertilizer application rate [kg N ha^{-1}]	01	823	864	614	704	726	545	553	662
	02	850	839	643	730	744	540	636	819
	03	609	632	507	536	652	396	418	542
	04	631	287	277	299	437	254	428	914
soil tillage [cm tillage depth]	01	120	158	196	251	160	158	113	193
	02	122	150	213	271	180	158	123	206
	03	100	118	187	215	132	152	96	141
	04	46	66	97	148	67	82	77	81
labor requirement [working hours ha^{-1}]	01	27	31	27	29	27	23	24	25
	02	30	31	28	31	30	24	24	32
	03	18	21	22	21	21	18	17	17
	04	25	25	29	30	24	22	22	37
number of observations	01	16	16	48	16	64	64	16	40
	01	16	8	16	16	16	16	16	16
	03	16	8	16	16	16	16	16	16
	04	16	8	16	16	16	16	20	16

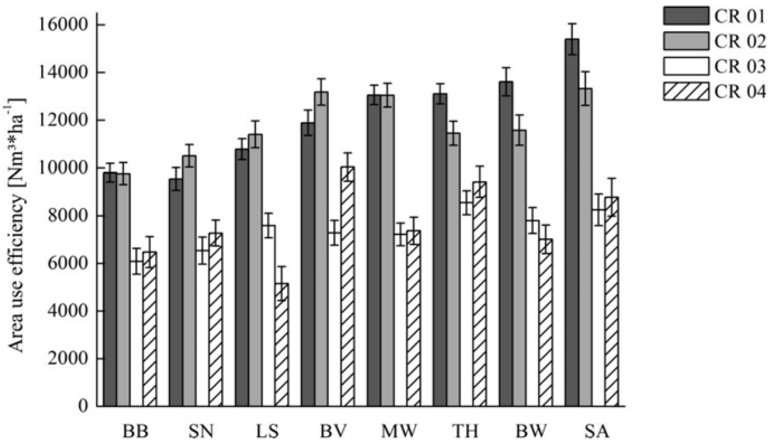

Figure 2. Comparison of area-related methane yields of CR 01–04 by site (sites ranked according to their soil fertility values from low (left) to high (right), average methane yield per ha, sum for four-year CR, marginal means over four rotations 2005–2013; the vertical bars represent standard error; the number of observations are described in Tab. 4).

el as that of CR 01; on highly fertile soils, CR 01 performed significantly better than CR 02. In general, CR 04 showed higher methane yields than those of CR 03, except for sites LS and BW. The relationship between soil value and methane yield differed among the CRs. For CR 01 and 03, a high dependence on soil fertility (R^2 = 0.599*** for CR 01; R^2 = 0.451*** for CR 03) was detected, but it was much lower for CR 02 (R^2 = 0.272***) and CR 04 (R^2 = 0.217***). The high impact of CR management can also be deduced from the standard deviation among CRs at each site, which ranged from 23.5 to 40.8 % of average methane yield, depending on the specific site.

3.2 Energy Efficiency

Despite the fact that the differences among the tested CRs showed similar trends for the EROI values as that for the methane yields, energy efficiency was less dependent on soil fertility. This was true both for the differences between CR 01/02 and CR 03/04, as well as between CR 01 and 02, and between CR 03 and 04 (Fig. 3). The standard deviation of the EROI values was 29.1 % of the average within the dataset under investigation. The coefficient of determination between EROI and soil value explained only 58 % of the variation among

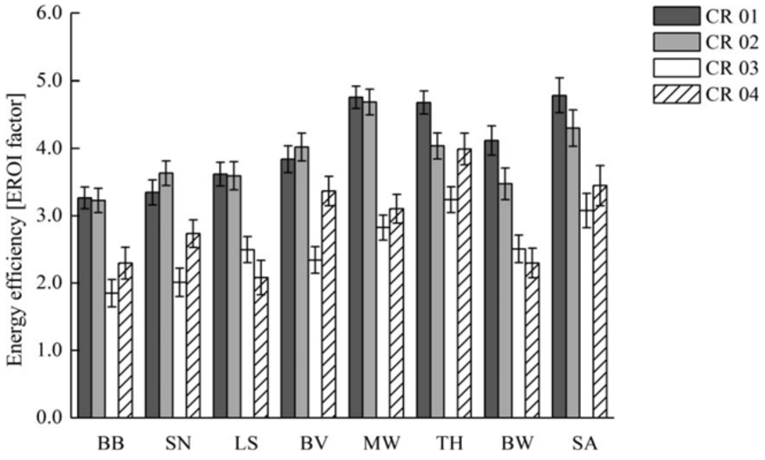

Figure 3. Comparison of energy efficiency of CR 01–04 by site (sites ranked according to their soil fertility values from low (left) to high (right), totals for the four-year CR, marginal means over four rotations 2005–2013; the vertical bars represent standard error; the number of observations are described in Tab. 4).

the sites ($R^2 = 0.579$). Energy efficiency revealed a relatively stronger dependence on soil fertility for CR 01 ($R^2 = 0.383$***), CR 03 ($R^2 = 0.260$***), and CR 04 ($R^2 = 0.286$***). CR 02 ($R^2 = 0.110$***) demonstrated a lower coefficient of determination. Fig. 3 indicates that the relationship between soil fertility and EROI more or less follows a saturation curve with polynomial curve fittings. Among the CRs tested, energy efficiency varied least among the different regions at CR 02 (standard deviation = 15 %), but the standard deviations of CR01 (22 %), CR 03 (29 %), and 04 (27 %) were almost twice as high.

3.3 Economic Efficiency

Economic efficiency showed a very different picture from that of the previously presented efficiency indicators (Fig. 4). In general, the performances of CR 01 and 02 are noticeably better than those of the other two CRs, but the differences are not significant for all sites (e.g., SN, BV, BW). The economic efficiency of CR 02 showed no significant relationship to soil fertility gradients ($R^2 = 0.05$, n. sign.). Differences in the economic efficiency of CR 01 and 02 differed only slightly between the sites, but the trend was significant for CR 01 (coefficient of determination with soil value $R^2 = 0.301$***). However, the economic efficiency of the mixed CR 03 varied greatly among sites and showed a trend to greater differences in sites with low soil fertility. Consequently, the standard deviation of CR 03 was the highest among the tested CRs, at 36 %. CR 04 tended to reach comparable economic efficiency with CR 01 and 02 on several sites (SN, BV, BW). This trend was not related to soil fertility.

3.4 Variance Explanation by Impact Factors

Analyzing the region and CR effects on the efficiency indicators, by taking variations caused by different management options into account, revealed a variance explanation between 70 and 87 % by the interaction of the two main factors: region and CR (Tab. 5). When broken down into individual factors, the choice of CR accounted for the higher part of the variance explanation. Regional impacts were particularly high for energy efficiency and low for economic efficiency. CR choice played an important role in area use efficiency.

Among the management covariates, the labor requirement fundamentally influenced the efficiency result. Soil tillage intensity had no direct impact on the efficiency indicators. Fertilization inputs strongly affected the energy efficiency, but only partly affected economic efficiency.

3.5 Integrative Efficiency Analysis

When analyzing the relationship between the efficiency indicators, a strong correlation emerged (Fig. 5). The EROI increased with higher methane yield per ha. This relationship was approximately linear, but with saturation tendency. The best fit could be achieved with potential approximation. The methane yield per € production cost increased with higher methane

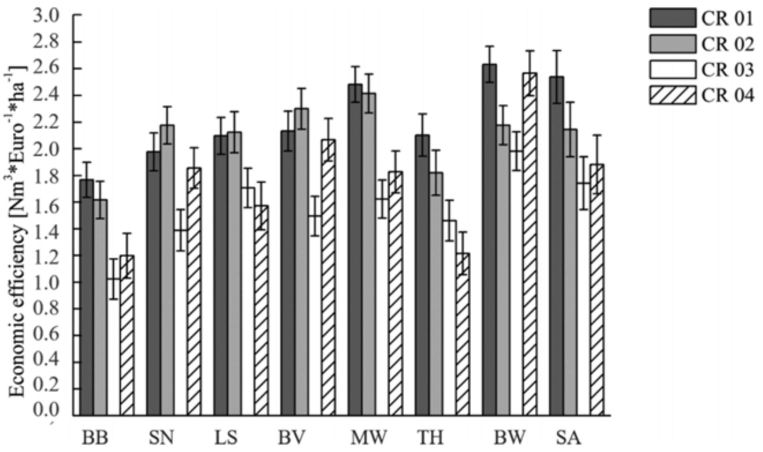

Figure 4. Comparison of economic efficiency of CR 01–04 by sites (sites ranked according to their soil fertility values from low (left) to high (right), sum for the four-year CR, marginal means over four rotations 2005–2013; the vertical bars represent standard error; the number of observations are described in Tab. 4).

Table 5. Details on the variance explanation, as provided by the particular model factors (upper part for fixed factors, lower part for co-variates; calculation based on covariance analysis performed by using GLMM).

Factor	Area use efficiency			Energy use efficiency			Economic efficiency		
	F value	Sign.	Variance explanation[a)]	*F* value	Sign.	Variance explanation[a)]	*F* value	Sign.	Variance explanation[a)]
CR	106.1	***	65.5	104.0	***	50.0	30.61	***	50.1
region	7.81	***	26.1	9.22	***	36.0	4.59	**	18.4
CR* region	12.83	***	86.8	10.41	***	77.0	8.84	***	66.1
CR × Region as co-variated by									
fertilization	0.54	n. sign.	17.1	26.0	***	32.9	8.94	***	5.2
soil tillage	0.01	n. sign.	13.1	0.37	n. sign.	4.6	0.00	n. sign.	0.6
labor requirement	134.29	***	57.8	47.95	***	36.9	55.46	***	50.2

[a)] Covariance tests after WALD; n. sign. = not significant; sign. = significance level, * = 0.05, ** = 0.01, *** = 0.001.

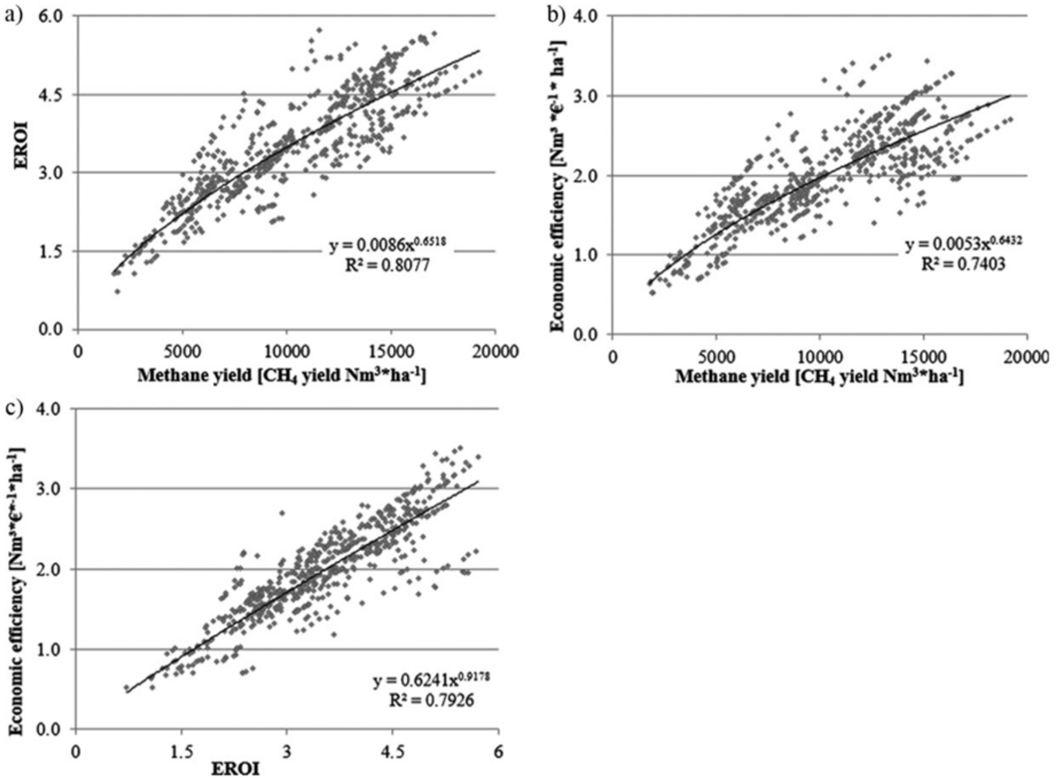

Figure 5. Internal relationships of the three efficiency indicators under review (correlation coefficient over all experimental sites and replications).

yields per ha and EROI factor. Both relationships could be best described with potential approximation. High methane yields served as prerequisites for high economic efficiency. From the graphs, it can be considered that this is not a single factorial relationship. Variation in economic efficiency increases considerably where yields exceed 10 000 $\mathrm{Nm^3}$ methane yield per ha over four years. On the other hand, cropping systems that guarantee a high energy efficiency (EROI) showed a strong relationship with high economic efficiency. Here, the relationship was approximately linear with a high gradient of the curve. Increasing EROI by 1.5 elevated the economic efficiency by 1 $\mathrm{Nm^3 €^{-1} ha^{-1}}$.

4 Discussion

Various cropping systems, including ECs, are feasible, but their sustainability depends on site-specific criteria and farm management [6]. In the USA, 35 million ha of maize were harvested in 2007 alone for bioethanol production with an upward trend [2]. In Germany, 73 % of total biomass used as feedstock for biogas production is maize [3]. To reduce the potential negative impact of this specification and increase biomass yield, several crops have been investigated as alternatives to maize, as well as cropping systems involving maize production (catch crops, double-cropping systems) [22–24]. In accordance with our results, these studies revealed that management intensities and regional site potentials were also of major importance for improving the sustainability of EC systems [23]. In addition to existing comparisons of ECs reported by other authors [25, 26], we would like to draw attention to the design of CRs as a suitable tool to balance economic and ecological effects of different crops.

4.1 Validity of the Results in the Context of Other Publications

4.1.1 Area Use Efficiency

The reasons why farmers opt for maize are apparent: the crop is characterized by a high biomass and energy yield, as well as high water and nutrient efficiency [27]; consequently, the widespread cultivation knowledge among farmers results in high profitability. Consistent with our results, Gissén et al. [25] found varying performance of ECs regarding methane yield per ha in Sweden. Maize provided higher methane yields than forage grasses and hemp (environmentally friendly crops), but sugar beets produced the highest methane yield. For single ECs under similar site conditions, the dry matter yield of EC might be strongly affected by the nutrient supply through fertilization [28], but our results questioned the validity of this relationship in a multiannual perspective, for CRs, and across a variety of site conditions. We determined that not only did the crop type have a major impact on the methane yield per ha, but so did the design of the CR (e.g., cover crops, double-cropping systems), the position of the crop within the CR (harvest date), the site characteristics, and the type of management related to the crops. Good farming practice applies an optimal fertilization plan, including mineral and organic fertilizer, crop residues, and cover crops to maintain soil fertility. The interactions between previous and assessed crops (CR effects), such as nutrient shifts, reductions of cultivation operations, and workload peaks and different timing of farming activities not only have a large impact on the achievable methane yield per ha, but also on production efficiency [29].

4.1.2 Energy Efficiency

In accordance with our findings, Alluvione et al. [30] concluded that, due to large differences in energy conversion efficiency among the crops (e.g., C_4 vs. C_3 crops), the CR design seemed to be at least as important as adaption of crop management practices to energy efficiency. Alonso and Guzmán [31] found that organic farming management in Spain reduced energy input during crop cultivation and thereby enhanced energy efficiency. Poor management practice, however, can lead to increased energy input during crop cultivation and decreased energy yield, which is likely to reduce energy efficiency. Börjesson and Tufvesson [23] investigated different biofuel production systems and revealed that a 35 % higher biomass harvest led to an improved energy efficiency of 10 % (on average). These figures are in accordance with our findings: with an increased yield of 30 %, energy efficiency could be improved by 10 %. Börjesson et al. [26] analyzed six ECs used for vehicle gas production and detected a variation in energy efficiency ranging from 35 to 44 % per energy unit. Triticale had the highest energy efficiency, followed by maize, wheat, sugar beet, ley crops, and hemp. This is consistent with our findings, where the triticale-/maize-/sorghum-based CRs (CR 01 and 02) performed best across all sites. Nemecek et al. [7] determined nitrogen management to be the key driver for CED of arable CRs (in France), but our results revealed the labor requirement to be equally important. According to Alluvione et al. [30], energy efficiency was a suitable indicator to be integrated into life cycle assessments or multicriteria analyses; CR design and management could be included in the evaluation of their environmental impacts.

4.1.3 Economic Efficiency

In contrast to our results, in Sweden, cereal-based biogas systems proved to be more favorable than EC systems based on maize [23]. In the study by Gissén et al. [25], triticale showed the lowest feedstock costs per GJ of methane followed by beet tops, maize, and first- and second-year ley. A study in Italy also found triticale to have the best economic performance per product unit, followed by maize (grown as a first crop) and grasses [32]. As demonstrated by our results, the combined implementation of triticale and maize in one CR is highly efficient. The pronounced economic efficiency of maize was caused by high yields; the attractiveness of triticale and grasses resulted from low production costs. The high variation of the yield for forage grasses among sites and cultivation years implies a high risk for economic efficiency or deficient cultivation management. When focusing on the cost per unit of greenhouse gas reduction, forage-based biogas cropping systems perform best [26]. In addition, current biogas prices can have a major influence on the relative economic attractiveness of particular feedstocks compared with food crops [25, 32].

4.2 Evaluation of the Design and Impact Factor of CRs

Most sustainability assessments conducted for annual and perennial crop cultivation typically take into account only one vegetation period, from seedbed preparation to harvesting. The influence of the previous crop on the assessed crop is often outside the system boundary [29]. We overcome this problem by expanding the system boundaries and taking the entire CR into account. A comparison of the four CRs showed that CRs including a C_4 crop were the most efficient ones at all sites and across the efficiency indicators, but the design of the CR was also relevant. CR 01 and 02 had exactly the same portions of maize and other C_4 crops, but varied with respect to the effects considered. In particular, at sites with lower soil values, CR 01 was more efficient in terms of energy and area use than CR 02, and vice versa for sites with higher soil values. The variation between the four CRs at each site was higher than the variation between the sites. In accordance with the results of Mayer et al. [33], we found strong interdependencies between the cropping environment (soil fertility) and achievable methane yields per ha. Perennial forage grasses demonstrated many advantages, such as low production costs (economic and energy related), environmental friendliness due to low nitrogen and tillage demand, and growth under unfavorable conditions. However, CR 04 was not the most efficient CR because the methane yield varied greatly among the sites and years, and under most cultivation conditions it was lower than that of CRs with maize (CR 01 and 02). Combining energy and cash crops (CR 03) within one CR may be a reliable alternative for improving diversification of the EC system, soil organic matter (if chopped straw is left on the field) and resource efficiency. However, the functional unit chosen for our assessment (methane yield) made it difficult to integrate cash crops into the efficiency assessment, causing an underestimation of the CR output and consequently interfering with the resource efficiency results for CR 03. This CR would have performed better if the alternative cash crop (oilseed rape) could have been included in the indicators.

Our results clearly demonstrate that there is no ideal CR for all sites, since regional conditions and the corresponding crop management have a significant impact on CR performance. The indicators discussed are strongly correlated; therefore, by improving one of the indicators, the other two benefit as well. This indicates that economic efficiency does not necessarily conflict with other efficiency goals. The improvement is limited, however, by the potential relationship of the efficiency indicators. Nevertheless, the design of CR adapted to regional site conditions can be a useful tool for steering and optimizing resource efficiency.

4.3 Drawbacks and Advantages of a Multiple Efficiency Indicator Set

Börjesson and Tufvesson [23] stated that a broad system analysis approach was needed when different crop production systems were compared. The most important results of such studies may be the identification of parameters with the highest impact on the energy and environmental performance of ECs. Therefore, analyses have to consider local conditions and apply multiple indicators; otherwise, assessment results contain a high level of uncertainty and a low quality of their predictions. However, it can be difficult to interpret the results of multiple indicators to derive recommendations for action. Often aggregation or normalization are used to overcome this problem, but both approaches show methodological weak points and can cause a loss of information [34]. In our approach, we initially analyzed and interpreted the indicators separately to identify the management, CR, and site-specific parameters that influenced each indicator; only afterward did we perform an integrative efficiency analysis to test the relationship between these indicators. This method offers a way to analyze a large number of CRs cultivated under different local conditions. It provides experts with the possibility to compare resource efficiency from agronomic, energy, and economic points of view, and based on these results allows potential improvements to be determined by selecting the optimal CR and management for the specific region.

For farmers and policymakers, resource efficiency is the focal indicator for biogas production pathways to identify efficient and high-yielding production lines to secure the global energy supply. However, to determine sustainable EC systems, it will be indispensable to extend our analysis to include social and environmental indicators to cover all indicators of sustainability assessment.

5 Conclusion

There is a critical lack of knowledge among farmers, policymakers, and scientists regarding the impact of new EC systems and their resource efficiency; this knowledge gap prevents the introduction of newly designed CRs. To close this gap, we evaluated four CRs in eight sites in terms of different aspects of their resource efficiency (area use, energy, and economic efficiency) to derive options for sustainable EC management. Our results revealed that the efficiency of each CR was dependent on the regional conditions and related management, and that the three indicators were strongly correlated. Consequently, by improving one of the efficiency indicators, the other two also benefitted. The approach presented above can contribute to the further improvement of indicators and models used for assessing the regional impacts of EC systems. Moreover, it was demonstrated that the design of CRs and regionally adopted management practices could be an appropriate steering option in land use management. By applying our approach to other regional datasets, more resource-efficient cropping systems could be identified and thereby help to improve the diversification of EC systems.

Acknowledgment

This study is part of the EVA joint research project. This project is funded by the German Agency for Renewable Resources (FNR), on behalf of the Federal Ministry of Food and Agriculture.

The authors have declared no conflict of interest.

Abbreviations

BB	Brandenburg
BW	Baden-Wuerttemberg
BV	Bavaria

CED	cumulative energy demand
CR	crop rotation
EC	energy crop
EROI	energy return on investment
EVA	Site-Adapted Cropping Systems for Energy Crops (project name)
FAO	Food and Agriculture Organization of the United Nations
MW	Mecklenburg-Western Pomerania
n. sign.	Not significant
LS	Lower Saxony
SN	Saxony
SA	Saxony-Anhalt
TH	Thuringia

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6 General discussion

Sustainability of energy cropping is the focus of an increasingly critical public debate. On the one hand, it is assumed that the substantial rise in energy production from agricultural biomass in recent years might cause environmental problems. On the other hand, bioenergy appears attractive as a renewable fuel since it can replace fossil fuel resources, aid biodiversity, create new land use management options for unattractive arable areas through new crops, diversify rural economies, support energy security, industrial growth and exports (Adams et al., 2013). Main key drivers for bioenergy production from biomass are the potential reduction of GHG emission and the high energy efficiency compared to fossil fuels.

In recent years, LCA has been increasingly used as an analytical tool for the assessment of bioenergy production pathways, which is able to capture the complexity and interdependencies of the system and thus providing a comprehensive and objective environmental balance, helpful to address sustainability of bioenergy chains (Blengini et al., 2011). However, as Cherubini and Strømman (2011) pointed out, LCA of bioenergy systems can be helpful to address sustainability, but, at the same time, differences in methodological assumptions might distort the results and make comparisons to other LCA studies nearly impossible.

Even through, the resource-related impacts like CED or GHG emissions are generally based on well-known processes and databases, the complexity of the processes and numerous influencing factors as e.g. the uncertainty of nutrient losses, makes the LCA modelling challenging and vulnerable for inaccuracies and errors (Nemecek et al., 2015).

6.1 Modelling uncertainties: field emission accountings at regional scale

In the first paper (Peter et al., 2016), it was shown that the choice of the methodological approach (Tier level) can considerably affect the calculated GHG emission result. Sufficient transparency is required to inform relevant parties about possible errors and shortcomings introduced by the selected method when applied to a case study. The comparison of methods for the assessment of land-based GHG emissions during crop cultivation on different complexity levels (Tier) identified appropriate, readily available, assessment methods at the Tier 2 and Tier 3 level with medium efforts for stakeholders. Furthermore, the consequences of the methodological choices on the CFPs of annual and perennial crops for field GHG emissions from crop cultivation were explored.

In the analyzed wheat case studies, field emissions from fertilizer application were an important factor, as they accounted for almost 50% of the total GHG emissions, calculated with the global Tier 1 approach. In contrast, for the perennial peach crop case study, emissions from fertilizer application contribute around 10% to the total GHG emissions. In all analyzed case studies, the estimated fertilizer-induced field emissions calculated by the regional assessment method (Tier 2) were lower than the Tier 1 estimations (up to 65%). Using the higher Tier method (Bouwman et al., 2002b) to calculate field

GHG emissions from fertilizer application resulted in a total GHG reduction of up to 21% for the wheat production and 7% for peach production compared to the Tier 1 assessment. As the yield from annual crops is strictly dependent on nutrient availability and weather conditions during a relatively short cultivation period, the fertilizer management system is often more intensive for the short annual crop cycle than for perennial crops. Consequently, the fertilizer management system has a larger influence on overall field emissions for annual crops than for perennial crops, which feature considerably lower fertilizer input throughout their entire life cycle.

To evaluate the modelling results, the Tier 1 and Tier 2 estimates for N_2O (nitrous oxide) and NH_3 (ammonia) emissions from two winter wheat case studies were compared with field-measured GHG emissions. For both investigated sites and both gases, the Tier 1 and 2 calculations overestimated the measured fluxes. However, for NH_3-N emissions, Tier 2 estimates only deviate 1% and 10% from measured data of site 1 and site 2, respectively. In contrast, Tier 1 calculated NH_3-N emissions are 87% and 168% higher than measured emissions for site 1 and site 2, respectively. Tier 2 estimates of fertilizer-induced N_2O-N field emissions were less accurate than estimates for NH_3-N, but more accurate than Tier 1 estimates. Comparing modeling data with measurements can be problematic since measured data and modeled data have also a risk of uncertainty. But based on the results, it is recommended to use a higher Tier approach when estimating the fertilizer-induced field emissions, whereas for perennial crops, it has a minor impact on the CFP result. However, a general conclusion on the efficacy of default emission factors for annual and perennial crops cannot be derived from this limited amount of data. Therefore, further studies are needed to confirm these findings.

Regarding soil carbon stock change, important differences were found between results calculated with Tier 1 and Tier 3 methodologies. The choice of either Tier 1 or Tier 3 for SOC change estimation had an high impact on the wheat case studies, as SOC change calculated with Tier 1 corresponds up to 194% of all other GHG emissions (the agro-ecosystem is a carbon sink), while the Tier 3 estimate amounts to approximately 13% of all other emissions. For the perennial peach case study, the use of the Tier 3 method resulted in a more realistic value of SOC change than Tier 1. During 8 years of sustainable management practices, 81% of all other GHG emissions can be offset through soil carbon storage, compared to only 19% estimated with Tier 1. The present study has underlined the relevance of SOC change from crop management change on CFP of perennial crops, which cannot be always adequately represented using a Tier 1 approach. Concerning annual crops, the influence of SOC change on the CFP of a 1-year crop cycle could be strongly related to the long-term SOC dynamic, subsequent to crop choice and to the management regime, which determine the amount of organic residues returned to soil. Thus, for annual crops, a simulation approach is advisable to evaluate SOC change as the default based Tier 1 method does not allow to represent the change of different crops in the rotation. However, if the crop management in a crop rotation changes every year e.g. through rotating crop types, it is nearly impossible to assess the SOC change of one year out of this rotation without measurements and it is not likely that in this short time period a new SOC equilibrium is reached. Consequently, further investigation efforts are needed in this direction.

The outcomes of the first paper suggest that it is necessary to foster more awareness and consensus within LCA practitioners and policy-makers about the importance of including regional field emissions into the CFP of agricultural products, as it can considerably affect the results of the analysis. Moreover, it is recommendable using modeling approaches for field emissions estimates, taking into account local pedoclimatic and crop management conditions, because this can significantly improve the reliability of GHG accounting for agriculture at farm level.

Furthermore, it could be demonstrated that only few site-specific data are needed to apply the higher Tier approaches, which can substantial improve the accuracy of the estimate of land-based GHG emissions from fertilization and SOC change. The development of user-friendly, crop-specific tools underpinning these modeling approaches could more efficiently increase the usefulness of CFP for agricultural sustainability assessment at farm and regional landscape level and thus supporting the assessment of the agricultural mitigation potential and the development of GHG reduction plans at farm level.

6.2 Methodological challenges: available LCA calculators and their ability to reflect actual energy crop management practices

As Blengini et al. (2011) pointed out, it is confirmed that bioenergy out of biomass is not automatically synonymous with sustainable energy, as differences in environmental performance can be remarkable. These differences not only originated from different biomass production chains including varying energy crop cultivation management, but also from differences in the used methods for LCA calculation. Therefore, Blengini et al. (2011) demanded to carefully consider all life cycle phases and subsystems when addressing environmental sustainability of bioenergy chains, as there is no single dominating item or aspect in the life cycle impacts, but rather several of them play an important role in the overall sustainability. The results should reflect the complex combination of the territorial context, including site-specific climate conditions, the local agricultural practices and the disposal of residues. LCA study results cannot be generalized, but transparency on both sites, the input data (energy crop management) and inventory results (used methods and system boundaries) are necessary and it should be possible to mathematically manipulate them. Only in this way LCAs study results from energy crop production can be comparable and can be used as background for further research.

Even though, large efforts have been made, there are still methodological challenges to bring life cycle modeling of crop production closer to agricultural reality (Brankatschk and Finkbeiner, 2015). In the second paper (Peter et al., 2017b) 44 currently available agricultural environmental assessment calculators were reviewed for their ability to assess GHG emissions from energy crop production. Only

18 calculators were capable of assessing GHG emissions from energy crop cultivation following the IPCC guidelines and using the LCA approach.

In accordance to Hennecke et al. (2013) the review results showed, that it is crucial for the complexity and accuracy of the LCA results: (1) which farming processes are integrated in the calculator, (2) which calculation pathway and allocation method is used and (3) if the whole cropping cycle (e.g. perennial crops) or crop rotation is included. The main limitations in the currently available calculators are the failure to account for land use change (LUC) and to distinguish among fertilizer types including digestate, the lack of distinction among tillage types, and the lack of parametrization of many energy crops in the calculators. Furthermore, the impact on the CFP result by using regional GHG emission assessment methodologies is often overlooked. The ability of the calculators to detect GHG mitigation options through improvements in cultivation management is therefore limited.

The accuracy of field based GHG emissions calculation method can be improved by including crop residues management in the calculation such as the amount of straw left on the field, the quantity of crop residues or the amount of stubble burnt and by using the real nitrogen (N) content of the above-ground biomass (grain and straw) to calculate the N content of the above-ground and below-ground biomass.

Another methodological challenge is the allocation of GHG emissions among the individual byproducts of energy crop cultivation, as well as the subsequent use of the byproduct's burdens in other production cycles. Different allocation methods can be used and each has its advantages and disadvantages, but the uncertainty of the LCA results increases with each allocation step performed in one LCA assessment, and the results are fundamentally affected by the choice of allocation method (Brankatschk and Finkbeiner, 2014). Especially the allocation of digestate from anaerobic digestion is a critical aspect and part of an ongoing debate (Adams et al., 2015; Rehl et al., 2012). So far, there is no consensus about whether and how emissions during organic fertilizer production are to be included in LCA calculations of crop production. However, the most suitable allocation approach should be chosen based on the LCA study goals and appropriately documented in order to be able to compare studies calculated with the same approach. In the developed MiLA tool, it is assumed that manure and digestate were residues (byproducts) of the livestock and bioenergy life cycle before they become productive inputs for the crop life cycle. In order to avoid double counting, the environmental burdens emerging during storage and field application of the organic fertilizer are accounted for the crop cultivation process – where the emissions occur – and not in the upstream biogas or animal production chain. The Agri-footprint database (Blonk Agri Footprint BV, 2015) follows the same approach. This allocation approach is easy to apply since (1) less knowledge about the first production chain is needed, (2) the problem of double counting is prevented, and (3) the high uncertainty associated with other allocation methods is reduced.

The reviewed calculators were not all designed for specific energy crop calculations. Most calculators are calibrated for a small number of crops and the special characteristics of energy crop cultivation, e.g. digestate application on the field and whole plant harvest, are often ignored or insufficiently considered.

Energy crop cultivation is a dynamic system and the amount of GHG emissions and energy efficiency can be influenced by many factors as site conditions, crop type, cultivation management and crop rotation design. Furthermore the amount of biomass yield, GHG emissions and CED are strongly correlated to the nutrient supply through fertilization, especially of N fertilizer (Ercoli et al., 1999; Nemecek et al., 2015). The environmental impact from energy crop cultivation can be influenced by regional adopted crop rotation design and management (Alluvione et al., 2011). Consequently, the reduction of GHG emissions and CED can only be obtained by regional adopted energy cropping systems and sustainable land use concepts (Smith et al., 2014). However, in current available LCA approaches and studies these aspects are insufficiently considered or even disregarded (Brankatschk and Finkbeiner, 2015).

Only seven calculators of the investigated calculators are capable of calculating GHG emissions from perennial crops and from energy crops in rotation. By expanding the system boundaries of a LCA by taking into account the whole energy crop rotation increases the likelihood of identifying GHG mitigation options. However, currently, no reviewed calculator can process the effects from energy crops in rotation as nutrient carryover, reduction in use of agricultural operating needs, sequence and composition of crop rotations as well as integration of green manuring crops. To overcome this shortcoming, existing calculators should be extended by integrating energy crop rotations, or new calculators and methods need to be created.

6.3 Crop rotation effects in LCA modelling

A new reliable approach for LCA of crop cultivation was needed in order to reflect actual agricultural practices. The integration of crop rotations and their effects in LCA studies can significantly contribute to more realistic modelling results and therefore to the development of more sustainable energy cropping systems. Existing LCA calculators have a limited ability to fully reflect crop rotation effects and their impact on the LCA result of each individual crop in the rotation (Peter et al., 2017b). To overcome these shortcomings, a new LCA calculator named MiLA was developed (Peter et al., 2017c). With MiLA, GHG emissions and CED from crop cultivation including energy crops can be estimated. MiLA considers current crop management practices including management practices specific to energy crops as well as crop rotations and their effects.

In MiLA, the system boundaries are expanded in order to take the entire crop rotation into account. Consequently, crop rotation effects such as nutrient carryover via basic fertilization or green manuring are automatically included in the LCA estimations. Furthermore, the tool takes into account all inputs and outputs related to crop management from the whole crop rotation on each field and thus includes inter-crop relationships. Typically, when single crops from the crop rotation are calculated separately, these considerations are omitted (Brankatschk and Finkbeiner, 2015). By, including the nutrient carryover in the MiLA tool a better attribution of the nutrient consumption of each individual crop is achieved. The crop will be charged only for its true nutrient consumption and carry no more environmental burdens than what is physically true. The case study results in the third paper (Peter et al., 2017c) showed, that through the consideration of crop rotation effects in LCA calculations, the GHG emission result of the individual crop are influenced by −34% up to +99% and the CED by −16% up to +89% compared to the results without this considerations. Consequently, including crop rotation effects improves the accuracy of LCA accounting for energy crop production and supports the assessment of energy-efficient cropping systems and the development of GHG reduction plans at farm level. The tool is well-suited for product-specific LCA for energy and food crops and helps users to draw a more realistic picture of the interactions between crops, thus increasing the reliability of the LCA results.

Modification of the system boundary is well known in LCA practice, but is not often used for agricultural systems. However, introducing the whole crop rotation into an LCA study of a specific crop can cause problems regarding the different outputs (products) of the crops grown in the rotation. It can be very difficult to handle the complexity of so many outputs. MiLA makes it possible to tackle these problems with a moderate amount of effort by including different functional units. This allows the assessment of the whole crop rotation without using an additional allocation method.

LCA calculations of energy crops can be performed with the MiLA tool with only a moderate level of modeling effort regarding data quantity and usability. Even though, the tool still contains modeling uncertainties regarding the approach to model crop rotation effects as well as calculation methods and default values, farmers, private businesses and researchers should find it suitable as a first step to understand the complexity of crop cultivation systems and the related environmental burdens as well as to identify sustainable crop management systems. This tool makes it easy to compare different crop rotations, and can thus contribute to increase the diversity on field by identifying alternatives to maize and hence increase the societal acceptance of energy crop cultivation.

6.4 Further applications of MiLA

In MiLA the system boundaries are set from cradle to farm gate, consequently only the emissions occurring during the crop cultivation are calculated. The biogas plant, including the production of biogas, is outside the system boundary. However, the modeled results can be used for further LCA studies of bioenergy or food production chains (cradle to grave).

6.4.1 GHG emission reduction potential

In the context of bioenergy production out of energy crops, the societal and political focus lies especially on the GHG emissions reduction potential and the energy efficiency compared to fossil fuels. The European Commission fixed a threshold of GHG emissions savings for biofuels and bioliquids in the Renewable Energy Directive (RED) (European Commission, 2009a) and in the Fuel Quality Directive (FQD) (European Commission, 2009b), and set the rules for calculating the GHG impact of biofuels, bioliquids and their fossil fuels comparator (FFC). In the annex of the RED and FQD, default and typical values are listed to help the stakeholders to declare the GHG emission savings of their products. The

European directives in Germany are implemented in the Biokraft-NachV (2009) and BioST-NachV (2011) regulations. The calculation rules recommend to include all production steps from cradle to grave (energy crop cultivation, transportation and bioenergy processing) in the CFP assessment. Furthermore, the directive provides a threshold for the GHG emissions savings of at least 35% from the biofuels compared to their FFC. This threshold increased in 2017 up to 50% and in 2018 up to 60% (Figure 1). The European Commission recommended to member states, in the report from the Commission to the Council and the European Parliament (European Commission, 2010), to use the GHG emission calculation approach and thresholds from bioliquids and biofuels regulations for other bioenergy production chains out of solid and gaseous biomass sources.

These regulations provide default values for the farmers and biofuel producers describing the amount of GHG emissions that arise during energy crop production and biofuel processing. The default values for the energy crop production are average values for specific regions so called NUTS2 (Nomenclature des unités territoriales statistiques) regions. If the farmers assure that the energy crop were sustainable cultivated, they can use the default values to verify their products GHG emissions. The biofuel producer can use these values to calculate the total CFP (Figure 1).

As Figure 1 illustrates, the current valid default values meet the threshold value of 35% GHG emissions savings, but not the new (2017) and the future 2018 threshold. Consequently, the farmers could use the valid default values to receive financial support by the government until the end of 2016, but as from the 01.01.2017 and in the future this could be more difficult. In many bioenergy production pathways up to 50% of the total GHG emissions are caused by the biomass production (Dressler et al., 2012; European Commission, 2009a). Consequently, crop management has a major impact on the amount of GHG emissions from energy crop cultivation and correspondingly on the entire bioenergy production chain (Blengini et al., 2011; Davis et al., 2013).

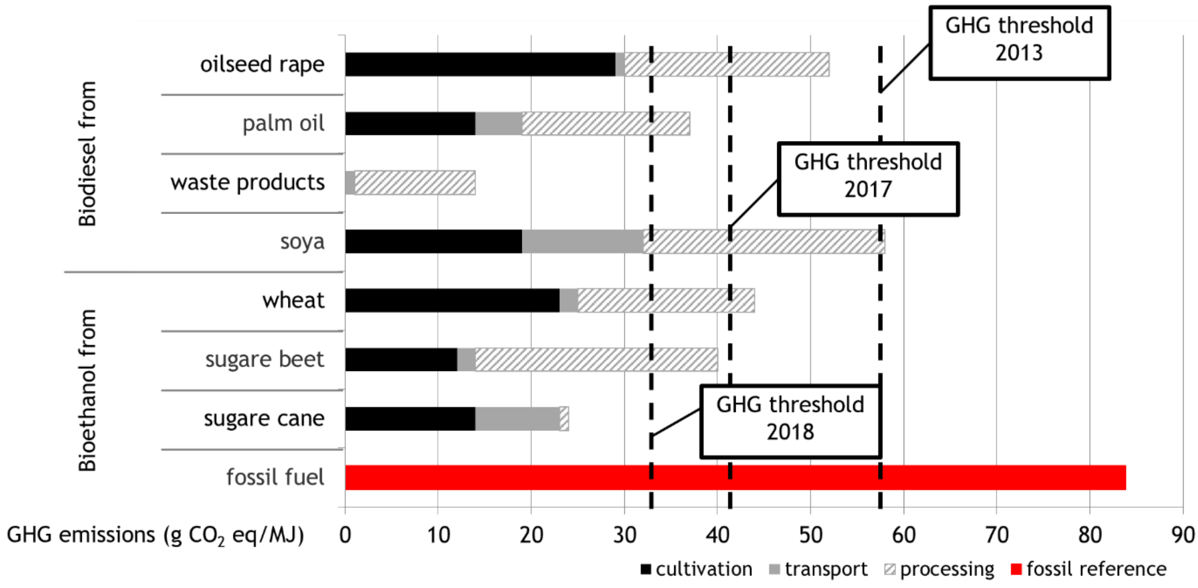

Figure 1: Overview of the GHG emissions default values [g CO_2 eq/MJ] of different biofuel production chains as provided in the RED (European Commission, 2009a) in comparison to the FFC, divided in production steps (energy crop cultivation, transportation and biofuel processing).

In addition to these default values, the European Commission and Germany developed calculators, BioGrace (2015) for Europe and $ENZO_2$ for Germany, to calculate the GHG emissions (from cradle to grave) of solid and liquid biofuel production from biomass (Figure 2). Both calculators were designed for farmers to calculate GHG emission from energy crop production and to evaluate the impact of management changes on the overall GHG emissions. The calculated results can be used as reporting basis for the certification of sustainable energy crop and biofuel production and for the verification of compliance with sustainability criteria for biofuels of the German and European directives.

However, the calculator review (Peter et al., 2017b) revealed that both calculators have some shortcomings and are not able to fully reflect actual agricultural practices. Both calculators use the Tier 1 approach for field emission calculation including global and some national default values and they only distinguish among mineral fertilizer ingredients (N, calcium oxide, potassium oxide and phosphorus pentoxide), while MiLA provides 88 different mineral fertilizer. BioGarce and $ENZO_2$ are specified to calculate the GHG emissions of a limited number of energy crops (e.g. oilseed rape and wheat) and cannot be extended. As a result, both calculators are not designed for the reflection of management changes and cannot take alternative and more sustainable management practices into account, since they disregard crop rotation effects and regional pedoclimatic site conditions. Consequently, it is difficult for the farmers to derive recommendations for GHG reduction options based on the calculator results and to prove sustainable energy crop production, using BioGrace and $EnZO_2$.

Figure 2, shows different GHG emissions arising during oilseed rape cultivation in 2011 and 2012 at the EVA field trial site Bernburg (Saxony-Anhalt, Germany), calculated with different calculation methods. The RED and NUTS2 default values are not influenced by yearly varying management, consequently each cultivation period of oilseed rape is rated with the same amount of GHG emissions. For the GHG assessment with the BioGrace and MiLA tool the actual cultivation management (yearly varying amount of fertilizer application and other farming materials as well as yield) were used. Though, only one crop at one site in the same crop rotation was analyzed, the GHG emissions results vary between the cultivation years, which is caused by the yearly varying crop management and crop yield. Consequently, in order to reach the highest GHG emission reduction potential, MiLA, the tool with the highest reflection of the actual agricultural practice should be used for GHG emission certification of energy crop production.

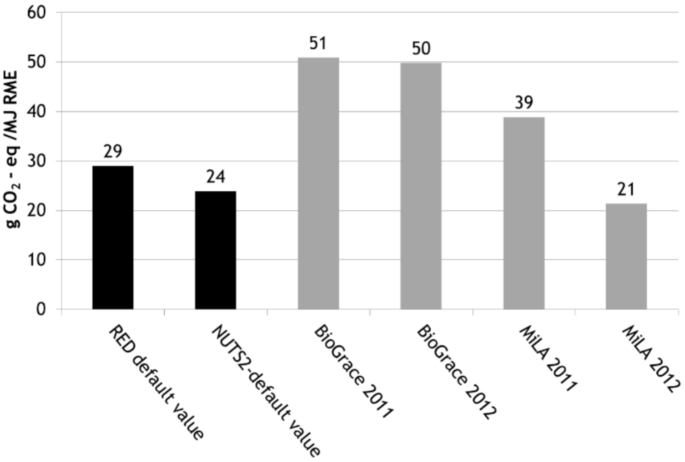

Figure 2: Comparison of product based (RME- rape methyl ester) GHG emissions of oilseed rape (at the EVA field trial site Bernburg, Saxony-Anhalt Germany for the cultivation years 2011 and 2012) calculated with different GHG emission calculation methods.

MiLA is well-suited for product-specific LCA of energy crops for different bioenergy production chains and helps farmers to draw a more realistic picture of the GHG emissions of different crop management practices. Furthermore, the tool results allows to calculate GHG emission reduction potentials for crop rotations and their use in different bioenergy production chains compared to their FFC. Especially, if the regulations for biofuels and bioliquids are also used to verify the sustainability of solid and gaseous biomasses for biogas production, reliable GHG emissions assessment tools are required, and MiLA could be an adequate option.

Biogas can be used for heat, electricity and biomethane production. After biogas production in the biogas plant the biogas is transformed to electricity and heat in a combined heat and power plant (CHP) at farm or purified to biomethane and feed in to the regional natural gas grid.

Using data from the EVA project, GHG emissions of one crop rotation (mustard/maize - winter rye/sorghum) cultivation and the processing of bioenergy in two different production pathways were evaluated (Figure 3). All emissions that arise after the energy crop production were calculated by using datasets from the Ecoinvent database 3.1. (Weidema et al., 2013) of a typical small biogas plant (500m³ biogas plant with 20 years lifetime and a covered digestate tank) and a typical small combined CHP (160 kW_{el} with a electricity production efficiency of 32% and 55% thermal efficiency) and a biomethane purification plant.

In accordance with the results of Dressler et al. (2012) the analysis revealed that up to 50% of the GHG emissions of the total production chain arise during the biomass production (Figure 3).

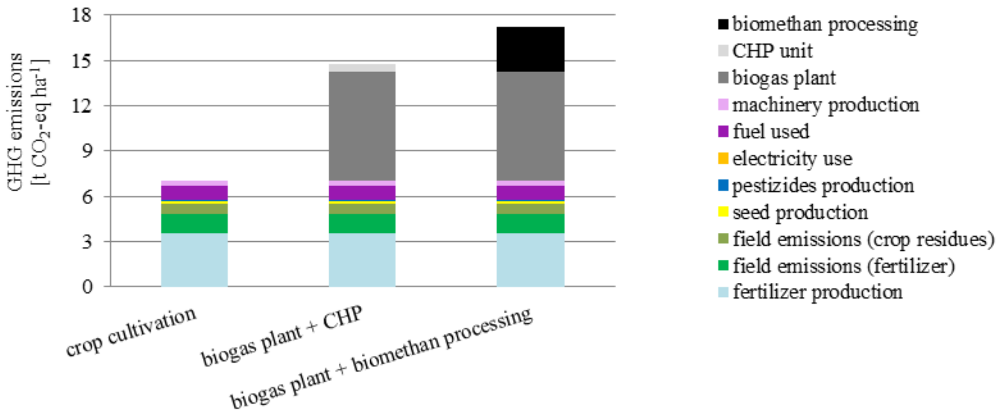

Figure 3: Area based GHG emissions of one crop rotation (mustard/ maize - winter rye/ sorghum) cultivated at the EVA field trial site Dornburg (Thuringia, Germany) and their processing in two different bioenergy production pathways (electricity and biomethane production).

Typical default GHG emission values for solid and gaseous bioenergy pathways as well as default values for the FFC ($FFC_{electricity}$ = 191.9 g CO_2-eq MJ^{-1} and FFC_{gas} = 73.7 g CO_2-eq MJ^{-1} calculated with the GWP of IPCC (2013) guidelines) were provided in the report of the Joint Research Center (Giuntoli et al., 2014). Calculating the GHG emission reduction potential of the analyzed production pathways showed that the highest GHG reduction potential has the combined production of electricity and heat (Figure 4). The GHG emission reduction threshold of 35% saving compared to the FFC could only be achieved through the production of heat and electricity. The threshold for 2018 of 60% savings cannot be achieved with the analyzed production systems. However, as stated before the GHG emissions can be reduced through regional adapted energy crop rotation design and optimized agricultural management practice.

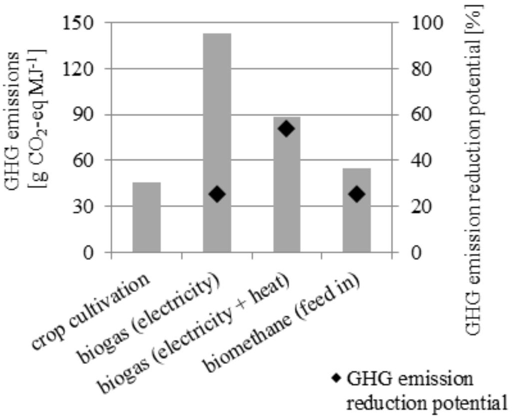

Figure 4: Comparison of the product based GHG emissions and GHG reduction potential of different bioenergy production pathways out of biogas produced from energy crops cultivated of one crop rotation (mustard/maize - winter rye/sorghum) cultivated at the EVA field trial site Dornburg (Thuringia, Germany).

As the results in Table 1 demonstrate, the GHG emission reduction potential of one crop rotation varies between sites. In each region one crop rotation could be identified which can save more than 50% GHG emissions compared to the fossil fuel alternative. In the context of bioenergy production out of energy crops, the GHG emission reduction potential of intensive crop cultivation systems is often questioned by researchers, because erroneous assumptions could be observed in the GHG emissions reduction potential calculations and the definition of "typical" energy crop cultivation systems differs. With the MiLA tool different crop rotations and cultivation systems at different regions were analyzed using data from the EVA project and up to 68% GHG emission savings have been detected. In further analysis the MiLA tool can be used to detect the crop rotation with the highest GHG emission reduction potential and to asses more information for the climate protection discussion of bioenergy production out of energy crops.

Table 1: Product based GHG emission reduction potential [in %] of bioenergy production (electricity and heat) from varying crop rotations at different EVA field trial sites (mean values from two replicates, red color highlights the lowest reduction potential and green the highest).

	EVA field trial location						
Crop rotation	Ascha (Bavaria)	Bernburg (Saxony-Anhalt)	Dornburg (Thuringia)	Ettlingen (Baden-Wuerttemberg)	Gülzow (Mecklenburg-Western Pmerania)	Güterfelde (Brandenburg)	Trossin (Saxony)
winter barley / sorghum – maize	49.4	61.0	56.9	61.2	57.1	63.0	62.3
mustard / sorghum – winter rye / maize	51.4	56.5	51.6	58.4	55.8	62.2	63.1
mustard /maize – winter rye/ sorghum	46.3	56.9	53.7	59.0	56.8	63.7	62.3
two year field forage*	47.4	68.9	62.6	62.5	66.2	64.9	48.0
Maize – Maize	51.6	63.0	60.9	65.6	61.1	67.5	65.2

*field forage: Ascha = clover-grass, Bernburg = alfalfa-grass, Dornburg = alfalfa-clover-grass, Ettlingen = alfalfa-clover-grass, Gülzow = alfalfa-clover-grass, Güterfelde = alfalfa-grass, Trossin = alfalfa-grass

6.4.2 CO_2 abatement costs of GHG mitigation

In accordance with our case study results, other LCA studies showed that using biogas for the production of electricity, heat or fuel produces fewer GHG emissions than the use of fossil fuels (Börjesson and Berglund, 2006; Thornley et al., 2015). However, these LCA studies only analyzed the environmental efficiency of the evaluated bioenergy systems but not the economic feasibility and usability. Therefore, it is important to evaluate not only the GHG emission reduction potential but also the costs that this reduction entails in order to fully assess a renewable energy source.

CO_2 abatement cost is an indicator that describes the cost efficiency of energy production technologies to reduce GHG emissions compared to other technologies in order to identify the optimal use of public funds. As a result, only technologies should be implemented when the resulting abatement costs are lower than those of other reduction strategies (Rehl and Müller, 2013). To calculate the abatement cost of a biogas production system, all costs of the established biogas plants in Euro and the associated CO_2 emissions in kg CO_2 eq per functional unit (1 MJ) are calculated relative to a business as usual scenario as baseline.

Rehl and Müller (2013) evaluated the abatement costs of different biogas production systems in Germany. They found that biogas production systems have a high potential for cost-efficient reduction of GHG emissions and the abatement costs are lowest when heat is produced as the main product and higher when electricity is the main or sole product of the biogas system. The German scientific advisory board for agriculture (WBA, 2008) estimated the CO_2 abatement cost of maize based biogas and biofuels production systems of 150 €/t CO_2 eq up to 300 €/t CO_2 eq. However, the WBA (2008) suggested that the German government should focus on renewable energy production chains with CO_2 abatement cost of under 50 €/t CO_2 eq in order to support efficient climate political development. For an example, this could be slurry based biogas production systems with 52 €/t CO_2 eq (WBA, 2008). The actual CO_2 abatement potential and the costs for the society to realize this potential highly depends on the regional conditions (e.g. local infrastructure) and the environmental and cost profile of the substituted energy systems in that region. A sensitivity analysis of Rehl and Müller (2013) revealed that abatement costs are strongly influenced by the GHG emission and cost profile of the reference system as well as the used abatement cost calculation method. Consequently, the calculated abatement costs are only a snapshot of the energy market at a particular moment in time and can become invalid if the energy market changes. For example, at the present, the national German fuel mix primly consists of energy from natural gas, coal and oil. By improving the environmental profile of input materials and energies in the reference system (national fuel mix), the difference in the GHG balance of the biogas systems and the reference system would decrease, which consequently increases the abatement costs.

Through an extension of the MiLA tool with the indicator CO_2 abatement cost, the informative value of the tool results could be increased and help to support the identification of promising bioenergy production options. This indicator is in general very useful for decision-making due to its eco-efficient basis and due to its value for engineers to optimize the production process in order to provide an overview of relevant environmental aspects in relation to costs and to identify the optimal application of the biogas technology. However, the methodology to assess the abatement cost still contains several shortcomings in terms of the transparency of the assumptions and the reliability of the instruments for assessing the efficiency and effectiveness of the energy production systems. But since the MiLA tool is a transparent and efficient tool to calculate the GHG emissions from energy crop production for biogas, the tool results could be used as a strong basis to develop a robust methodology to estimate the abatement cost of bioenergy production out of energy crops in order to evaluate the regional bioenergy investment potential.

6.5 Application of MiLA in sustainability assessments

LCA in the context of sustainable crop production assessment comprises a wide range of impact categories e.g. resource depletion, ozone depletion, human toxicity, acidification of water and soil, eutrophication of surface water, erosion potential. For the promotion of biogas production from energy crops by experts and politicians, the key drivers were the potential for GHG emission and CED reduction relative to fossil fuels (Dressler et al., 2012). Therefore, the MiLA tool focuses on the impact categories “climate change” and “CED.” In order to close this gap and include more sustainability indicators in the impact assessment of energy crops the MiLA tool can be extended with additional indicators or as presented in (Peter et al., 2017a) the results of the MiLA tool can be used in combination with other indicator results to perform an resource efficiency analysis.

The results of this study revealed that the efficiency of each crop rotation is dependent on regional conditions and related management. The results also showed that the three indicators (area use, energy and economic efficiency) are strongly correlated. This study demonstrated that it is possible to use the MiLA tool results in further sustainability assessments of crop production. By combining the indicator results, the relationship between the indicators can be assessed. In this case study the analysis revealed that by improving one of the efficiency indicators, the other two benefit as well. Moreover, it was demonstrated that the design of crop rotations and regional adopted management practices can be an appropriate steering option in land use management. By applying this approach to other regional datasets, more resource-efficient cropping systems could be identified and could thereby help to improve the diversification of energy cropping systems.

Nevertheless, it is necessary to take all sustainability indicators into account to assess sustainable energy cropping systems since a reduced GHG emissions crop production does not imply low erosion or economic efficiency. By expanding the presented approach ideally by additional environmental and social indicators a complete sustainability assessment could be performed in order to assess the most sustainable regional adopted cropping system. The presented approach in (Peter et al., 2017a) can contribute to the further improvement of indicators and models used for assessing the regional impacts of energy cropping systems.

6.6 Upscaling possibilities

Even though the presented tool and modelling approach contains some uncertainties regarding the approach to modeling crop rotation effects as well as the used calculation methods and default values, the results of this thesis demonstrated that by including pedoclimatic conditions and crop rotation effects into GHG emission calculations decreases the uncertainties in CFP modelling results. Consequently, by including these aspects into national and global GHG emission agricultural inventory accountings a better reflection of agricultural reality could be achieved and as a result more detailed GHG emission reduction plans could be developed. However, the implementation of this approach at a larger scale, e.g. in German national GHG emissions agricultural inventory calculations, could be difficult since the required data are barely available at this level of resolution, and any modeling of such CFP results would be extremely complex and time-consuming. In order to include crop rotation effects in larger-scale CFP assessments, a less data-intensive approach still needs to be developed.

7 Conclusion

Only few publications are available that focus on the impact of energy crop cultivation in rotation on the environment and on the modeling approaches of the assessment of complex agricultural systems. This critical lack of knowledge among farmers, policymakers and scientists and the uncertainties regarding the available modelling tools and their results prevented the introduction of newly designed diverse and environmental friendly energy crop rotations. The studies of this thesis present a new tool which is well-suited for product-specific LCA for energy and food crops in rotation and helps the users to draw a more realistic picture of the interactions between crops, and thus increasing the reliability of the LCA results. The MiLA tool offers a way to analyze a large number of crops cultivated in rotations and under different local conditions. It can be used (1) to assess GHG emissions and energy efficiency of site-specific energy crop cultivation and (2) to compare these indicator results to other agronomic, social and economic indicators. Based on the results potential improvements can be determined by selecting an optimal crop rotation and management for a specific region.

The evaluation of different crop rotations at various sites in Germany in terms of different aspects of their resource efficiency (area use, energy and economic efficiency) revealed that the efficiency of each crop rotation is dependent on the regional condition and related management. Consequently, there is no ideal crop rotation for all sites but the efficiency indicators were strongly correlated. Therefore, by improving one of the indicators, the other two benefit as well. This indicates that economic efficiency does not necessarily conflict with other efficiency goals and the design of crop rotation adapted to regional site conditions can be a useful tool for steering and optimizing resource efficiency. Furthermore, it was demonstrated that there are alternatives to the dominant cultivation of maize as energy crop in Germany. Perennial field forage crops demonstrated many advantages as environmental-friendliness due to low nitrogen and tillage demand and growth under unfavorable conditions. At some sites with the cultivation of perennial field forage comparable methane yields to maize could be reached. Combining energy and cash crops within one crop rotation (e.g. C_4 including maize or sorghum and C_3 crops) may be as well a reliable alternative for improving diversification of the energy cropping system, soil organic matter (if chopped straw is left on the field) and resource efficiency. As a result, environmental damages and thus the negative image of energy crop cultivation could be reduced.

For farmers and policymakers, resource efficiency and GHG emissions are focal indicators for biogas production pathways to identify efficient, high yielding and environment- friendly production lines to secure the global energy supply. However, in order to determine sustainable energy cropping systems, it will be indispensable to extend the MiLA tool by including additional social, economic and environmental indicators to cover all indicators of sustainability assessment.

In this thesis it could be demonstrated, that by taking crop rotation effect in LCA studies of crop cultivation into account, a better reflection of agricultural reality is achieved and modelling uncertainties could be reduced. Consequently, these aspects should also be included in national and global GHG emission agricultural inventory accountings in order to derive reliable and regional adopted GHG emission reduction plans. However, the implementation of this approach on a larger scale, e.g. in German national GHG emissions agricultural inventory calculations, could be difficult since the required data are barely available at this level of resolution, and any modeling of such LCA results would be extremely complex and time-consuming. A possible solution could be the downscaling of the GHG inventory calculations from the national to the regional (federal states or even districts) level. The regional authorities could perform the regional calculations with support of the farmer and derive farm-specific GHG mitigation potentials. For national and global comparison purpose the regional results can be summarized. Although, this solution is time and data-intensive and requires a high level of motivation by the government and farmers, the increase of agricultural system understanding and improvement of the environmental situation including the achievement of the German climate protection targets should justify the effort.

8 Summary

Sustainability of energy cropping is in the focus of an increasingly critical public debate. It is broadly assumed that the substantial rise in energy production from agricultural biomass in recent years might put additional pressure on biodiversity, the environment, GHG emission savings and landscape aesthetics. Most of the criticism of biogas production in Germany is related to the substantial increase in the cropping area of one particular crop, namely maize. The unproblematic management of maize combined with a high profitability were leading to a trend of maize cultivation in short rotations up to monoculture. Such practices result in diversification losses of crop rotations which can generate potential environmental damages.

At the moment few empirical data are available regarding the impact of energy crops and their management on different sustainability indicators. Additionally most communications have been based on modelling approaches estimating the potential impacts of energy cropping and thus are strongly related to the model assumptions. As a result, the limitation of information in combination with the agronomic, ecological and economic risks for the farmer of establishing new cropping systems were leading to a specification of a limited number of energy crops, mostly maize. On the other hand, there is growing pressure on farmers to prove the sustainability of their energy cropping system to society. Consequently, appropriate assessment tools are needed to detect sustainable energy cropping systems especially in the context of GHG emission mitigation and energy efficiency.

Different LCA tools and environmental assessment approaches are available for the evaluation of agricultural crop production systems. However, most of these tools are lacking in their ability to fully reflect current agricultural practices. These tools can account for differences in local agricultural management practices, pedoclimatic conditions, and farming technologies but all are lacking in the consideration of the characteristics of perennial crops and crop rotations and their effects.

The aim of this thesis was the development of a tool to calculate and analyze the GHG emissions and energy efficiency of energy crop cultivation in rotations. Furthermore, the challenges and special features of energy crop rotation modeling were investigated including the review of currently available tools for GHG emission assessments as well as an analysis of GHG emissions calculation methods from energy crop cultivation and a demonstration of the performance of the developed new tool.

Energy crop cultivation is a dynamic and complex system influenced by many factors as crop type, pedoclimatic conditions and management practices. This complexity hampers a sufficient realistic representation of GHG emission from energy crop cultivation using a model. In this thesis “medium effort” regional specific GHG emission assessment approaches are identified, which (1) require little additional effort compared to global approaches and (2) improve the accuracy of the estimate of land-based GHG emissions from fertilization and SOC change.

Crop rotations are part of current agricultural practice, since they and their effects can contribute to a sustainable agricultural cropping system. Typical LCA studies from annual energy crops take only one vegetation period into account and disregard the interactions between the previous crops on the assessed crop (crop rotation effects). Ignoring these effects may lead to incorrect interpretation of LCA results and consequently to poor agricultural management as well as poor policy decisions. The review of 44 currently available agricultural environmental assessment calculators revealed that 18 calculators were capable of assessing GHG emissions from energy crop cultivation following the IPCC guidelines and using the LCA approach. Only seven out of these 18 could calculate GHG emissions from energy crop rotations but none of these calculators were able to consider actual crop rotation effects as .g. nutrient carryover.

To overcome the shortcomings of available LCA tools, a new tool called “Model for integrated Life Cycle Assessment in Agriculture”, short MiLA was developed. MiLA can calculate the GHG emissions and CED of cropping systems by taking the characteristics of crop cultivation in rotation into account. Furthermore, differences in local agricultural management practices, pedoclimatic conditions, farming practices and farming technologies as well as energy crop specifications are considered.

The tool was applied to a case study in Germany, which results showed that including crop rotation effects influenced the GHG emission result of the individual crop by -34% up to +99% and the CED by -16% up to +89 %. Expanding the system boundary by taking the whole crop rotation into account as well as providing the results based on different functional units improves LCA of energy crop production and helps to draw a more realistic picture of the interactions between crops while increasing the reliability of the LCA results.

The MiLA tool results can be used in further “cradle to grave” LCA studies in order to calculate the GHG emission savings from bioenergy production out of energy crops compared to their fossil alternatives. The conducted analysis of different crop rotations at different regions in Germany revealed that up to 68% GHG emission savings can be reached and that the crop rotation design has a substantial impact on the GHG emission result of the whole bioenergy production pathway.

Furthermore, the MiLA tool indicator results can be combined with other indicator results e.g. in order to assess the resource efficiency (area use, energy and economic efficiency) of different crop rotations at various sites. The case study results revealed that the efficiency of each crop rotation is dependent on the regional condition and related management, and that the efficiency indicators were strongly correlated. Consequently, the economic efficiency does not necessarily conflict with other efficiency goals and the design of crop rotation adapted to regional site conditions can be a useful tool for steering and optimizing resource efficiency. However, in order to determine sustainable energy cropping systems, it will be indispensable to extend the MiLA tool by including additional social, economic and environmental indicators to cover all indicators of sustainability assessment.

In this thesis it could be demonstrated, that MiLA tool results have a wide range of application possibilities. Through the consideration of crop rotation effect in LCA studies a better reflection of agricultural reality was achieved and modelling uncertainties could be reduced. Consequently, these aspects should also be included in national and global GHG emission agricultural inventory accountings in order to derive reliable and regional adopted GHG emission reduction plans.

9 Zusammenfassung

Die Nachhaltigkeit des Energiepflanzenanbaus steht zunehmend im Fokus einer kritischen öffentlichen Debatte. Im Allgemeinen wird angenommen, dass der Anstieg der Energieproduktion aus landwirtschaftlich erzeugter Biomasse in den letzten Jahren einen zusätzlichen Druck auf Biodiversität, Umwelt, Treibhausgaseinsparungspotential und Landschaftsästhetik ausgeübt hat. Der zunehmende Anbau von Mais für die Biogasproduktion in Deutschland wird am meisten kritisiert. Eine einfache Anbaupraxis in Kombination mit der hohen Profitabilität von Mais führte zu einem Anbau von Mais in verkürzten Fruchtfolgen bis hin zu Mais in Selbstfolge. Dieser Trend führt zu Diversitätsverlusten in den Fruchtfolgen, die sich negativ auf die Umwelt auswirken können.

Zurzeit sind nur wenige empirische Daten bezüglich des Einflusses des Energiepflanzenanbaus und dessen Management auf einzelne Nachhaltigkeitsindikatoren verfügbar. Zusätzlich basieren die Aussagen verschiedener Studien zur Abschätzung des potentiellen Einfluss des Energiepflanzenanbaus auf Modellierungsansätze, deren Qualität stark von den getroffenen Modellannahmen abhängt. Aufgrund der eingeschränkten Informationsverfügbarkeit sowie erhöhten ökonomischen, ökologischen und agronomischen Risikos beim Anbau neuer Energiepflanzenkulturen, etablierte sich nur eine begrenzte Anzahl von Energiepflanzen. Jedoch steigt auch der gesellschaftliche Druck auf den Landwirt, einen nachhaltigen Energiepflanzenanbau vorzuweisen.

Aktuell stehen verschiedene Ökobilanzierungstools und Umweltbewertungsansätze zur Beurteilung von landwirtschaftlichen Pflanzenbauproduktionssystemen zur Verfügung. Jedoch sind viele dieser Tools nicht in der Lage, die aktuelle landwirtschaftliche Praxis wiederzugeben. Die derzeitig existierenden Tools berücksichtigen Unterschiede in regionalen und landwirtschaftlichen Management, den Einfluss von verschiedenen Boden-Klimatischen-Bedingungen und die eingesetzte landwirtschaftlichen Technik. Allerdings fehlt ihnen die Fähigkeit, mehrjährige Fruchtarten, Fruchtfolgen und Fruchtfolgeeffekte zu berücksichtigen.

Das Ziel dieser Dissertation war die Entwicklung eines Ökobilanzierungstools, für die Berechnung und Analyse von Treibhausgasemissionen (THG-Emissionen) und den kumulierten Energieaufwand (KEA) beim Energiepflanzenanbau. Das Tool soll dabei die aktuell gängige Praxis des Energiepflanzenanbaus wie dem Anbau mehrjähriger Früchte, die Kombination von Markt- und Energiepflanzen in Fruchtfolgen und die daraus resultierenden Fruchtfolgeeffekte berücksichtigen können. Aus diesem Grund wurden zunächst die Herausforderungen und Spezifikationen des Energiepflanzenanbaus in

Fruchtfolge untersucht. Dies beinhaltete ein Review der aktuellen verfügbaren THG-Emissionsbilanzierungstools, eine Analyse der gängigen THG-Emissionsberechnungsmethoden im Energiepflanzenanbau sowie eine Demonstration der Leistungsfähigkeit des neu entwickelten Tools.

Der Energiepflanzenanbau ist ein dynamisches und komplexes System, welches durch verschiedenste Faktoren wie z.B. Fruchtart, Boden-Klima-Bedingungen und Anbaumanagement beeinflusst wird. Diese Komplexität erschwert jedoch eine zufriedenstellende Genauigkeit bei der Darstellung der THG-Emissionen des Energiepflanzenanbaus durch ein Modell. Im Rahmen der Dissertation wurden „leicht anwendbare mit mittleren Aufwand verbundene“ regionalspezifische Ansätze zur Modellierung von THG-Emission identifiziert, die nur einen geringfügig höheren Aufwand als globale Ansätze besitzen, jedoch die Genauigkeit der berechneten Feldemissionen verursacht durch Düngemittelapplikation und Bodenkohlenstoffänderungen, steigern.

Fruchtfolgen sind Teil der aktuellen landwirtschaftlichen Praxis, da Fruchtfolgeeffekte zu einem nachhaltigen Anbau beitragen können. Typische Ökobilanzstudien von einjährigen Energiepflanzen berücksichtigen nur die aktuelle Anbauperiode und missachten somit Interaktionen zwischen den Vorfrüchten und der aktuellen Frucht (Fruchtfolgeeffekte). Durch die Vernachlässigung der Fruchtfolgeeffekte kann es zu Fehlinterpretation der Ökobilanzstudienergebnisse kommen und demzufolge zu schlechten landwirtschaftlichen Anbaupraktiken und falschen politischen Entscheidungen. Die Untersuchung von 44 derzeit verfügbaren landwirtschaftlichen Umweltbewertungstools zeigte, dass nur 18 davon in der Lage sind, THG-Emissionen des Energiepflanzenanbaus nach den IPCC Richtlinien und der Ökobilanzmethode zu berechnen. Nur sieben von den 18 Tools konnten die THG-Emissionen vom Energiepflanzenanbau in einer Fruchtfolge berechnen. Jedoch war kein Tool in der Lage, Fruchtfolgeeffekte wie Nährstoffnachlieferungen mit in die Berechnung mit einzubeziehen.

Um die Unzulänglichkeiten der aktuellen Ökobilanzierungstools zu überwinden, wurde ein neues Tool mit dem Namen „Model for integrative Life Cycle Assessment in Agriculture“ (MiLA), entwickelt. Dieses Tool kann die THG-Emissionen und KEA im Energiepflanzenanbau unter Einbeziehung der Eigenschaften des Energiepflanzenanbaus in Fruchtfolge berechnen. Des Weiteren werden Unterschiede im Anbaumanagement, Boden-Klima-Eigenschaften, verwendete landwirtschaftliche Technik und die Spezifikationen des Energiepflanzenanbaus berücksichtigt.

Die Leistungsfähigkeit des Tools wurde anhand von Daten einer Feldstudie in Deutschland getestet. Die Ergebnisse zeigten das die Einbeziehung von Fruchtfolgeeffekten einen Einfluss von -34% bis +99% auf die berechnet THG-Emissionen und von -16% bis +89% auf den KEA der einzelnen Früchte in der Fruchtfolge haben kann im Vergleich zu der Berechnung ohne Einbeziehung der Fruchtfolgeeffekte. Durch die Erweiterung der Systemgrenze auf die gesamte Fruchtfolge und die Einbeziehung unterschiedlicher funktionaler Einheiten kann die Ökobilanzmethode zur Berechnung des

Energiepflanzenanbaus verbessert werden. Dies trägt dazu bei, ein realitätsnahes Bild der Interaktionen zwischen den Früchten zu skizzieren um somit die Zuverlässigkeit der Ökobilanzergebnisse zu erhöhen.

Die Ergebnisse des MiLA Tools können in weiterführenden „Wiege-zur-Bahre“ Ökobilanzen verwendet werden, um z.B. die THG-Emissionseinsparungspotentiale bei der Bioenergieherstellung aus Energiepflanzen im Vergleich zu deren fossilen Alternativen zu berechnen. Die durchgeführte Analyse von unterschiedlichen Fruchtfolgen an verschiedenen Standorten in Deutschland zeigte, dass bis zu 68% THG-Emissionen eingespart werden können. Die Ergebnisse zeigten auch, dass das Fruchtfolgedesign einen starken Einfluss auf das THG-Emissionsergebnis des gesamten Energieherstellungsweges hat.

Des Weiteren können Indikatorergebnisse von MiLA mit weiteren Indikatoren kombiniert werden um z.B. die Ressourceneffizienz (Flächen-, Energie und ökonomische Effizienz) von unterschiedlichen Fruchtfolgen an verschiedenen Standorten zu ermitteln. Die Ergebnisse aus dieser Studie zeigten, dass die Effizienz jeder Fruchtfolge abhängig von den regionalen Bedingungen und dem damit verbundenen Management ist und dass die einzelnen Effizienzindikatoren stark miteinander korrelieren. Demzufolge steht die ökonomische Effizienz nicht ausschließlich im Konflikt mit anderen Effizienzzielen. Regional angepasste Fruchtfolgen können ein nützliches Werkzeug zur Steuerung und Optimierung der Ressourceneffizienz darstellen. Um jedoch nachhaltige Energiepflanzensysteme zu identifizieren, ist es unverzichtbar, MiLA zur Durchführung einer ganzheitlichen Nachhaltigkeitsbewertung um zusätzliche soziale, ökonomische und ökologische Indikatoren zu erweitern.

In dieser Arbeit wurde die vielfältige Einsatzfähigkeit von MiLA und dessen Ergebnisse demonstriert. Durch die Einbeziehung von Fruchtfolgeeffekten in Ökobilanzstudien kann eine bessere Reflektion der landwirtschaftlichen Realität erzielt und Unsicherheiten in der Modellierung reduziert werden. Demzufolge wäre es von Vorteil, wenn dieser Ansatz in die nationale und globale THG-Emissionsberichterstattung und Berechnung mit aufgenommen wird um zuverlässige regionale angepasste THG-Emissionsreduktionspläne zu entwickeln.

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Danksagung

Meinen besonderen Dank gelten Prof. Dr. Joachim Aurbacher und Dr. Claas Nendel für die stets freundliche und engagierte fachliche Betreuung dieser Doktorarbeit.

Bei Dr. Michael Glemnitz möchte ich mich recht herzlich für die wertvolle Unterstützung bei der Erstellung der Manuskripte sowie die konstruktiven Gespräche bei der statistischen Auswertung der Daten bedanken. Er hat mich motiviert und gefördert in allen Facetten des wissenschaftlichen Arbeitens und hatte dabei stets ein offenes Ohr für mich während der Erarbeitung meiner Dissertation.

Weiterhin richtet sich mein Dank an alle Mitarbeiter im EVA-Projekt für die Erarbeitung und Bereitstellung aller notwendigen Daten und die gute Zusammenarbeit.

Dr. Xenia Specka danke ich für das gründliche Korrekturlesen des Manuskriptes.

Bei allen Mitarbeitern des Instituts für Landschaftssystemanalyse des Leibniz-Zentrums für Agrarlandschaftsforschung e.V. Müncheberg, insbesondere bei den Kolleginnen und Kollegen der EVA-Projekt-Arbeitsgruppe, möchte ich mich für die angenehme Arbeitsatmosphäre, die gute Zusammenarbeit und Freundschaft bedanken. Mein besonderer Dank gilt Frau Dr. Anne-Katrin Prescher, Frau Katrin Lück, Frau Karin Luzi und Frau Carola Voigt für das Korrekturlesen und editieren meiner Manuskripte, die Unterstützung beim Erstellen von Grafiken und die Aufbereitung der Daten.

Ganz herzlich möchte ich mich bei meinen Eltern für die uneingeschränkte Förderung meiner Ausbildung bedanken und das Sie immer und in jeder Lebenslage für mich da seid.

Zuletzt möchte ich mich ganz herzlich bei meinem Freund Michael bedanken, der durch seinen stetigen Zuspruch, motivierende Worte, der Unterstützung in allen Lebenslagen sowie seinen landwirtschaftlichen Fachwissen und kreativen Ideen zum Gelingen dieser Arbeit maßgeblich beigetragen hat.

Eidesstattliche Erklärung

Ich erkläre: Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe.

Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht.

Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der „Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ niedergelegt sind, eingehalten.

Christiane Peter

Dresden, 22.06.2017

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