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

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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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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.

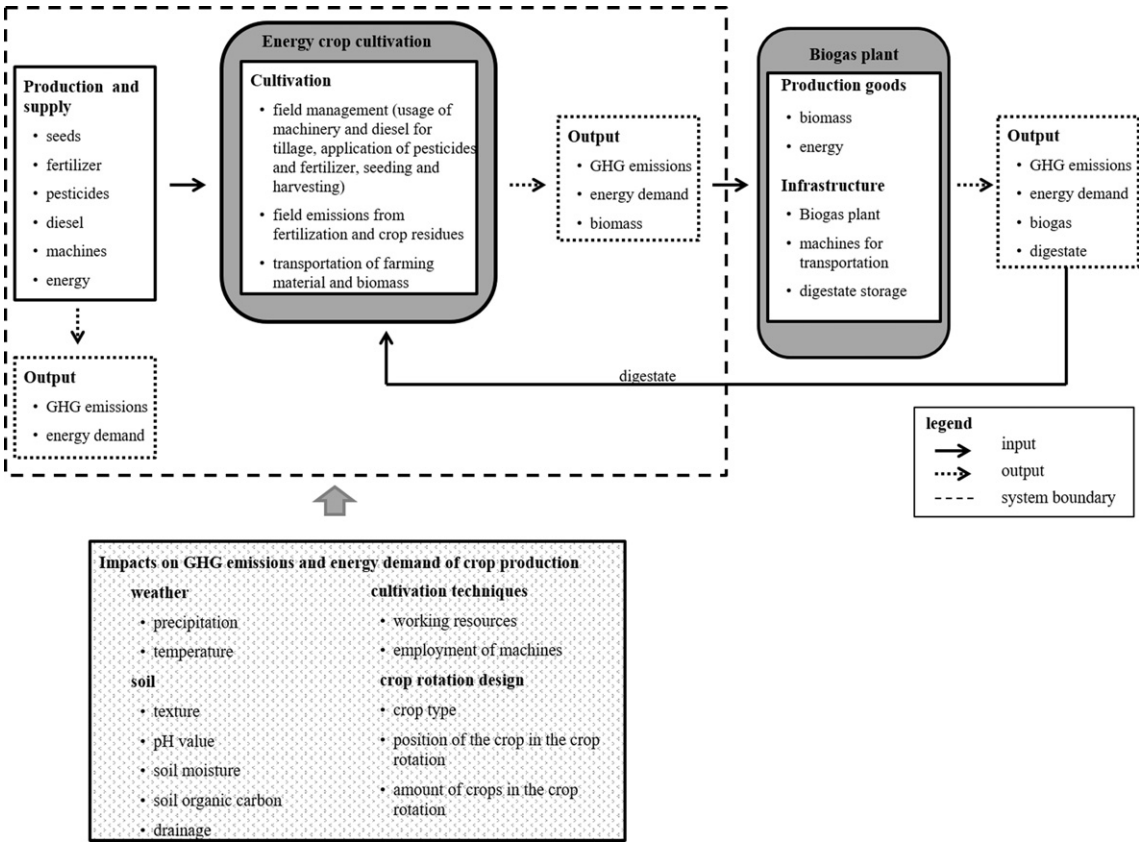

Fig. 1. System boundary and impact factors on GHG emissions and CED of EC production integrated in MiLA.

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

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 gas-tight (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.

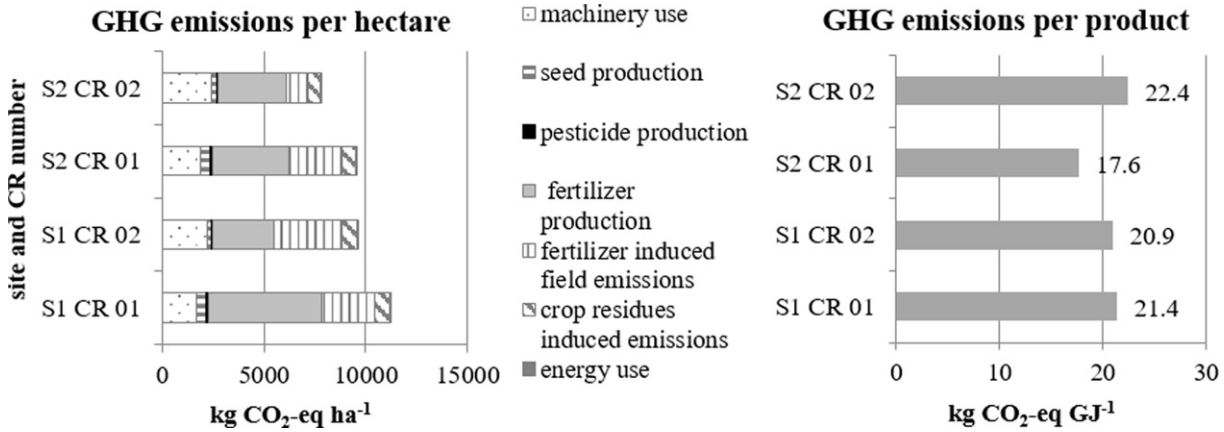

Fig. 3. Comparison of GHG emissions totaled over the whole CR per ha (left) divided into GHG emission categories, and the GHG emissions per product energy yield (right) at both sites.
Source: MiLA, based on authors' calculations.

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.

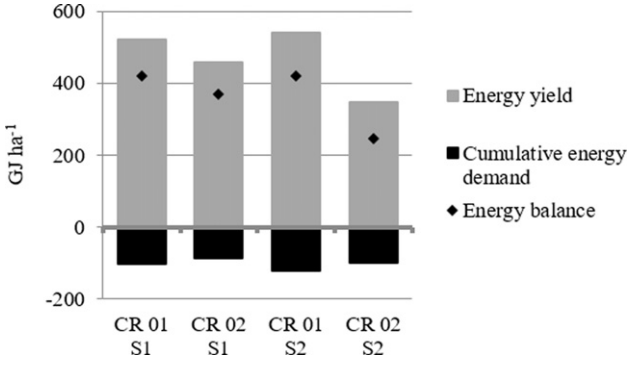

Fig. 4. Comparison of the energy yield, CED, and energy balance of CR 01 and CR 02 at both sites.
Source: MiLA, based on authors' calculations.

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.

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