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

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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.

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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.

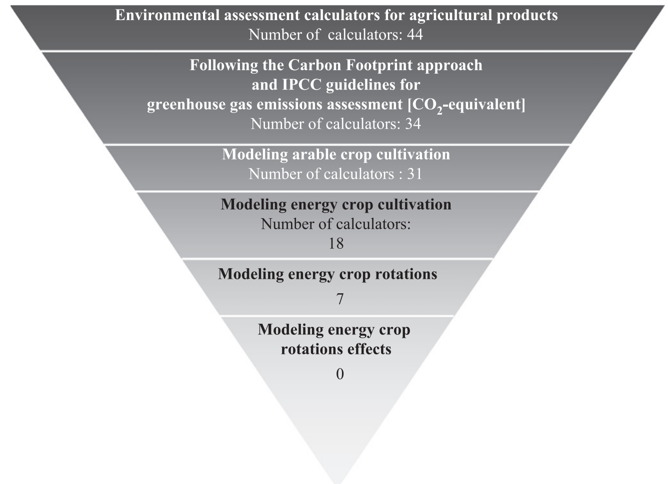

Fig. 1. Selection process for GHG emission calculators for energy crop cultivation.

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** *(Are-caceae)*	**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 belowground 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.

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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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