Environmental potential and sustainability estimation of crop production from the agricultural Life Cycle Assessment perspective

Habilitation Thesis

to obtain the *Venia docendi* in the Field of Applied and Landscape Ecology (*Aplikovaná a krajinná ekologie*) at the University of South Bohemia (USB), České Budějovice

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Ing. Jaroslav Bernas, Ph.D.

Faculty of Agriculture and Technology
University of South Bohemia (USB), České Budějovice
Studentská 1668, 370 05 České Budějovice

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Form of the habilitation thesis: A set of published scientific papers supplemented by a commentary and related discussion. Only articles published in the Journal papers with Impact Factors, Recensed papers, and Book chapters were used for the submitted habilitation thesis.

The Statement

I declare that I have prepared the presented habilitation thesis entitled ***"Environmental potential and sustainability estimation of crop production from the agricultural LCA perspective"*** independently using available literary sources and my scientific work results. I achieved the results of my scientific work in cooperation with colleagues from the Faculty of Agriculture and Technology, University of South Bohemia, or colleagues from other workplaces in the Czech Republic and elsewhere in Europe from the time of doctoral studies until the writing of this work (period 2012 - 2021).

In České Budějovice, ………………… Ing. Jaroslav Bernas, Ph.D.

Signature …………………

Preface

The submitted habilitation thesis documents my research results of the last years with a special focus on environmental aspects of agriculture from the perspective of the Life Cycle Assessment. The habilitation thesis is a compilation of related publications supplemented by commentary and general discussion.

I would like to thank the Department of Agroecosystems for its support and cooperation in the last years, the Faculty of Agriculture and Technology for the opportunity to be a member of this institution, and the Department of Applied Ecology for collective support and motivation. I am grateful to all of the colleagues I have cooperated with over the last several years.

I finally want to warmly thank all my family members, especially my wife Tereza and daughter Antonie for their inspiration, energy, and love.

Jaroslav Bernas
České Budějovice

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Úvod (CZ)

Zemědělský sektor hraje strategickou roli v ekonomickém růstu, plní základní environmentální a sociální funkce a poskytuje širokou škálu ekosystémových služeb vázaných na životní prostředí. Zejména vztah zemědělství a životního prostředí je velmi úzký. Avšak stálá intenzifikace zemědělství tento vztah mnohdy až zásadním způsobem narušuje.

Současné zemědělství disponuje environmentálně šetrnějšími alternativami, jakými je zemědělství ekologické, integrované nebo precizní. Mezi potenciální přínosy těchto systémů patří snížení nákladů aplikací, nebo zlepšení správy vodních zdrojů. Kromě toho přináší více možností z hlediska technicko-produktivního, ekonomického a environmentálního managementu. Jedná se o výrobní systémy založené na principu používání zemědělských postupů, u nichž se očekává, že zvýší ekologické procesy a zároveň silně redukují použití externích syntetických vstupů a celkově množství všech vstupů do procesu. Celospolečenský zájem o udržitelnější formy hospodaření a šetrnější či udržitelnou produkci potravin i nadále narůstá, což vede k poptávce po informacích o environmentálních vlastnostech zemědělských systémů, technologií služeb a výrobků téměř ze všech částí společnosti. Tomu přispívá i diskutovaná problematika změny klimatu a zhoršování životního prostředí, což představuje hrozbu pro Evropu a celý svět. I díky tomu vznikla například Zelená dohoda pro Evropu (*European Green Deal*), která má Evropskou unii transformovat na moderní, konkurenceschopnou ekonomiku, jež účinně využívá zdroje a kde se do roku 2050 dosáhne nulových čistých emisí skleníkových plynů. V důsledku toho jsou v popředí aspekty jako: porovnání dvou a více produktů či služeb z hlediska dopadů na životní prostředí; přechod na výrobní systém který snižuje dopady na životní prostředí; podpora inovativní technologie řízení z hlediska životního prostředí atd.

K vyhodnocení těchto aspektů lze využít řadu sofistikovaných metod. Jednou z nejčastěji používaných metod pro zodpovězení těchto otázek je proces posuzování životního cyklu (*Life Cycle Assessment - LCA*), který je široce přijímanou metodikou pro hodnocení potenciálních dopadů na životní prostředí, spojených se zemědělsko-potravinářským řetězcem a systémy zemědělské výroby. Jde o analytickou metodu, která hodnotí environmentální dopady výrobků, služeb, technologií a obecně lidských produktů a organizací. Při analýze dopadů zemědělského systému na životní prostředí je zohledněno využití zdrojů, vstupů jak interních tak externích, emise znečišťujících látek a nebo využití půdy. Zjištěné dopady jsou kvantifikovány pomocí souboru indikátorů, tzv. dopadových kategorií (např. změna klimatu, sladkovodní či mořská eutrofizace, suchozemská či vodní ekotoxicita, dopady na lidské zdrav, spotřeba fosilních paliv, spotřeba vody, dopady na ozonovou vrstvu, land use aj.) a vykazovány například na jednotky produktu (např. g bílkoviny v obilném zrnu) nebo plochy (např. 1 ha orné půdy) a následně je hodnocena ekologická účinnost posuzovaného systému.

Metoda posuzování životního cyklu je rovněž základem pro: Environmentální prohlášení o produktu; Uhlíkovou stopu; Environmentální stopu produktu a organizace; Ekodesign a ekoinovace; Vodní stopu a další. Studie LCA mohou sloužit jako nástroj pro snižování environmentálních dopadů podniků, jako motivační aspekty při komunikaci se zákazníkem, motivační nástroje pro environmentálně orientovanou politiku (např. zemědělskou), pro zvýšení konkurenceschopnosti či pro vývoj a výzkum. Benefitem metody LCA je její schopnost interpretovat data do přehledné sady environmentálních indikátorů. S pomocí LCA lze porovnávat environmentální dopady produktů s ohledem jejich funkci či hodnotit environmentální dopady s ohledem na celý životní cyklus produktu. Studie LCA má obecně schopnost identifikovat přenášení environmentálních problémů jak v prostoru, tak mezi různými kategoriemi dopadu. Lze tedy odhalit přenášení problémů tzv. z místa na místo. Výstupy z konkrétní LCA studie nejsou platné obecně, ale vždy za daných a jasně specifikovaných podmínek. Přínosem metody LCA je právě jasná definice podmínek platnosti studií, zasazující dané poznatky o interakcích technologických procesů a životního prostředí do konkrétního technologického, environmentálního, ale i socioekonomického kontextu.

V zemědělství lze tuto metodu velice efektivně uplatňovat například při porovnání environmentálních dopadů pěstitelských postupů, chovů hospodářských zvířat, systémů posklizňového zpracovaní, přepravy, technologií zpracování půdy, odrůd, energetických rostlin, aj. Možnosti využití popsaného přístupu k řešení otázek dopadů zemědělských aktivit na životní prostředí může dokreslit předložená habilitační práce a publikované studie uplatňující koncept zemědělské LCA nebo její zjednodušenou verzi.

1 Introduction

The agricultural sector plays a strategic role in economic growth, fulfills basic environmental and social functions, and provides a wide range of ecosystem services linked to the environment. In particular, the relationship between agriculture and the environment is very close. However, the constant intensification of agriculture often severely disrupts this relationship.

The current agricultural sector has more environmentally friendly alternatives, such as organic, integrated, or precision agriculture. Potential benefits of these systems include reduced application costs or improved water resource management. In addition, it brings more options in terms of technical-productive, economic and environmental management. These are production systems based on the principle of using agricultural practices, which are expected to increase ecological processes while strongly reducing the use of external synthetic inputs and the overall amount of all inputs to the process. Society-wide interest in more sustainable forms of farming and more environmentally friendly or sustainable food production continues to grow, leading to a demand for information on the environmental characteristics of agricultural systems, service technologies, and products from almost all parts of society. The discussed issue of climate change and environmental degradation also contributes to this, posing a threat to Europe and the world. This has led to, for example, the European Green Deal, which aims to transform the European Union into a modern, competitive, resource-efficient economy with zero net greenhouse gas emissions by 2050. As a result, aspects such as: comparing two or more products or services in terms of environmental impact are at the forefront; transition to a production system that reduces environmental impact; support for innovative environmental management technologies, etc.

A number of sophisticated methods can be used to evaluate these aspects. One of the most commonly used methods to answer these questions is the Life Cycle Assessment (LCA) method, a widely accepted methodology for assessing the potential environmental impacts associated with the agri-food chain and agricultural production systems. It is an analytical method that assesses the environmental impacts of products, services, technologies, and human products and organizations. The analysis of the agricultural system's impacts on the environment considers the use of resources, inputs, both internal and external, emissions of pollutants, land use, and general resource consumption. The identified impacts are quantified using a set of indicators, so-called impact categories (e.g. *climate change*, *freshwater* or *marine eutrophication*, *terrestrial* or *aquatic ecotoxicity*, *human toxicity*, *fossil depletion*, *water depletion*, ozone depletion, *land use*, etc.) and reported in functional units, for example, per unit of product (e.g. of protein in cereal grain) or area (e.g. 1 ha of arable land) and then the ecological efficiency of the system under assessment is evaluated.

The life cycle assessment method is also the basis for Environmental Product Declaration; Carbon footprint; Environmental footprint of the product and organization; Ecodesign and eco-innovation; Water footprint, and more. LCA studies can serve as a tool for reducing the environmental impact of companies, as motivational aspects in communication with the customer, as motivational tools for environmentally oriented policy (e.g. agriculture), for increasing competitiveness, or as development and research. The benefit of the LCA method is its ability to interpret data into a clear set of environmental indicators. With the help of LCA, it is possible to compare the environmental impacts of products concerning their function or evaluate the environmental impacts with respect to the entire life cycle of a product. The LCA study generally has the ability to identify the transmission of environmental problems both in space and between different impact categories. It is, therefore, possible to detect the transmission of problems so-called from place to place. The outputs of a specific LCA study are not valid in general but always under given and clearly specified conditions. The benefit of the LCA method is a clear definition of the conditions of validity of studies, placing the knowledge about the interactions of technological processes and the environment into a specific technological, environmental, and socio-economic context.

This method can be very effectively applied in agriculture, for example, when comparing the environmental impacts of cultivation practices, livestock breeding, post-harvest processing systems, transport, tillage technologies, varieties, energy plants, etc. The possibilities of using the described approach to address the issues of the impact of agricultural activities on the environment can be illustrated by the submitted habilitation thesis and published studies applying the concept of agricultural LCA or its simplified (streamlined) version.

2 Agriculture and environmental impact assessment

As the global population grows, so does the demand for resources and their consumption. This trend also affects the agricultural sector (Bruinsma, 2017; Willer and Lernoud, 2019). At the same time, it is not expected that the trend of increasing environmental impact related to primary agricultural production will be reversed spontaneously in the foreseeable future (Sarkar et al., 2020). In this respect, climate change also affects the agricultural sector (Parry, 2019). Therefore, it is necessary to apply concepts that lead to sustainable farming systems (Scialabba & Hattam, 2002). These can also include the Green Deal for Europe, a set of policy initiatives by the European Commission with the overarching aim of making Europe climate neutral in 2050 (EC, 2021). Agricultural activity is part of ecosystems, and most processes (e.g. agrotechnical operations, fertilization, and plant protection) in agricultural production systems bring an environmental impact. It can reduce water and soil quality through excessive use of fertilizers, pesticides, and heavy metals and the production of acidifying substances and greenhouse gases (Dijkman et al., 2018). Agriculture is also the anthropogenic activity with the greatest surface impact, and agroecosystems are the most widespread type of terrestrial habitat and occupy about a third of the land (Šarapatka et al., 2008). The increase in the environmental impact influences all components of the environment and, last but not least, the climate (Lomborg, 2003; Kurukulasuriya and Rosenthal, 2013). Climate change and its anthropogenic role have thus become a much-discussed issue in recent years (Arora, 2019). The environmental impacts of agricultural activities need to be constantly monitored while looking for ways to mitigate their most important sources (Franks and Hadingham, 2012). The intensity of the environmental impact due to agricultural activity can be strongly influenced, among other things, by the farming system (Agovino et al., 2019) or tillage methods (Kramer et al., 1999). The emerging environmental footprint of agriculture is related to both biotic and abiotic processes, and these should be assessed comprehensively. Significant contributions to the overall environmental impact of agriculture can come from the soil, livestock, animal waste, fossil fuel consumption, fertilizer production and fertilizer application, plant protection products, etc. (Huang et al., 2018). Agricultural trends towards sustainability should increasingly establish more environmentally friendly ways while maintaining the food security capacity of the population. One of the goals of sustainable agriculture should be the general reduction of environmental impacts (Mishra et al., 2020).

To take measures to reduce the environmental impacts of agriculture is necessary to understand the impacts of agricultural activity and quantify these impacts (Weißhuhn et al., 2018). Accurate quantification of the overall environmental impacts is relatively difficult, but there are methods by which it can be implemented. One of these methods is Life Cycle Assessment Analysis (LCA). With the application of LCA, it is possible to quantify environmental impacts and thus look for opportunities for environmental savings (Dijkman et al., 2018). LCA is a transparent scientific tool (Hauschild et al., 2018), assessing the environmental impacts of a product based on an assessment of the impact of material and energy flows that the monitored system exchanges with the environment (Haas et al., 2000; Kočí, 2009). The original goal was to improve the product life cycle or to choose a variant with a lower environmental impact (Consoli, 1993). Insufficient protection of natural resources and high pollution of the environment are two aspects of the same issue: insufficient resource protection means excessive consumption, and excessive pollution of the environment means the insufficient provision of a healthy environment (Jílková, 2003).

The LCA method is one of the most important information tools for an environmentally oriented product policy. In the sense of ČSN 14040 (CSN, 2006a, and CSN, 2006b), the LCA method can be defined as the collection and evaluation of inputs, outputs, and possible impacts on the environment of a product system during the entire life cycle. In addition, LCA appears to be one of the few tools offering a comprehensive approach to environmental impact assessment (Kim and Dale, 2005; Hauschild et al., 2018). LCA is a valuable tool due to its ability to include and compare different agricultural systems, their individual processes and products, and most of their environmental impacts (Charles et al., 2006). Over the last decades, LCA analysis has been supplemented with sophisticated methods, libraries, and databases that allow its use in impact assessments within the agricultural sector in great detail (Jensen et al., 2005). LCA is an analytical method of evaluation. Life cycle assessment can be briefly characterized as a systematic process. Based on the substance and energy balances, it tries to determine the extent and magnitude of the complex negative impact on the environment that causes the existence of the evaluated system during its entire life. Therefore, the negative environmental impacts of the raw materials, including the methods of obtaining them, through their treatment, the actual production of the product, its consumption, and its final disposal, are assessed (Remtová and Přibylová, 2001; Hauschild et al., 2018). Anthropogenic activities have a very strong impact on the environment. With the growing human population, globalization, technological progress, and higher consumption demands, environmental pressure and impacts on the environment are also increasing. By environmental impacts, we mean the adverse effects of human activity on the quality of the environment, human health, and the amount of abiotic or biotic raw materials reserved in LCA studies. The LCA methodology does not quantify real environmental impacts but potential impacts on specific environmental problems called impact categories (Kočí, 2010). LCA is also a tool for comparing the environmental impacts of products or services regarding their entire life cycle, the so-called cradle to grave or from the cradle to the gate. Emissions to all environmental compartments during production, use, and disposal of the product are considered. Also included are raw material extraction processes, materials, and energy production, auxiliary processes, or subprocesses (Hauschild et al., 2018). The use of LCA for agricultural production has been described, for example, in a study by Haas et al. (2000), Nemecek et al. (2007), and Dijkman et al. (2018). Commercially available databases of processes and material and energy flows are used to efficiently process LCA studies (Hauschild et al., 2018).

2.1 Basic principles of agricultural LCA

Every anthropogenic activity causes impacts on the environment. Their rate is related to basic demographic factors, especially population density, technological maturity, level of education, and value attitudes of society (Goudie, 2018). In addition to energy, transport, and industry, agriculture is also one of the main anthropogenic activities causing negative impacts (Foley et al., 2011). Perhaps the most discussed area is greenhouse gas (GHG) production and the impact on the Global Warming Potential (GWP) (Niggli et al., 2009). For example, agriculture is the third largest sector in the Czech Republic, producing 6.46% of total GHG emissions incl. Land

Use, Land-Use Change and Forestry (LULUCF) and indirect emissions in 2018 with 8 606 kt CO_2 eq.; 49% of emissions came from Managed Agricultural Soils, 35% from Enteric Fermentation and 12% from Manure Management. Carbon dioxide emissions from liming and urea application on managed soils contributed 3% to the total agricultural emissions in 2018. (Beranova et al., 2020). In addition to air quality, agriculture affects the quality of water, soil, and biodiversity. It contributes to the depletion of resources, and the pesticides used cause toxicity to organisms, including humans. As a result of agricultural production, there are changes in land use, especially land occupation. Thus, it is certain that agriculture and related food production and consumption are among the important drivers of environmental burden (Notarnicola et al., 2015). Over the next years, it was predicted that food, energy, and water consumption would increase by 60% due to the growing world population and changes in eating habits (Alexandratos and Bruinsma, 2012). At the same time, in the fight against climate change, the demand for biofuels, which will compete on agricultural land intended for food production, will increase. All these changes will destabilize the sustainable use of natural resources and can cause associated social and geopolitical tensions. Given the context projected above, sustainable development, production, and consumption in the agri-food sector are key topics stimulating the development of many international activities and strategies to reduce environmental impacts and seek sustainable production routes (Notarnicola et al., 2015). Due to the large number of impacts and their diversity, it is not easy to evaluate the complex effects of the agricultural system within one method. There are various methods for evaluating one or more indicators that determine the magnitude of an impact (Goedkoop et al., 2009). LCA seeks a comprehensive assessment of the environmental profile of the product system and is one of the most holistically applicable methods in agriculture (Dijkman et al., 2018). Currently, the number of studies evaluating the impact of agricultural products using the LCA method is increasing. Comparative studies are often used to compare the environmental sustainability of products from different agricultural production systems (Meier et al., 2015). In an effort to minimize the negative impacts of sustainable agricultural systems, scientists and decision-makers need sufficient information about the positives and negatives of different production systems with respect to their productivity (Hauschild et al., 2018). The LCA method provides a suitable assessment tool that meets the requirement of a comprehensive assessment of the environmental impacts of different production systems (Meier et al., 2015). Generally compared production systems include conventional, integrated and organic farming. These systems vary according to the intensity of inputs such as fertilizers, pesticides, the number of agrotechnical operations, and the resulting environmental impacts (Stolze et al., 2000). The most intensive stage is conventional agriculture, whose primary target the high production (Mondelaers et al., 2009). Organic farming is then often seen as a solution to reduce the environmental impact of agricultural activity (Gomiero et al., 2011). However, the biggest problem here is the yield level (Seufert et al., 2012), which is lower on average (Wallén et al., 2004; Ponti et al., 2012). A larger area is required for the same yield that can be achieved in a conventional system, while the environmental benefits of evaluating a unit of production can be eliminated (Tuomisto et al., 2012). A more detailed description of the LCA method and its application in agriculture and food production was described in the book chapter Jelínková et al. (2016).

Publication 1

Life Cycle Assessment Method–Tool for Evaluation of Greenhouse Gases Emissions from Agriculture and Food Processing

Jelínková, Z., J. Moudrý, J. Moudrý (jr.), Kopecký, M. and **J. Bernas**

Book chapter

The chapter focuses on the use of the Life Cycle Assessment method to monitor the emission load of foods from different systems of farming production. The products of the conventional and organic farming production intended for public catering are compared within the SUKI and UMBESA international projects. Conventional farming is mainly characterized by high inputs of mineral fertilizers, chemical pesticides, the use of hormones and stimulants in animal husbandry. It is a system based on the highest possible yields without respecting the natural principles of nature. Conversely, organic farming is a system of production established by the legislation that respects fundamental natural cycles, such as crop rotation, ensures welfare of animals, prohibits the use of fertilizers, pesticides, and other substances of synthetic origin. However, lower yields are a big disadvantage. In the Czech Republic, only about one tenth of the agricultural fund is currently used for organic farming. Arable land constitutes only about 10% of the total area of agricultural land, other areas are mainly grasslands and orchards. The work primarily aims to answer to the question whether the selection of foods may contribute to decrease in greenhouse gas emissions, which is a part of the objectives of many policies. Besides the comparison of agricultural production, processed and unprocessed foods, local and imported foods and fresh and stored foods were compared as well. The Life Cycle Assessment (LCA), which is used to assess environmental impacts of products and services throughout their entire life cycle, was used to quantify the emission load. This method may be briefly characterized as a gathering of all inputs and outputs that take place during the production in the interaction with the environment. These inputs and outputs then also determine the impact on the environment. The LCA consists of four successive and iterative phases: This concerns the definition of objectives and scope, inventory analysis, impact assessment and interpretation of the results. The LCA was originally developed for the assessment of impacts of especially industrial products. Certain methodological problems and deficiency, which bring a level of uncertainty of the results, have been caused by its adaptation to agricultural product assessment, but this method is still recommended for comprehensive assessment of environmental impacts of agricultural production and the comparison of different agricultural products. In this study, a Cradle-to-Gate assessment was performed, which means that the impacts of products (in this case the emission formation) were evaluated only to the delivery of foods to public facilities, further treatment and waste management was not assessed. About 20 most frequently used foods for school catering facilities were compared. The results of the project confirm the general assumption about the less emission load of unprocessed, fresh and local products. It may not clearly state that products from organic farming produce less emissions when comparing agricultural systems. It always depends on the particular crop. The absence of synthetic substances such as fertilizers and pesticides reduces the emission load of organic farming, on the other hand, a higher number of mechanical operations and especially the lower income clearly increase the emission burden, therefore, in several cases, lower emission loads of crops were achieved using the conventional farming system. However, less emission may be achieved within the organic farming system. Among 11 evaluated agricultural products, 8 organic products and only 3 conventional ones go better. The situation is different regarding the following phases of food production, processing and transport. The transport phase significantly worsens the environmental profile of organic foods, because transport distances are too far due to insufficient processing capacity and underdeveloped market networks, and often exceed the emission savings from the agricultural phase. On the contrary, conventional foods are carried within relatively short distances, therefore the final emission load of conventional foods is in many cases fewer than the load of organic foods. This fact is also confirmed by the result of the study, because among 22 evaluated foods, organic food goes better in 11 cases and conventional food in 11 cases as well.

Access to the book chapter: Jelínková, Z., Moudrý Jr, J., Moudrý, J., Kopecký, M., and **Bernas, J.** (2016). Life Cycle Assessment Method–Tool for Evaluation of Greenhouse Gases Emissions from Agriculture and Food Processing. doi: 10.5772/62300. In: Llamas Moya, B. and Pous, J. Greenhouse Gases. Rijeka: Intech, ISBN 978-953-51-4323-9.

2.2 LCA as an instrument for the Carbon footprint quantification

The world's total energy consumption is constantly increasing, and so is the amount of CO_2 emissions in the atmosphere (Acheampong, 2018). Climate change is also having a significant impact on agricultural systems worldwide and can be a major factor in ensuring long-term sustainable food production. Emissions from agriculture represent about 10-14% of the total greenhouse gas emissions produced on Earth (Jantke et al., 2020). The largest share of emissions from the agricultural sector is then attributed to rice fields, biomass combustion, and fossil fuels (IPCC, 2015). Thus, it is necessary to monitor the production of greenhouse gases in agriculture constantly and, at the same time, look for ways to mitigate their most important sources (Franks and Hadingham, 2012). Agricultural trends towards sustainability should increasingly establish more environmentally friendly ways while maintaining the food security capacity of the population. Reducing greenhouse gas emissions should also be one of the goals of sustainable agriculture (EC, 2021).

A possible way to detect and solve problems associated with the production of greenhouse gases in agriculture is the so-called footprint method, including the Carbon footprint method. The emergence of footprint methods is closely related to the requirement to create indicators that would quantify environmental problems in the context of evaluating sustainable development strategies. Among these indicators, so-called "footprints" play an important role. These represent a means for quantification of consumed natural resources or pressure on the environment caused by the requirements of human existence. The most widespread indicators used in the agri-food sector are ecological, carbon, and water footprint (Čuček et al., 2012). Water, ecological, and carbon footprint indicators are grouped into a footprint family (Galli et al., 2012). The carbon footprint can be defined as EPD (Environmental product declaration), which focuses only on climate impacts. The indicator is linked to human pressure on the planet in terms of greenhouse gas production. The carbon footprint is quantified using the Global Warming Potential (GWP) and is expressed in carbon dioxide equivalents. Its calculation is performed according to standards, protocols, and instructions (Greenhouse Gas Protocol, 2016) or according to the standard ČSN ISO 14067 Greenhouse gases - Carbon footprint - Requirements and guidelines for quantification and communication (ISO 14067, 2015).

The LCA method also covers this approach within the impact category of Climate change (Hauschild et al., 2018). Such studies are referred to as streamlined or simplified. The LCA study should always cover the entire product life cycle. As the compilation of complete LCAs is sometimes difficult in practice, simplified LCA studies are used in justified cases (Hochschorner and Finnveden, 2003; Hur et al., 2005). Often, the LCA study is compiled with a narrower focus, for example, to evaluate one specific parameter during the entire product life cycle (energy consumption) or to assess environmental impacts that occur only at some selected stages or processes of the product life cycle (Kočí, 2009). The simplified LCA study is also used to calculate the carbon footprint of an installation or product, where the entire life cycle is assessed. Still, its impacts are only expressed concerning the global warming impact category as CO_2 equivalents (Graedel and Graedel, 1998). It should be emphasized that while simplified LCA studies can provide a lot of useful information, they cannot be considered full-fledged LCA studies, as they have a very limited scope. For some assignments of LCA studies focused on the material, energy, or financial flows, it may not be necessary to express the results using impact categories. Thus, only the goal and scope definition, inventorization, and interpretation are performed (Kočí, 2009). However, it is not correct to call such a study LCA, but only LCI (Life Cycle Inventory) (Rebitzer et al., 2004). From an environmental point of view, the LCI study should be considered limited (Kočí, 2009).

The streamlined (simplified) LCA approach to obtaining information related to the impact category of Climate change has been applied, for example, in studies dealing with oat, rye, wheat, and spelt wheat cultivation in conventional and organic farming systems in the conditions of Central Europe (Moudrý et al., 2018).

<u>Publication 2</u>

Influence of farming system on greenhouse gas emissions within cereal cultivation

Moudrý, J., **Bernas, J.**, Kopecký, M., Konvalina, P., Bucur, D., Moudrý, J., Kolář, L., Stěrba, Z., Jelínková, Z.

Journal paper with Impact Factor

The emissions of greenhouse gases (GHG) from anthropogenic activities have still been a topical and much-discussed issue. In farming, room for reducing GHG emissions may also be available in crop farming. The measures aimed at the mitigation of GHG emissions may include a change in the farming system or partial switch to more extensive farming methods, including organic farming. The life cycle of oat, rye, wheat and spelt wheat cultivation in conventional and organic farming systems in the conditions of Central Europe was evaluated by LCA method, impact category: climate. The results clearly show that there are considerable differences between conventional and organic farming systems in individual subcategories of the farm phase of the production of cereals. The CO_2e emissions produced in the cultivation of the monitored cereals are lower in organic farming systems, both when converted to an area unit and when converted to a production unit.

Access to the manuscript: Moudrý, J., **Bernas, J.**, Kopecký, M., Konvalina, P., Bucur, D., Moudrý, J., Kolář, L., Štěrba, Z., Jelínková, Z. (2018). Influence of farming system on

greenhouse gas emissions within cereal cultivation. Environmental Engineering & Management Journal (EEMJ), 17(4). doi: 10.30638/eemj.2018.091.

3 Organic farming from the Carbon footprint perspective

Choosing a system and management method could be one way to reduce the anthropogenic share of greenhouse gas emissions, with organic farming appearing to be an option (Eyhorn et al., 2019). Organic farming could be an important element in environmental friendliness and quality policy in food production in Europe, as it reduces, among other things, the use of synthetic fertilizers and other chemicals such as pesticides (Backer et al., 2009). However, a reduction in the overall environmental impact of agriculture can also be achieved in conventional and integrated farming systems (Smith et al., 2008) and food production in general. Reducing the emission and overall environmental burden is necessary for long-term sustainability in the current population conditions (Lomborg, 2003).

The level of emissions from agriculture is also affected by the intensity of agricultural systems. Organic farming (or organic farming systems) can provide a solution, which generates lower emissions (especially CH_4, N_2O, and CO_2) due to generally lower inputs (Küstermann et al., 2008). The environmental or emission burden of conventional agriculture is usually greater than the emission burden of organic farming (Brandt and Svendsen, 2011). The main tool for reducing emissions in the environmental management system is the elimination of inputs of synthetic fertilizers, chemical plant protection products, and industrially produced feeds. These products consume a large amount of energy in their production and transport and thus create a significant environmental burden (Eyhorn et al., 2019). It is changes in the fertilization system, or its reduction and the correct use of organic fertilizers, that can reduce CO_2eq emissions (an indicator of the impact category Climate change) (Smith et al., 2008). The rate of nitrogen application in organic farming is usually 60 to 70% lower than in conventional farming due to the recycling of organic waste and fertilizers (Niggli et al., 2009). Intercrops are also considered an important tool for organic farming (Neugschwandtner et al., 2021; Neugschwandtner and Kaul, 2014). Intercrops growing can be a suitable tool for reducing mineral fertilizer inputs (Bernas et al., 2021c). Intensive crop production (often based on monocultures and high productivity) is highly dependent on external inputs such as mineral fertilizers and pesticides (Niggli et al., 2009). Sustainable farming practices, including organic farming, severely reduce such dependence on inputs (Eyhorn et al., 2019).

Organic farming has a greater potential to reduce greenhouse gas emissions than conventional farming systems. The difference is very significant if the emission reduction is related to a unit of area; per unit of production, it is partially reduced (Brandt and Svendsen, 2011; Nemecek and Erzinger, 2005). The disadvantage of organic farming is lower production per unit area (yield level), thereby increasing the unit load of production by emissions. Organic farming does not always reduce emissions per unit of the yield of the main crop due to the generally lower yields in the organic farming system. The conversion from conventional to organic farming reduces emissions per unit area, but emissions per production unit are not usually reduced (Tuomisto et al., 2012). The transition to organic farming can reduce greenhouse gas emissions from agriculture if agricultural policy seeks to reduce the overall intensity of agricultural production (Flessa et al., 2002; EC, 2021). For example, average yields in Europe for organic wheat are 80% compared to conventional production (Backer et al., 2009; Mondelaers et al., 2009). On the other hand, for some high-yielding plants, such as maize, organic farming systems can achieve yields comparable to conventional systems (Pimentel et al., 2005).

Several studies have been compiled to address this issue to assess the impact on the environment from the perspective of the Climate change impact category or to assess selected organic and conventional agricultural production segments. The assessment of environmental impacts from the point of view of greenhouse gasses (respectively from the point of view of the climate change impact category) and the assessment of conventional versus ecologic farming systems were paid attention to, for example, in studies by Moudrý et al. (2013), and Jelínková et al. (2016).

<u>Publication 3</u>

Influence of farming systems on production of greenhouse gas emissions within cultivation of selected crops

Moudrý Jr, J., Jelínková, Z., Moudrý, J., **Bernas, J.**, Kopecký, M., & Konvalina, P.

Journal paper

The study presents a comparison of an effect of greenhouse gas emission load on the environment caused within the production of crops (rye, wheat, potato, carrot, cabbage, onion and tomato) under the conventional and organic farming system in the Czech Republic. For evaluation, the simplified LCA analysis focused on the evaluation of greenhouse gas emission load, expressed in carbon dioxide equivalents, was used. Outputs were converted into 1 kg of agricultural production. Within the evaluation of the agricultural phase, total emissions from the cultivation of crops and emissions from particular parts of the agricultural phase (agricultural engineering, fertilizers, pesticides, seeds and seedlings, field emission) were surveyed. The results show that except for onion growing, there is a reduction of emissions for all studied crops.

Access to the manuscript: Moudrý Jr, J., Jelínková, Z., Moudrý, J., **Bernas, J.**, Kopecký, M., Konvalina, P. (2013). Influence of farming systems on production of greenhouse gas emissions within cultivation of selected crops. Journal of food, agriculture & environment, 11(3&4), 1015-1018. Corpus ID: 130270845

<u>Publication 4</u>

Environmental and economic aspects of *Triticum aestivum* L. and *Avena sativa* growing

Jelínková, Z., Moudrý, J. jr., **Bernas, J.**, Kopecký, M., Moudrý, J., Konvalina, P.

Journal paper with Impact Factor

This paper deals with the assessment of cultivation of bread wheat (*Triticum aestivum* L.) and oat (*Avena sativa*) grown in Central Europe within the conventional and organic farming systems in terms of greenhouse gas emissions and economic profitability. Organic farming may be one of the tools for mitigation of greenhouse gas emissions from agricultural production. In the context of crop production, cereals rank among the most commonly grown crops and therefore bread wheat and oat were chosen. The Climate change impact category was assessed within the simplified LCA method and the production of greenhouse gas emissions expressed in CO_2e per the production unit was calculated. Economic balance of the cultivation of monitored cereals was compiled based on the yields, farm gate prices and costs. On its basis, the cultivation of wheat within the organic farming system appears to be the most profitable. From an environmental point of view, the emission load of the organic farming system is reduced by 8.04% within the wheat production and by 15.46% within the oat cultivation. Therefore, the organic farming system in the Czech Republic appears to be more environmentally friendly and economically efficient within the cereals production.

Access to the manuscript: Jelínková, Z., Moudrý, J. jr., **Bernas, J.**, Kopecký, M., Moudrý, J., Konvalina, P. (2016): Environmental and economic aspects of *Triticum aestivum* L. and *Avena sativa* growing, Open Life Science, 11(1), p. 533-541. doi.org/10.1515/biol-2016-0069.

4 Sustainability in agriculture and the concept of Agroecology

Like any anthropogenic activity, agriculture creates significant externalities, both positive and negative (Paudel and Crago, 2021). The agricultural sector plays a strategic role in the country's economic growth. Despite its small contribution to GDP, it plays a key role in producing food and raw materials for its production (Gołębiewska and Pajewski, 2018). Agriculture has always performed basic environmental, economic, and social functions and provided a wide range of ecosystem services (Bommarco et al., 2018). These include food security, agrobiodiversity, improving the quality of the environment, and more (Waas et al., 2011). Food production depends on healthy ecosystems and the ability to provide these services (Sunderland, 2011). The intensification of agriculture significantly reduces biological and landscape diversity (Loos et al., 2014). This can have negative consequences where ecosystem services are crucial for agricultural production (Altieri, 1999). However, alternative management systems also use the knowledge of science and technology or take more significant account of environmental issues (Altieri et al., 2012). The most common alternatives are mainly organic, integrated, or precision agriculture (Cejpek, Musilová, 2016). Public interest in more sustainable farming and food production continues to grow, leading to a demand for information on the environmental performance of agricultural systems and food products from almost all sections of society (Willett et al., 2019; Eyhorn et al., 2019). Also, the concept of agroecology is closely related to sustainable farming systems (Gliessman, 2021). Agroecology is at the interface of several scientific disciplines, and its name is based on two basic ones, namely ecology and agronomy. The primary focus of ecology is on natural systems, while agronomy focuses on research and the application of scientific knowledge relevant to agricultural practice (Šarapatka et al., 2010; Gliessman, 2021; Altieri, 2018). Agroecology focuses on research into the use and functioning of field and generally agriculturally used ecosystems. It deals with the relationships between plants, animals, microorganisms, and agricultural land and the relationships of these organisms in the landscape (Gliessman, 2018), and evaluates the impact of agrotechnical on ecosystems of agricultural land or water management in agricultural land (Bernas et al., 2020). The main goal is to optimize farming methods on the farm and in the countryside (Altieri, 2018) and to strive for a general reduction of environmental impacts (Gliessman, 2016). The principle of agroecology and the history of this concept related to selected East European countries was summarized in the study of Moudrý et al. (2018).

<u>Publication 5</u>

Agroecology Development in Eastern Europe—Cases in Czech Republic, Bulgaria, Hungary, Poland, Romania, and Slovakia

Moudrý, J.; **Bernas**, **J**.; Moudrý, J.; Konvalina, P.; Ujj, A.; Manolov, I.; Stoeva, A.; Rembiałkowska, E.; Stalenga, J.; Toncea, I.; Fitiu, A.; Bucur, D.; Lacko-Bartošová, M.; Macák, M.

Journal paper with Impact Factor

Agroecology is a discipline of science that is based on several disciplines, primarily ecology and agronomy. Although the first mention of agroecology was more than 100 years ago, it has recently been more intensely developed throughout Eastern European countries, beginning in the 1990s. Basically, such interest developed due to the intensification of agriculture in the second half of the 20th century, which was based on the premise of agricultural research, and related specifically to production. Agroecology is also strongly associated with sustainable agricultural activities, especially organic farming, which began to develop in Eastern European countries around 1990. Due to the unique environment of Eastern European countries, and a combination of several disciplines within them as well as other factors, agroecology in these different countries can be perceived as somewhat different from one another. This overview focuses on the current state of agroecology in the Czech Republic, Poland, Hungary, Bulgaria, Romania, and Slovakia.

Access to the manuscript: Moudrý, J.; **Bernas**, **J**.; Moudrý, J.; Konvalina, P.; Ujj, A.; Manolov, I.; Stoeva, A.; Rembiałkowska, E.; Stalenga, J.; Toncea, I.; Fitiu, A.; Bucur, D.; Lacko-Bartošová, M.; Macák, M. (2018). Agroecology Development in Eastern Europe—Cases in Czech Republic, Bulgaria, Hungary, Poland, Romania, and Slovakia. *Sustainability*, *10*, 1311. doi.org/10.3390/su10051311.

5 Energy crops production from the environmental perspective

Phytomass of energy crops is a universal source of energy, through which it is possible to produce both heat and electricity, as well as fuels in a gaseous, solid, and liquid state (Knápek et al., 2010). Biomass is considered a renewable energy source (RES) and has long had huge potential for mitigating the effects of global warming (Scheer, 2005). Of particular importance is the multifunctionality of biomass, which includes food production, energy and feed sources, biodiversity conservation, and social services in society. It also brings new opportunities for managing and researching strategies in forestry, agriculture, agroforestry, and pasture to mitigate global warming (Dhillon and von Wuehlisch, 2013). Although energy crops, as a renewable energy source, offer a number of advantages over fossil fuels, it is necessary to determine the impacts on all components of the environment that may be affected by their cultivation (Saidur et al., 2011).

Forest stands are generally an important source of biomass. However, there is not enough forest waste biomass across countries, and therefore it is necessary to use other sources of biomass, especially targeted cultivation of energy crops (Pastorek et al., 2004). The choice of the most suitable energy crops is crucial, especially in terms of strategic and effective replacement of fossil fuels and reduction of greenhouse gas emissions (Vaughan et al., 2018). Energy crops should have a high yield and energy potential along with only minimal environmental impacts (Boehmel et al., 2008). The question of whether to choose annual or perennial plants for these purposes is also often addressed (Jasinskas et al., 2008; Bernas et al., 2019). Total energy efficiency (i.e. the ratio of energy input to energy gain) is higher for perennial crops than for annual (depending on yields and intensity of cultivation) (Kára et al., 2005; Bernas et al., 2019). The positive effects stem mainly from the plantations of perennial crops. These provide soil coverage and CO_2 sequestration (Clifton-Brown et al., 2004 Deckmyn et al., 2004) and mediate biodiversity promotion (Chmelíková and Wolfrum, 2019). In general, they have a better impact on the environment than traditional annual crops and are associated with higher biomass yields, better stability of clean energy, and lower environmental impacts (Ericsson et al., 2009). The area that will then be defined for growing energy crops should be based primarily on yield potentials, production intensity, and the type of technology used (Boehmel et al., 2008, Bernas et al., 2021a).

Also, the production of annual crops can become more environmentally friendly, for example, when tillage in crop rotation is carried out in a minimized mode, and the soil can function as a carbon sink (Smith et al., 2008). However, the advantage of annual energy crops is the well-known and routine production technology, the flexibility to change the type of crop and acreage, as well as the possibility of applying part of the production at market food, feed, or energy prices (Bernas et al., 2016a and 2016b; Bernas et al., 2019; Bernas et al., 2020; Bernas et al., 2021a; Bernas et al., 2021b; Bernas et al., 2021c).

Crops intended for eco-energy compete on arable land with food crops (Ochodek et al., 2006). Therefore, their cultivation is recommended, especially in marginal areas (Lewandowski et al., 2003) or on low-production or otherwise degraded soils (Vassilev et al., 2012). There are main criteria for rating the sustainability of bioenergy production systems: use and changing the use of lands, "Water footprint" of energy crops, the impact of energy crops on biodiversity, climatic change, C sequestration, and mitigation of GHGs (balance and life cycle), maintenance of soil fertility (Lopez-Bellido et al., 2014).

To apply the principles of sustainability, it is necessary to identify cost-effective ways to avoid, at least in part, greenhouse gas emissions in the agricultural sector as well. If we are to think about mitigating greenhouse gas production within the selected cultivation processes, it is necessary to focus primarily on their strongest sources. These are, as the results of thematic work suggest (Bernas et al., 2014; Bernas et al., 2015; Bernas et al., 2016a; Bernas et al., 2016b; Bernas et al., 2019), the production and use of nitrogenous fertilizers and field emissions arising after their production, and application. In this respect, the issue of reducing the dose of fertilizers, the overall change in the agricultural system, is often addressed (Smith et al., 2008; Gattinger et al., 2012). Reducing the dose of fertilizers used in the agricultural sector has long been considered a key activity in reducing N_2O and NO emissions (Mosier et al., 1998). To a large extent, the amount of greenhouse gas emissions from agriculture is also affected by the management system. Conventional agricultural systems are based on higher inputs of fertilizers (organic and mineral), which are key factors for the mitigation of N_2O and NO emissions from soil. N_2O can be considered the main greenhouse gas, and ecological management systems usually produce less (also CO_2) due to generally lower inputs (Bos et al. 2014).

Another way to reduce greenhouse gas emissions is to replace existing crops, in the case of Bernas et al. (2014); Bernas et al. (2015); Bernas et al. (2016a), and Bernas et al. (2019) maize, another crop, also suitable for the chosen purpose. These can be, for example, perennial energy grasses, which are also suitable due to their properties (Amon et al., 2007; Strašil, 2012, Bernas et al., 2019). Although, for example, maize cannot yet be fully replaced by them (Grieder et al., 2012, Bernas et al., 2019). Nevertheless, due to the nature of perennial crops and generally lower fertilization requirements, energy grasses are expected to have lower environmental impacts during their life cycle than annual energy crops grown so far. The type of feedstock, such as maize, grass, or manure, is a determining factor for the final environmental impact assessment, for example, in biogas production (Hijazi et al., 2016).

The results of thematically oriented studies (Bernas et al., 2014; Bernas et al., 2015; Bernas et al., 2016a; Bernas et al., 2016b; Bernas, 2018; Bernas et al., 2019) indicate the level of emission load expressed Climate change impact category through selected functional units (area and production unit) and their individual sub-processes. The emission load depends not only on the inputs and outputs of the growing cycle itself but also on the final yields per hectare. It is, therefore, predictable that the emission burden will decrease while maintaining the same growing cycle and increasing yield per hectare. The studies also showed that the strongest emission load, which is based on the final hectare yields of dry matter and the intensity of inputs into the growing cycle, was not always expected to be tied to the most intensive variant of cultivation.

Regardless of the intended use of selected energy plants (Bernas et al., 2014; Bernas et al., 2015; Bernas et al., 2016a; Bernas et al., 2016b; Bernas, 2018; Bernas et al., 2019), the majority of emission flow (expressed in kg CO_2 eq) can be considered the one that is connected to the production and use of mineral fertilizers and the consequences of their application - emissions arising after the application of fertilizers (so-called field emissions). In the agricultural sector and especially in the crop production sector, nitrogen fertilizers as such represent a relatively complex problem. For example, Boehmel et al. (2008) state that N fertilizer tends to have a 41-64% share of energy consumption in annual crops and a 17-45% share in permanent crops. At higher doses of N, there is no longer a significant increase in phytomass. The efficiency of the fertilizer used decreases with increasing fertilization doses because the plant does not take up a large part of the fertilizer and instead enters the water or air (Niggli et al., 2009), in the form of so-called field emissions. One of the general advantages of perennial grasses is that they require fewer nutrients and inputs in the form of chemical protection products than annual crops (Massé et al., 2010).

Another assessed category within the environmental impacts related to the monitored energy crops is the environmental impact per unit area. This category includes all material and energy flow in the given years (within the farm phase). In this case, yields per hectare are not included in the calculation itself. Based on the results of studies evaluating the environmental aspects of energy crops from the perspective of Climate change (Bernas et al., 2014; Bernas et al., 2015; Bernas et al., 2016a; Bernas et al., 2016b; Bernas, 2018; Bernas et al., 2019) it is possible to point out the possibilities of mitigation of greenhouse gases in the cultivation of less energy-intensive perennial plants (which is confirmed by some of the studies such as Bellarby et al., 2008 and Lehtomäki et al., 2008), even with relatively satisfactory yield potential, which can be compared in the longer term, for example, with maize (Bernas et al., 2021a). Another positive benefit of perennial crops is permanent soil cover and carbon sequestration (Clifton-Brown et al., 2004; Deckmyn et al., 2004) and the promotion of biodiversity (Chmelíková and Wolfrum, 2019). From the point of view of the possibilities of greenhouse gas mitigation in the cultivation of maize, issues related to crop rotation, the inclusion of catch crops in sowing procedures, and no-till tillage systems are addressed (Smith et al., 2008; Al-Kaisi and Yin, 2004; Antille, 2015), or effective N fertilization management (Millar et al., 2010).

In all respects, biomass (in this case, phytomass) as a RES has the potential to reduce GHG production only under the assumption of sustainable production (Dornburg et al., 2008) because the use of renewable energy sources should not increase greenhouse gas emissions. Agricultural activity contributes significantly to environmental damage, mainly due to land use, fertilizer use, and energy consumption (mainly from non-renewable sources). The main potential for improvement often includes increased biogas yield, the choice of gentle agricultural practices, and the exclusive cultivation of perennial crops (Jury et al., 2010). Subsequent savings in GHG production for biofuels should then be expressed not per kg of biofuel (MJ/kg) - i.e. per unit of production, as determined by many LCA outputs (Roy et al., 2009), but in relation to the area (land demand), from obtained and time (MJ/ha/year) (Kočí, 2013; Bernas et al., 2021a; Bernas et al., 2021b; Bernas et al., 2021c). However, many LCA outputs are usually targeted at a production unit (Roy et al., 2009). Alluvione et al. (2011) also state the high dependence of agriculture on non-renewable raw materials and the consequently increased production of greenhouse gas emissions. However, agriculture produces emissions in a number of other ways. For example, CO_2 is released when reducing the content of organic matter in the soil due to various agrotechnical interventions [reducing the depth and intensity of tillage, can lead to reduced carbon dioxide emissions from soil to air (Hůla et al., 2008)], or CH_4 from the digestive tract of some livestock species. From this, it can be deduced that the amount and composition of our food reflect the specific features of the relevant technological processes in agriculture, and thus the different production of greenhouse gases. Therefore, to ensure sustainable development (undoubtedly conditioned by the stabilization of anthropogenic greenhouse gas emissions), a change in the population's diet in industrialized countries can be extremely important (Agovino et al., 2019).

5.1 Biogas production and agricultural LCA implementation

The region of Central Europe is characterized by intensive agriculture, which, however, has long struggled with overproduction and problematic sales of produced commodities (raw materials and food). Energy production from biogas offers some stabilization for the agricultural sector (Scarlat et al., 2018). Agricultural products and waste can be used to produce biogas. Usable products are energy plants, organic waste, and livestock excrement (Oslaj et al. 2010). In technical practice, the word biogas is used to denote a mixture of gases formed by anaerobic fermentation of moist organic substances in artificial technical equipment (reactors), generally called biogas plants (BP) (Kára et al., 2007). Fermenter waste (commonly referred to as digestate) serves as a quality organic fertilizer (Koszel and Lorencowicz, 2015). From the point of view of assessing the impacts of digestate on the environment, the environmental impact depends largely on related nitrogen emissions from digestate treatment, storage, and field application. Another important aspect is the amount and kind of fuel used for heat supply (biogas, natural gas) and the procedure chosen for the allocation of heat and power (Rehl and Müller, 2011).

The basic positive ecological advantage of biogas production or anaerobic digestion is the reduction of greenhouse gas production from fossil fuels, which makes biogas technology gain worldwide importance, especially in discussions about climate protection and the need to reduce carbon dioxide and methane in the air (Hijazi et al., 2016). However, attention must be paid to undesired methane and nitrous oxide (N_2O) (Paolini et al., 2018). In addition, the combustion of biogas, unlike the direct combustion of biomass and fossil fuels, does not produce harmful emissions of SO_2 or heavy metals (Weiland, 2010 or Montingelli et al., 2015). During the formation of plant phytomass, significantly more CO_2 is fixed than is emitted by burning biogas. This technology limits the increase in the anthropogenic greenhouse effect and the onset of irreversible climate change. Emissions from biogas combustion (approx. 60 kg CO_2 GJ^{-1}) are significantly lower than, for example, brown thermal coal (100 kg CO_2 GJ^{-1}) and do not worsen the greenhouse effect, as the CO_2 produced was previously bound by crops and a large part of the carbon it remains in stabilized compost, the plant root system and subsequently in agricultural soil (Schulz and Eder, 2001). Biogas production from agricultural biomass is becoming increasingly important as it offers significant environmental benefits and is an additional source of income for farmers (Oslaj et al., 2010).

However, the year-round operation of biogas plants requires a continuous supply of organic matter to the fermenter. Most materials suitable for biogas production are produced in agriculture. These are mainly livestock excrement, crop production products, or purposefully grown energy crops (Lehtomäki, 2006; Holm-Nielsen et al., 2009; Weiland, 2010 Meyer et al., 2018). However, for example, municipal waste and municipal wastewater can also be used to produce biogas (Kajan et al., 2008). However, the type of feedstock, such as maize, grass, or manure, is a determining factor for the environmental impacts of biogas plants (Hijazi et al., 2016). For example, in the Czech Republic, the biomass from crops (phytomass, respectively) makes up over 50% by weight of all substrates. Of this, up to 80% is maize silage, and the rest is other phytomass, mainly from permanent grassland. In terms of energy content, the input of crops biomass represents up to 80% of the energy content of all substrates (Lhotský and Kajan, 2011). The use of grasslands for energy purposes is also gaining importance, especially in terms of the use of fallow land for the cultivation of energy crops and in connection with biomass produced by permanent grasslands (Prochnow et al., 2009). Using this grass biomass for energy purposes seems to be a promising solution (Seppälä et al., 2009). However, it is always necessary to evaluate environmental aspects and energy and economic aspects (Bernas, 2018).

In connection with this issue, several studies were conducted that addressed the possibility of including alternative energy crops on arable land for the production of phytomass for biogas production from the perspective of environmental impact assessment (Bernas et al., 2014; Bernas et al., 2015; Bernas et al. ., 2016 and Bernas et al., 2019).

<u>Publication 6</u>

Szarvasi-1 and its potential to become a substitute for maize which is grown for the purposes of biogas plants in the Czech Republic

Bernas, J., Moudrý, J., Kopecký, M., Konvalina, P., Štěrba, Z.

Journal paper with Impact Factor

The domestic biogas market has been developing rapidly, and legislation (The Act) supporting the use of renewable energy sources has come into force. In light of this act and investment support from national programs co-financed by the European Union (EU), the total number of biogas plants has recently increased from a few to 600. The total capacity of electricity generation of those 600 installed plants exceeds 360 Megawatts (MW) (as of mid-2018). Such dynamic growth is expected to continue, and the targets of the National Renewable Energy Action Plan are projected to be met. The use of waste material, which was urgently needed, was the original aim of biogas plants. However, in certain cases, the original purpose has transformed, and phytomass is very often derived from purpose-grown energy crops. Maize is the most common and widely grown energy crop in the Czech Republic. Nevertheless, maize production raises several environmental issues. One way to potentially reduce maize's harmful effects is to replace it with other suitable crops. Perennial energy crops, for example, are possible alternatives to maize. A newly introduced species for the conditions of the Czech Republic, *Elymus elongatus* subsp. *ponticus* cv. Szarvasi-1, and some other well-known species—*Phalaris arundinacea* L. and *Miscanthus* × *giganteus*—are suitable for the Czech Republic climate conditions. This paper presents the findings of the research and evaluation of environmental, energy-related, and economic aspects of growing these crops for use in biogas plants. These findings are based on 5-year small-plot field trials. The energy-related aspects of producing *Elymus elongatus* subsp. *ponticus* cv. Szarvasi-1, *Phalaris arundinacea* L., and *Miscanthus* x *giganteus* are reported on the basis of experiments that included measuring the real methane yield from a production unit. The economic analysis is based on a model of every single growing and technological operation and costs. The environmental burden of the individual growing methods was assessed with a simplified life cycle assessment (LCA) using the impact category of Climate Change and the SimaPro 8.5.2.0 software tool, including an integrated method called ReCiPe. The research findings show that Szarvasi-1 produces 5.7–6.7 Euros (EUR) per Gigajoule (GJ) of energy, depending on the growing technology used. Szarvasi-1 generates an average energy profit of 101.4 GJ ha^{-1}, which is half of that produced by maize (214.1 GJ ha^{-1}). The environmental burden per energy unit of maize amounts to 16 kg of carbon dioxide eq GJ^{-1} compared with the environmental burden per energy unit of Szarvasi-1, which amounts to 7.2–15.6 kg of CO_2 eq GJ^{-1}, depending on the yield rate. On the basis of the above-mentioned yield rate of Szarvasi-1, it cannot be definitively recommended for the purpose of biogas plants in the Czech Republic.

Access to the manuscript: **Bernas, J.**, Moudrý, J., Kopecký, M., Konvalina, P., Štěrba, Z. (2019). Szarvasi-1 and its potential to become a substitute for maize which is grown for the purposes of biogas plants in the Czech Republic. Agronomy, 9(2), 98. doi.org/10.3390/agronomy9020098.

Publication 7

Greenhouse gasses emissions during maize growing for energy purposes

Bernas, J., J. Moudrý jr., Z. Jelínková & M. Kopecký

Journal paper

Due to the increasing energy consumption and depletion of fossil fuels, alternative energy sources are becoming an increasingly important topic. One of the most important renewable energy sources is the energy from phytomass. Recently, also in the conditions of the Czech Republic, there has been a significant development of production of energy crops as raw material for the biogas production in biogas plants (BGP). However, farming and particularly technical processes associated with it participate in the anthropogenic emission production. This article presents the results of monitoring of emission load resulting from the cultivation of maize (*Zea mays* L.) for energy purposes. As a tool for emission load measuring (expressed in CO_2e where $CO_2e = 1x\ CO_2 + 23x\ CH_4 + 298x\ N_2O$), the simplified LCA method, respectively its climate impact category, was used. For calculation, the SIMA Pro software and the Recipe Midpoint (H) method was used. From the results, it is obvious that the cultivation of maize for energy purposes produces the greatest amount of CO_2e emissions within nitrate fertilization (0.052455 kg $CO_2e.1kg^{-1}$ of dry matter) and field emissions (0.050359 kg $CO_2e.1kg^{-1}$ of dry matter). Maize cultivation for energy purposes shows a higher emission load as compared for example with energy grasses.

Access to the manuscript: **Bernas, J.**, Moudrý jr., J., Jelínková, Z., Kopecký, M. (2014). Greenhouse gasses emissions during maize growing for energy purposes. In. MendelNet 2014. MENDELU, Brno, pp. 219-223, ISBN 978-80-7509-174-1.

Publication 8

Miscanthus – Possibility of greenhouse gas emission mitigation

Bernas, J., Jelínková, Z. Moudrý, J. jr., Kopecký, M., Moudrý, J.

Journal paper

One of the most important renewable energy sources is the energy from phytomass. Recently, there has been significant development of growing energy crops as raw materials for biogas production in biogas plants (BGP). In the conditions of the Czech Republic, it is mainly maize. Maize cultivation itself and especially technical processes associated with it participate significantly in the anthropogenic emission production. One of the ways of reducing these emissions is the substitution of maize with another plant suitable for such purposes. This may be *Miscanthus* x *giganteus*. This article presents the results of monitoring of emission load resulting from the cultivation of maize (*Zea mays* L.) and *Miscanthus* x *giganteus* for energy purposes. The tool to determine the level of emission load (expressed in CO_2e where $CO_2e = 1x\ CO_2 + 23x\ CH_4 + 298x\ N_2O$) is the simplified Life Cycle Assessment (LCA) method, respectively its Climate Impact category. For the calculations, the SIMAPro software and the ReCiPe Midpoint (H) method is used. The results show that within the cultivation of *Miscanthus* x *giganteus* for energy purposes, the CO_2e production decreases during the second year of cultivation by nearly 40% per 1 kg of dry matter. While in comparison with maize, it is almost half the production of CO_2e per production unit, depending on the yields and energy inputs.

Access to the manuscript: **Bernas, J.**, Jelínková, Z. Moudrý, J. jr., Kopecký, M., Moudrý, J. (2015). Miscanthus – Possibility of greenhouse gas emission mitigation. In. MendelNet 2015. MENDELU, Brno, p. 183-188, ISBN 978-80-7509-363-9.

Publication 9

Energy crops growing-impact on greenhouse gases emissions

Bernas, J., Moudrý Jr, J., Jelínková, Z., Kopecký, M., Konvalina, P., Moudrý, J.

Journal paper with Impact factor

In the Czech Republic, an important phytomass with energetic value is maize. Besides other environmental impacts, maize cultivation is highly associated with anthropogenic emission production, which could suggest the substitution of maize with other energy plants (e.g. grasses - Reed canary grass (*Phalaris arundinacea* L.), *Elymus elongatus* subsp. *ponticus* cv. Szarvasi-1). Results of monitoring of emission load resulting from their cultivation for energy purposes were presented in this paper in the frame of a study case, where a simplified (streamlined) LCA method (Climate change impact category) was used based on the SIMAPro software (ReCiPe Midpoint (H) method). Within the cultivation of both grasses for energy purposes, CO_2e production decreases on average by more than 20% per 1 kg of dry matter in the first three years of cultivation in comparison with maize, while it is possible to produce up to 80% less CO_2e per the area unit. The lower emission load falls then on methane production.

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5.2 Dry way of phytomass utilization from the agricultural LCA perspective

In the coming decades, the shift to biomass-based electricity production will be inevitable due to the negative impact of fossil-based fuels (Tzelepi et al., 2020). Biomass combustion is still being technically improved (Krzywanski et al., 2013) and still has strong positives (Nishiguchi and Tabata, 2016). Biomass combustion does not burden the environment with carbon dioxide production, as burning releases as much CO_2 as plants consume during their lifetime (Abbasi and Abbasi, 2010). Phytomass has an important and positive effect on the global ecosystem regarding the carbon cycle, especially CO_2. When used for energy purposes (direct combustion or biogas production and subsequent combustion of biogas or other ways of utilization), carbon is thought to enter the atmosphere and be re-introduced into the plant body during photosynthesis (Park et al., 2011). Phytomass thus becomes a partial storehouse of carbon during the plant's growth (Sebastián et al., 2011). Biomass as an energy source is mainly perceived as a strategic and safe source in terms of mitigating greenhouse gas emissions in the atmosphere (Rosillo-Calle et al., 2015), and biomass energy may be a driver of economic growth and decarbonization (Destek and Aslan, 2019). However, it should be added that the production and processing of biomass also produce CO_2, which is not included in this balance. In addition, the process of releasing CO_2 back into the atmosphere is significantly faster than its sequestration. So it should not be considered a zero CO_2 balance (MA Assessment, 2005).

What's more, biomass energy extraction destroys the ecosystem. Therefore, reducing biomass energy exploitation may contribute to improving environmental quality in the G7 countries. Policymakers in these countries may turn their attention to other renewable energy sources like solar and wind power, which have less negative environmental impacts (Wang et al., 2020). A number of plant species are grown for energy purposes, and for direct combustion purposes, respectively. However, perennial grasses are more advantageous (Lewandowski et al., 2003; Kára et al., 2005; Boehmel et al., 2008). These include, for example, ovsík vyvýšený, psineček veliký, kostřavu rákosovitou, sveřep bezbranný, sveřep horský, chrastici rákosovitou a ozdobnici čínskou (Lewandowski et al., 2006). A number of aspects need to be taken into account when using energy crop material for direct incineration. An important factor in determining the optimal grass harvest time for energy use is knowledge of the behaviour of key parameters affecting the energy properties of biofuels: calorific value, ash content, volatile combustibles, fixed carbon, nitrogen, alkali content, and ash melting temperature (Reed and Gaur, 2009). However, for individual potentially interesting energy plants, it is also necessary to take into account environmental aspects, which can be quantified, for example, by the agricultural LCA method (Monti et al., 2009). Environmental aspects of the energy crops growing or using agricultural waste for energy utilization (combustion) from the point of view of agricultural LCA, were evaluated, for example, in a study by Bernas et al. (2016b); Bernas et al. (2019) or Bernas et al. (2020).

Publication 10

Cultivation of tall wheatgrass and reed canary grass for energy purposes in terms of environmental impacts

Bernas, J., Kopecký, M., Moudrý Jr, J., Jelínková, Z., Moudrý, J., Suchý, K.

Journal paper

Cultivation of energy crops for the production of thermal energy through direct combustion has become one of the trends within the ecological energetics. A number of perennial plants are grown in the conditions of the Czech Republic, too, for this purpose. One of them is reed canary grass (RCG). This species might gradually be replaced by another grass, better-performing tall wheatgrass (*Elymus elongatus* subsp. *ponticus* cv. Szarvasi-1). Greenhouse gas emission savings may be achieved due to the higher yield potential and energy yield when growing it. This article presents the results of emission load monitoring resulting from the RCG and Szarvasi1cultivation for energy purposes. The simplified LCA method, respectively its *Climate change* impact category is used as a tool for emission load measuring. The results show that the emission savings of up to 45% per 1 GJ can be achieved when growing Szarvasi-1 for energy purposes in comparison with RCG.

Access to the manuscript: **Bernas, J.**, Kopecký, M., Moudrý Jr, J., Jelínková, Z., Moudrý, J., Suchý, K. (2016b). Cultivation of tall wheatgrass and reed canary grass for energy purposes in terms of environmental impacts. In Proceeding of 6th International Conference on Trends in Agricultural Engineering (pp. 64-70). EID: 2-s2.0-85041955456.

Publication 11

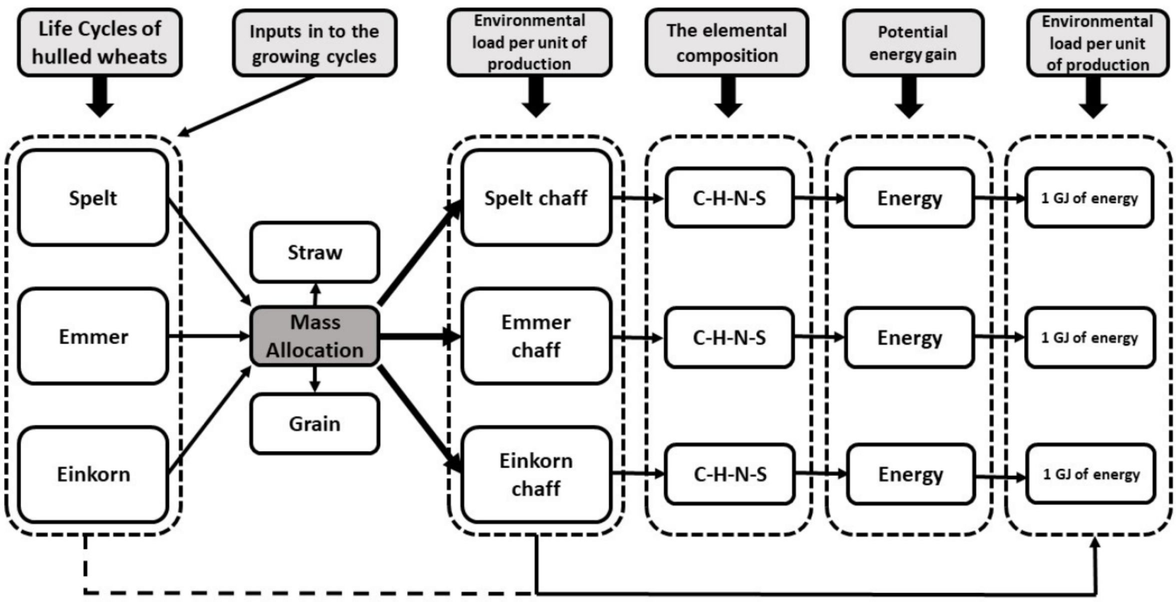
The energy and environmental potential of waste from the processing of hulled wheat species

Bernas, J., Konvalina, P., Burghila, D. V., Teodorescu, R. I., Bucur, D.

Journal paper with Imapct Factor

Organic farmers farming on arable land have often had, in addition to the cultivation of common species of cultivated crops (such as wheat, rye, triticale or potatoes), interest in the cultivation of marginal crops such as hulled wheat species (Einkorn, Emmer and Spelt wheat). The production of marginal cereals has seen significant developments in the European Union related to the development of the organic farming sector. Just the average annual organic production of spelt in the Czech Republic reached more than 9000 tons in 2018. The cultivation of these cereals requires post-harvest treatment in the special method of dehulling. The waste emerging after dehulling of spikelet (i.e., chaff) accounts for about 30% of the total amount of harvest and can be used as an alternative fuel material. When considering the energy utilization of this waste, it is also necessary to obtain information on the energy quality of the material, as well as environmental aspects linked to their life cycle. For evaluating the energy parameters, the higher and lower heating value, based on the elemental (CHNS) analysis, was determined. The environmental aspects were determinate according to the Life Cycle Assessment (LCA) methodology where the system boundary includes all the processes from cradle to farm gate, and the mass unit was chosen. The SimaPro v9.1.0.11 software and ReCiPe Midpoint (H) within the characterization model was used for the data expression. The results predict the energy potential of chaff about 50–90 TJ per year. The results of this study show that in some selected impact categories, 1 kg of chaff, as a potential fuel, represents a higher load on the environment than 1 kg of lignite, respectively potential energy gain (1 GJ) from the materials.

Figure 1 Graphical workflow



Bernas et al. (2020)

Access to the manuscript: **Bernas, J.**, Konvalina, P., Burghila, D. V., Teodorescu, R. I., Bucur, D. (2020). The Energy and Environmental Potential of Waste from the Processing of Hulled Wheat Species. Agriculture, 10(12), 592. doi.org/10.3390/agriculture10120592.

6 Special crop production and full agricultural LCA application

Environmental impact assessment through a full agricultural LCA (from cradle to farm gate approach) can also be implemented in the field of special crop production. Specifically, this concept of life cycle assessment has been applied in the field of forage production (Bernas et al., 2021a), in the field of food oil production (Bernas et al., 2021c), or in the field of intercrops growing (Bernas et al., 2021b).

The common agricultural policy (CAP) combines social, economic, and environmental approaches for achieving a sustainable agricultural system in the European Union. The aim of the "European Green Deal", and one of the targets of the "From Farm to Fork strategy", is to find ways to reduce the excess nutrients in the environment, which are a major source of air, soil, and water pollution and thereby negatively impact biodiversity and climate. The target of the agricultural policy is to reduce nutrient losses by at least 50% and reduce fertilizer use by at least 20% by the year 2030 while ensuring no deterioration of soil fertility. Different strategies can help meet these goals; among those in the effort to way a most sustainable farming strategy (Bernas et al., 2021c), implementation of crops with lower environmental impact (Bernas et al., 2021a), or inclusion of legumes into crop rotations or their use in intercrops to improve nutrient management (Bernas et al., 2021b).

Publication 12

Cup plant, an alternative to conventional silage from a LCA perspective

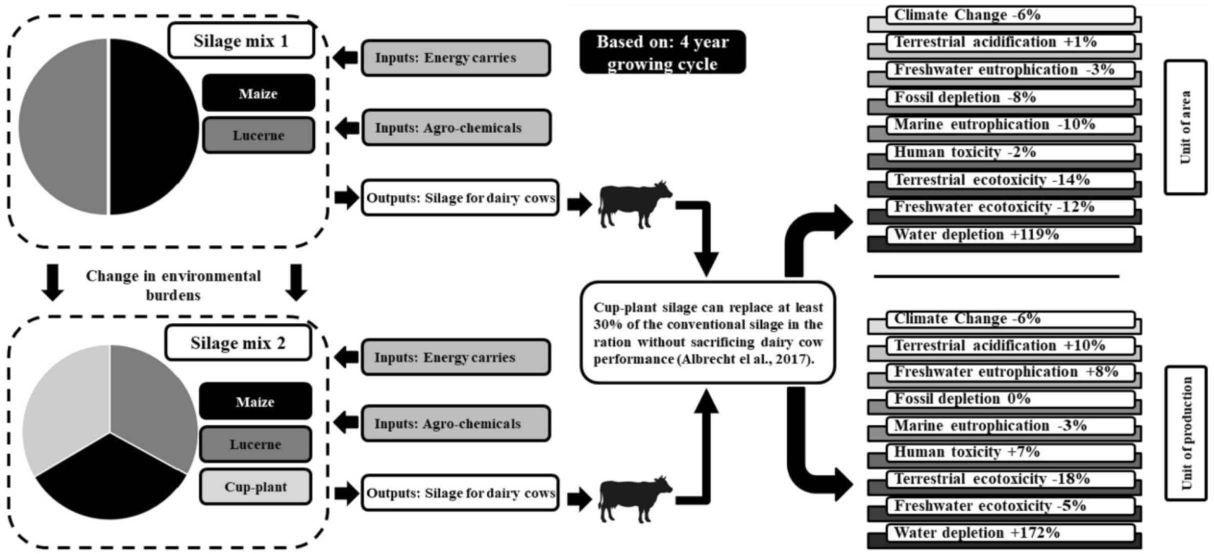
Bernas, J., Bernasová, T., Gerstberger, P., Moudrý, J., Konvalina, P., Moudrý, Jr., J.

Journal paper with Impact Factor

Purpose: The growing awareness of the importance of biodiversity in agroecosystems in increasing and ensuring the supply of biomass has led to heightened interest from governments and farmers in alternative crops. This article assesses one such alternative crop, cup plant (*Silphium perfoliatum* L.), in terms of the environmental aspects of cultivation for forage production. Many studies have previously focused on cup plant, but so far, this plant has not been assessed using the life cycle assessment (LCA) method. Materials and methods: This study compares the environmental load of cup plant with the most commonly grown silage crops in Central European conditions—maize—and with another common forage crop—lucerne using LCA. The system boundaries include all the processes from cradle to farm gate and both mass-based (1 ton of dry matter) and area-based (1 ha of monoculture) functional units were chosen for the purposes of this study. The results cover the impact categories related to the agricultural LCAs, and the ReCiPe Midpoint (H) characterization model was used for the data expression, by using SimaPro 9.0.0.40 software. Results: This study compares the cultivation of cup plant with the most commonly grown silage crop in Central European conditions—maize—and with another common forage crop—lucerne. The paper shows the potential of cup plant to replace conventional silage (maize and lucerne silage mix) with certain environmental savings in selected impact categories, and importantly, while still maintaining the same performance

levels in dairy farming as with conventional silage, as already reported in previous publications. For the Czech Republic alone, this would, in practice, mean replacing up to 50,000 ha of silage maize and reducing the environmental load by about tens of percent or more within the various impact categories and years of cultivation. Conclusion: Cup plant can replace the yield and quality of silage maize, represents a lower environmental load per unit of production and unit of area and generally carries many other benefits. Thus, cup plant is a recommendable option for dairy farming. Given the recent experience and knowledge of the issue, the cup plant can be considered an effective alternative to conventional silage.

Figure 2 Graphical conclusion



Bernas et al. (2021a)

Access to the manuscript: **Bernas, J.**, Bernasová, T., Gerstberger, P., Moudrý, J., Konvalina, P., Moudrý, Jr., J. (2021a). Cup plant, an alternative to conventional silage from a LCA perspective. The International Journal of Life Cycle Assessment, 26(2), 311-326. [doi.org/10.1007/s11367-020-01858-x.](https://doi.org/10.1007/s11367-020-01858-x)

<u>Publication 13</u>

Agricultural LCA for food oil of winter rapeseed, sunflower, and hemp, based on Czech standard cultivation practices

Bernas, J., Bernasová, T., Nedbal, V., Neugschwandtner, R.W.

Journal paper with Impact Factor

Abstract: The demand for food vegetable oil is rising and this trend is reflected in the agricultural sector of the Czech Republic. The traditional oil crops of the Czech Republic are winter rapeseed and sunflower. These oil crops have high demands on energy inputs, for example, in the form of land preparation and chemical protection. At the same time, they are characterized by high food oil production and oiliness. Moreover, marginal oils crops, such as hemp, are also gaining prominence. This work aimed to evaluate the environmental impacts associated with the cultivation of winter rapeseed and sunflowers based on standard cultivation practices typical of the conditions of the Czech Republic. For comparison, an intensive cultivation strategy for hemp was modelled, also corresponding to the conditions of the Czech

Republic. This study assessed the environmental impact of traditional oil crops from the agricultural Life Cycle Assessment (LCA) perspective. The system boundaries included all the processes from the cradle to the farm gate. Mass-based (volume of food oil) and area-based (land demand for generating the same volume of food oil) functional units were employed. The results cover nine impact categories related to the agricultural LCA. ReCiPe Midpoint (H) characterization and normalization models were used for the data expression. Hemp is a plant with generally low demands on the inputs of the growing cycle but generally has a low oil production, which affects the character of the results relating to the goal and scope definition of the study. Hemp food oil thus generated a higher environmental impact per unit of production and area compared to sunflower and rapeseed food oil.

Access to the manuscript: **Bernas, J.**, Bernasová, T., Nedbal, V., Neugschwandtner, R.W. (2021). Agricultural LCA for food oil of winter rapeseed, sunflower, and hemp, based on czech standard cultivation practices. Agronomy, 11, 2301. doi.org/10.3390/agronomy11112301.

Publication 14

Sustainability estimation of oat:pea intercrops from the agricultural life cycle assessment perspective

Bernas, J., Bernasová, T., Kaul, H.-P., Wagentristl, H., Moitzi, G., Neugschwandtner, R.W.

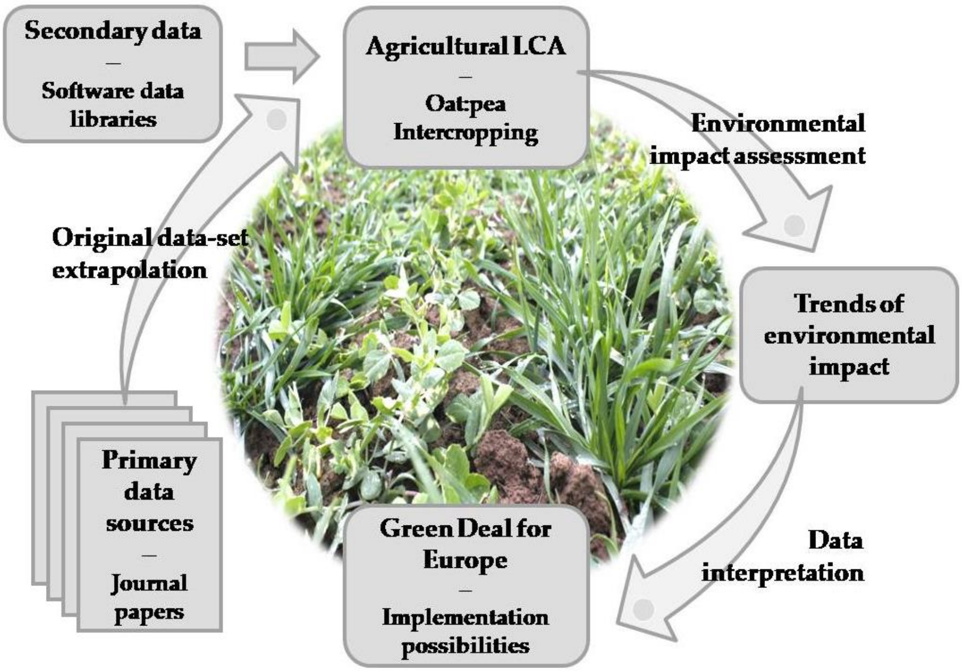
Journal paper with Impact Factor

Winter cereal:legume intercropping is considered a sustainable arable farming system not only in temperate regions but also in Mediterranean environments. Previous studies have shown that with suitable crop stand composition, high grain yield can be achieved. In this study, a life cycle assessment (LCA) of the influence of sowing ratio and nitrogen (N) fertilization on grain nitrogen yield of oat (*Avena sativa* L.) and pea (*Pisum sativum* L.) in intercrops was performed to find the optimal design to achieve low environmental impact. This study compared the environmental impact of oat:pea intercrops using agricultural LCA. Monocrops of oat and pea and substitutive intercrops, which were fertilized with different levels of N, were compared. The system boundaries included all the processes from cradle to farm gate. Mass-based (grain N yield) and area-based (land demand for generating the same grain N yield) functional units were used. The results covered the impact categories related to the agricultural LCAs. The ReCiPe 2016 Midpoint and Endpoint characterization model was used for the data expression. According to the results, an unfertilized combination of oat and pea (50%:50%) had the lowest environmental impact in comparison with the other 14 assessed variants and selected impact categories. In the assessed framework, pea monocrops or intensively fertilized oat monocrops can also be considered as alternatives with relatively low impact on the environment. However, an appropriate grain N yield must be reached to balance the environmental impact resulting from the fertilizer inputs. The production and use of fertilizers had the greatest impact on the environment within the impact categories climate change, eutrophication, and ecotoxicity. The results indicated that high fertilizer inputs did not necessarily cause the highest environmental impact. In this respect, the achieved grain N yield level, the choice of allocation approach, the functional unit, and the data expression approach played dominant roles.

Access to the manuscript: **Bernas, J.**, Bernasová, T., Kaul, H.-P., Wagentristl, H., Moitzi, G., Neugschwandtner, R.W. (2021b). Sustainability estimation of oat:pea intercrops from the Agricultural Life Cycle assessment perspective. Agronomy, 11, 2433. doi.org/10.3390/agronomy11122433

Any study assessing environmental impacts through the LCA method, its outputs, respectively, should be interpreted in such a way that they are easy to understand and can be used for possible implementation in the target area. Graphical representations can also be used for this purpose (for example, the following Figure 3).

Figure 3 Graphical workflow and data implementation potential



Author: Bernas, J.; Illustration photo from Úroda (2020)

7 Conclusion, importance, and perspective

Agriculture and food systems bring an important contribution to global environmental impact. The market access for farmers, agricultural producers, and distributors in the food chain will likely become increasingly contingent on the ability to quantify and communicate their environmental performance and prove the ability to continuous improvement over time concerning environmental aspects. The concept of Life cycle thinking and the Life Cycle Assessment method has become a critical component of effective environmental management in all agricultural areas. A Life cycle assessment (LCA) is presented as a tool for analyzing the environmental impacts and resources used throughout a product's life, from raw materials extraction to production and extending through product use and disposal. LCA also provides a holistic view of the environmental impact connected to agriculture. A number of standardized methods, decision-support tools, and certification/labelling schemes are now available or under development for agricultural and food sector applications in relation to LCA. The LCA phenomenon predicts the emergence of new norms and requirements that agricultural producers will face to maintain a social license to operate and ensure access to current and emerging green markets and strategies.

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9 Full publication profile of the author (period: 2012 - 2021)

9.1 List of scientific publications included in the habilitation thesis

9.1.1 Journal papers with Impact factor

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Annex of the habilitation thesis

Selected publications

The following fourteen publications in the full version are included in the habilitation thesis as the abstracts:

Chapter 12

Life Cycle Assessment Method – Tool for Evaluation of Greenhouse Gases Emissions from Agriculture and Food Processing

Zuzana Jelínková, Jan Moudrý Jr, Jan Moudrý, Marek Kopecký and Jaroslav Bernas

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/62300

Abstract

The chapter focuses on the use of the Life Cycle Assessment method to monitor the emission load of foods from different systems of farming production. The products of the conventional and organic farming production intended for public catering are compared within the SUKI and UMBESA international projects. Conventional farming is mainly characterized by high inputs of mineral fertilizers, chemical pesticides, the use of hormones and stimulants in animal husbandry. It is a system based on the highest possible yields without respecting the natural principles of nature. Conversely, organic farming is a system of production established by the legislation that respects fundamental natural cycles, such as crop rotation, ensures welfare of animals, prohibits the use of fertilizers, pesticides, and other substances of synthetic origin. However, lower yields are a big disadvantage. In the Czech Republic, only about one tenth of the agricultural fund is currently used for organic farming. Arable land constitutes only about 10% of the total area of agricultural land, other areas are mainly grasslands and orchards. The work primarily aims to answer to the question whether the selection of foods may contribute to decrease in greenhouse gas emissions, which is a part of the objectives of many policies. Besides the comparison of agricultural production, processed and unprocessed foods, local and imported foods and fresh and stored foods were compared as well. The Life Cycle Assessment (LCA), which is used to assess environmental impacts of products and services throughout their entire life cycle, was used to quantify the emission load. This method may be briefly characterized as a gathering of all inputs and outputs that take place during the production in the interaction with the environment. These inputs and outputs then also determine the impact on the environment. The LCA consists of four successive and iterative phases: This concerns the definition of objectives and scope, inventory analysis, impact assessment and interpretation of the results. The LCA was originally developed for the assessment of impacts of especially industrial products. Certain methodological problems and deficiency, which bring a level of uncertainty of the results, have been caused by its adaptation to agricultural product assessment, but this method is still recommended for comprehensive assessment of environmental impacts of agricultural production and the comparison of different agricultural products. In this study, a Cradle-to-Gate assessment was performed, which means that the impacts of products (in this case the emission formation) were evaluated only to the delivery of foods to public facilities, further treatment and waste management was not assessed. About 20 most frequently used foods for school catering facilities were compared. The results of the project confirm the general assumption about the less emission load of unprocessed, fresh and local products. It may not clearly state that products from organic farming produce less emissions when comparing agricultural systems. It always depends on the particular crop. The absence of synthetic substances such as fertilizers and pesticides reduces the emission load of organic farming, on the other hand, a higher number of mechanical operations and especially the lower income clearly increase the emission burden, therefore, in several cases, lower emission loads of crops were achieved using the conventional farming system. However, less emission may be achieved within the organic farming system. Among 11 evaluated agricultural products, 8 organic products and only 3 conventional ones go better. The situation is different regarding the following phases of food production, processing and transport. The transport phase significantly worsens the environmental profile of organic foods, because transport distances are too far due to insufficient processing capacity and underdeveloped market networks, and often exceed the emission savings from the agricultural phase. On the contrary, conventional foods are carried within relatively short distances, therefore the final emission load of conventional foods is in many cases fewer than the load of organic foods. This fact is also confirmed by the result of the study, because among 22 evaluated foods, organic food goes better in 11 cases and conventional food in 11 cases as well.

Keywords: LCA, conventional farming, organic farming, greenhouse gases, food

1. Introduction

Currently, agriculture is one of the largest anthropogenic activities with global impact. The area of agroecosystem that covers about one third of the landmass [1] is directly related to the need of humans to survive and it follows the population growth to a large extent. With the growing population curve, the pressure on natural habitats and their conversion to agricultural land and intensification of farming on existing agricultural land also increases. Since the population growth continues very rapidly and also the consumption of meat, respectively animal products, and the energy consumption in agriculture increase, we cannot expect that in the foreseeable future, a spontaneous reversion of the trend of increasing environmental load will come [2].

The environmental load increase impacts the soil, water, biodiversity and, last but not least, the atmosphere. Climate changes and anthropogenic contribution to them have become a frequently discussed issue in recent years. It is not clear yet to what extent these changes are natural and to what extent they are influenced by human activities. Many questions have not been answered yet and the discussion on whether the climate change is determined by natural evolution or negative consequences of human activity is still held [3]. Just the anthropogenic share of changes, especially in terms of GHG (Greenhouse gases) emission production, may be regulated while this activity is one of the priorities of sustainability.

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Climate changes have a significant impact on agricultural systems in the world and can be a crucial factor in ensuring sustainable food production. [4] states that, within the European Union, the largest polluters are energetics, which releases 27.8% of anthropogenic greenhouse gas emissions, transport with 19.5% and industry with 12.7%. Agriculture is with 9.2% in fourth place. Current agricultural trends tending to sustainability should establish more environmentally friendly ways while maintaining the ability of the population food assurance. In order to take steps in this direction, it is necessary to understand agricultural impacts and be able to quantify them. In the case of greenhouse gases, the accurate quantification is quite difficult. However, there are some methods that can help to implement it. One of the methodological tools is the Life Cycle Assessment - LCA. It can be used to quantify GHG emissions, respectively emission saving options. It is a transparent scientific tool [5] which evaluates the environmental impact on the basis of inputs and outputs within the production system [6]. Additionally, LCA analysis currently offers (as one of the few tools) a comprehensive approach to assess the environmental effects [7]. A very valuable tool is LCA analysis thanks to its ability to incorporate and compare different farming systems, their individual processes and products and most of their environmental impacts [8].

Considering the choice of farming system, respectively changes within particular farming systems, as a tool for mitigation, we need to quantify their total impact first and to find the most problematic areas in terms of emissions that can provide space for an effective change. The choice of farming system could be one of the ways to reduce the anthropogenic share of GHG emissions while organic farming seems to be one of the ways. In the last decade, organic farming has become an important element in the environmental friendliness policy and the policy of quality of food in Europe because, inter alia, it reduces the use of synthetic fertilizers and other chemicals such as pesticides [9]. However, mitigation can be achieved also within conventional and integrated farming systems and within food production in general. Reduction of emissions and environmental load in general is a necessary way to long-term sustainability within current population conditions.

2. Literature search

2.1. Climate change and agriculture activities

Anthropogenic activities have a very strong impact also on the environment. With increasing population curve, globalization, technological progress and higher consumer demands, also environmental pressure and environmental impacts grow. There are many impacts from impacts on water, soil, biodiversity to the impacts on the air. Just the anthropogenic air pollution and its relation to climate changes is a big current issue.

Agriculture is ranked among the five major anthropogenic activities contributing most to the production of greenhouse gases. Global GHG emissions from agriculture reach values from 5,1 to 6,1 billions tons of CO_2 equivalent [10]. [11] sets out the share of emissions of greenhouse gases (CO_2, N_2O and CH_4) from particular fields of human activities, while his findings indicate that agriculture in 2000 contributed to the anthropogenic emissions with 13.5%. More than one third of agricultural emissions are field emissions (especially N_2O), methane (CH_4) makes up about one third. Also [12] states that agriculture contributes to the worldwide emission production with the share of 10-12%, while until 2030, we can expect an increase of even half these values [13]. Agriculture is a significant emission producer in the EU also according to [14]. The total share of GHG emissions from agriculture within the EU-27 was 10.1% in 2011 [15]. We can find similar values also in the paper by [16] who states that this share within the EU-15 was 10.2% in 2009. In the Czech Republic, the share of agricultural emissions in total greenhouse gas emissions is calculated at 6.42% [17].

According to [18], 29% of emissions produced within the EU is related to the food production. However, these emissions arising within food production are related not only to the field cycle but also to the production of fertilizers and agrochemicals, processing or all process transport. [18] sets the share of food production to anthropogenic emissions to 22-31% while the most significant proportion (15%) is related to transport.

[19] also stated the high dependence of agriculture on non-renewable materials and to a great extent, the resulting increased GHG emissions production. Agriculture produces emissions in many ways. For example, CO_2 is released during the consumption of fossil fuels or within reduction of organic matter content in the soil. N_20 is released as a result of fertilizer application, CH_4 from the digestive tract of some livestock species. We can conclude that the amount and composition of our diet reflect the specific features of particular technological processes in agriculture and thus the different GHG emission production. Therefore, the change in the way of nutrition in industrialized countries can be extremely important to ensure sustainable development (admittedly conditional on the stabilization of anthropogenic GHG emissions) [20].

2.2. Farming systems

Production systems have their own characteristics and can be categorized into groups e.g. according to density and the resulting impact on the environment. Conventional farming systems are commonly widespread, alternatively, there are integrated and organic farming systems.

2.2.1. Conventional farming

Conventional farming is the most common way of farming in agriculturally advanced countries. Its main objective is to maximize production. Other farming aspects are secondary. Conventional farming is implemented in various intensity degrees. Environmentally friendly processes beyond the ordinary laws are not enforced and monitored. Still, conventional farmers can implement these processes and farm in accordance with environmental protection. However, the European Union introduces a number of rules and legislative provisions for conventional farming leading to limiting inputs in order to protect the environment. On the contrary, in its extremely intensive forms, the conventional farming often leads to excessive environmental damage. The precision farming is a technologically advanced form of conven-

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tional farming that reduces environmental load to some extend through more efficient and optimized inputs.

2.2.2. Integrated farming

Integrated farming is a kind of an intermediate step between conventional and organic farming systems, originally based on integrated plant protection and extended to other agrotechnical processes. Its objective is the sustainability of farming system and it is largely focused on procedures friendly to the environment. However, unlike organic farming, it is not strictly limited by legislation and it is possible, if necessary, to apply procedures that are forbidden within organic farming (e.g. the use of some agrochemicals).

2.2.3. Organic farming

Organic farming is a special kind of farming that cares about the environment and its particular components through restrictions or bans on the use of substances and procedures that burden the environment or increase the risk of contamination of the food chain. Within livestock breeding, it ensures their behavioural and physiological needs in accordance with the requirements of specific legislation. It becomes an environmentally friendly alternative to other farming systems [21]. The main goals of organic farming include:

- Maintenance and improvement of soil fertility.
- Genetic resources protection and biodiversity maintenance.
- Preservation of landscape features and their harmonization.
- Water management, keeping water in landscape and the protection of surface and groundwater against contamination.
- Efficient use of energy, focusing on renewable resources.
- The pursuit for maximum nutrients recirculation and a prevention of the entry of extraneous substance into agroecosystem.
- Production of quality food and raw materials.
- Optimization of life for all organisms, including humans.

Organic farming systems create more potential to reduce greenhouse gas emissions than conventional. The biggest difference is due to the absence of chemical fertilizers. The Farming Systems Trial at Rodale Institute, an American long-term research comparing organic and conventional agriculture, states that the introduction of organic farming nationwide in the USA would manage to reduce CO_2 emissions by up to a quarter due to increased carbon sequestration in soils [22]. The disadvantage of organic farming is less production per the area unit that increases the unit emission load. [23] states that yields of organic farms are on average 17% lower than within conventional farming systems. The impact of organic system on the mitigation is usually measured per the area unit in order to enhance the objectivity. However, it is important to convert it also to the production unit.

2.3. A Life Cycle Assessment

The aim of the assessment of the effects of agricultural products on the environment is to evaluate their impact on environment sustainability [24], especially in terms of food consumption patterns [25]. As stated by [26], the system sustainability can be evaluated on the basis of inputs and outputs and their conversion to CO_2e. [27] states that the measurement of GHG emissions suffers from certain inaccuracy. The reason for this error is that emissions in agriculture are influenced by complex biological processes with a wide range of variables.

There are some suitable methods to assess environmental impacts of agricultural activities [28] such as Life Cycle Assessment (LCA), Ecological Footprint or Emergy Analysis. [29]. The LCA method may be briefly characterized as an assessment of all inputs, outputs and possible impacts on the environment during the entire life cycle [30]. LCA analysis is a tool that enables to assess environmental impacts within the product life cycle. Social or economic aspects may be included as well, however, the calculation of their impacts has only just begun [31] and the main focus is on the environmental component which evaluates, according to [32], the environmental impact of a product based on the assessment of the material and energy flows, that the monitored system shares with its surrounding space (environment).

[33] states that the LCA is an appropriate instrument because it enables to express the relationships between the food production, transport and production of CO_2.

With the LCA analysis, the impact categories - the impact on climate, water pollution and air pollution - are mostly evaluated. Whereas, impacts such as biodiversity or pesticide toxicity are seldom evaluated because of methodological problems [34]. The LCA study consists of four basic stages: Definition of objectives and the scope, Inventory, Impact assessment and Interpretation [32].

2.3.1. Goal and Scope definition

In the first stage of the LCA analysis, it is necessary to define the objective and the scope of the paper before the actual start [35]. The study goal and scope definition determine the next procedure character and the circumstances in which the study outputs are valid [32]. [36] requires to establish a study goal and scope while the study scope means to determine the product system, the functional unit and system boundaries, to determine allocation rules, the assessment methodology, hypothesis and limits and data quality.

In the objectives of the study, there must be clearly specified who it is addressed to, the reasons for the study and the intended use of the results [36]. This increases the transparency of the study and the comprehensibility of the context of the results since different recipients emphasise different aspects.

The study scope results form goals and is determined by financial resources of the ordering authority and the available time of the processor [5]. The study scope describes the most important methodological choices, hypothesis and limits [35] that are described below.

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2.3.1.1. Function and functional unit

To compare products (systems), it is necessary to define also the functional unit. The functional unit is described as a quantified performance of a product system which serves as a reference unit in a study of life cycle assessment [36]. It is an essential element which all study results are related to. It must be chosen so as to be easily expressible and measurable. The functional unit is the starting point for searching for alternative ways how to fulfil the function with a lower negative impact on the environment [5]. [37] states that the determination of functional units is as a crucial step especially when comparing systems with different levels of production per hectare such as conventional and organic farming system. [38] sees fit to set the production unit instead of the area unit as a functional unit. On the contrary, [9] recommends to involve both functional units into calculations and perform the calculations for both the unit area and the unit of production. This is confirmed also by [39] who states that LCA analysis outputs are usually set per the production unit. Some authors, such as [40], state that LCA outputs should by calculated in relation to the area unit allowing the better expression of environmental load carrying capacity. With the LCA analysis, we cannot perform both calculation methods and use the production unit as well as the area unit as a functional unit [2].

2.3.1.2. System boundaries

Each product system consists of a variable number of processes involved in the product life cycle. However, the product under consideration is often related to other processes that may no longer be important for the LCA study. The system boundary serves to the separation of essential and non-essential processes of the product life cycle. Since the choice of system boundaries significantly affects LCA study outcomes and in addition, its intensity and complexity, system boundaries should always be well considered and clearly defined. The choice of system boundaries is carried out with regard to the studied processes, studied environmental impacts and selected complexity of the study. Not-including any life cycle stages, processes or data must be logically reasoned and clearly explained [32].

Determination of system boundaries is always a very important step, especially in the area of food production and agriculture, where the clearly identifiable technological processes and systems meet the natural processes and procedures influenced by a number of factors [41]. The system boundary defines which unit processes will be included in the monitored system [36]. The system boundary definition virtually defines which life-cycle stages will be analysed (in the case the whole life cycle was not included) or what unit processes and elementary flows will or will not be considered. The system boundaries can be restricted to the processes within the farm [42], or can extend into other phases from pre-farming processes, through transport and storage, to the end user, respectively consumption. [43] states that although it would be desirable to include the entire product cycle, most studies of food production omit some phases, usually trade and other related sections. Their impact is mostly negligible in relation to e.g. the agricultural phase [44]. When comparing conventional and organic farming systems, we can also omit the calculation of load from buildings and infrastructure because there are only small differences between farming systems while slightly more noticeable difference is apparent within animal production [45].

System boundaries determine not only which processes will be incorporated into the product scheme, but also define the geographic and temporal scope of the study to determine its purview. Defining the geographical scope (local, regional, national, continental or global) or determination of the exact study location is important for the environmental aspects of various material and energy flows because their impacts may be different in different geographical conditions. E.g. due to different ways of development of power in each country, the environmental impact of power development and hence of energy consuming processes is different. Using unsuitable system boundaries or oversight of important factors such as the place and method of energy development can lead to false results.

2.3.1.3. Allocation principles

During the life cycle assessment, the study authors are very often confronted with the fact that the product system has at its end more than one output. In these cases, we use the allocation. Allocation means the assignment of the share of total environmental burden to particular outputs [32]. The Standard recommends to avoid the allocation whenever possible, e.g. by extending systems or sub-division processes [36].

In the case we cannot avoid the allocation using the above mentioned methods, the Standard proposes to use the allocation based on the physical principle such as weight or energy content of final products.

2.3.1.4. Data quality

The quality of data entering the LCA study is to be determined in view of temporal, spatial, technological, data sources (it must be determined whether primary data required or secondary data can be used), their accuracy etc. It concerns the determination of all requirements for the input data [5].

2.3.2. Life Cycle Inventory

The inventory tasks is to collect environmentally important information about relevant processes involved in the product system. Inventory collects information about unit processes at first and subsequently, an inventory of inputs and outputs of the system and its surroundings is carried out. The goal is the identification and quantification of all elementary flows associated with product system. Inventory analysis is the nature of the technical implementation of LCA studies. It is an essential part of a study, has high demands for data availability, practical experience in modelling product systems and, in the case of using database tools, it is necessary to master them perfectly and to understand their function [46]. The inventory phase principle is data collection that is used to quantify values of the elementary flows. This phase represents a major practical part of the LCA study, time consuming and with demands for data availability and author's experience with modelling product system studies [47].

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2.3.3. Life Cycle Inventory Assessment

The inventory results should be presented in clear form, how much and what substances from the environment enter the system and how much get out. These results serve for subsequent life cycle impact assessment [48]. The aim of the life cycle impact assessment is to measurably compare the environmental impacts of product systems and to compare their severity with new quantifiable variables identified as impact category. The impact categories are areas of specific environmental problems such as global warming, climate changes, acidification, eutrophication, ecotoxicity and others. Already in the phase of definition of the LCA study scope, it is necessary to describe what impact category will be applied and which of their environmental mechanisms will serve as a basis for impact assessment [46].

2.3.4. Interpretation

The outcome of the LCA study is a large amount of different values from the inventory as well as from the life cycle assessment. An important task for the study author is to sort the data and their appropriate and understandable interpretation [32]. The need for proper interpretation is also stated by [49] who states that on the basis of LCA outcomes, there are often taking steps with significant economic, environmental and other impacts, while there is the risk that incorrect and misleading interpretation of outputs can lead to a deepening of existing or creating new problems. Since the form of presentation of data often affects their meaning, the life cycle interpretation has become an integral part of LCA studies and gained some rules. On the general, interpretation of LCA consists of structuring data with regard to the most important processes or process groups and the most important substances, performing sensitivity analyses and evaluation of the uncertainties of the study, discussion of the data meaningfulness in relation to the study completeness and the input data quality, and the final summary and formulation of realistic recommendations.

3. Goal of the study

The main objective of the Czech - Austrian SUKI (Sustainable Kitchen) project was to assess the total amount of GHG emissions produced by public catering facilities.

These emissions originate both within energy consumption for the kitchen operation (ie. lighting, heating, ventilation, cooling, operating kitchen appliances, cooking process), but mainly in the food production, processing and transport to catering facilities. While direct energy consumption in the kitchen can be determined relatively easily, emissions from food production are unexplored areas in the Czech Republic. The project set the target to answer following questions using the emission quantification:

- What is the influence of the production method (conventional, organic) on the GHG emission production?
- What is the influence of the place of the food origin (region / outside the region) on the GHG emission production?

- What is the influence of the food processing method (raw, processed, fresh, frozen) on the GHG emission production?

By answering these questions, we can deduce the possibilities and limits of greenhouse gas emission savings without compromising the food quality which is also subject to the actual selection of foods, meals and a preparation process. The aim is to promote catering facilities on the path to sustainable production and at the same time to the food nutritional quality improvement. Through targeted food selection, they can take a step towards sustainable development and a healthy diet, contribute indirectly to the global reduction of greenhouse gas emissions while promoting regional organic farming.

4. Methodological procedure

In the first project stage, it is necessary to identify the most widely used ingredients heading for school catering facilities. For this purpose, we used annual lists of purchased raw materials from partner catering facilities that were processed by tabulating and from them, all the ingredients that made up at least 80% of the raw materials used kitchens during the year were selected. These lists also provide a good comparison between Czech and Austrian cuisines.

The second step and the focus of this chapter was to evaluate the emission load of individual foods from the list of most common foods. There was used the simplified Life Cycle Assessment method in which only the Climate change Impact category was assessed. Detailed description of the LCA methodology is shown in the literature review, the following text describes practical method implementation.Food emission load evaluation using the LCA method

4.1. Goal and Scope definition

On the basis of evaluation of consumption of involved catering facilities, 11 most commonly used products were selected. When work them into other raw materials, we can expand the list to final 22 products that heading for school kitchens. For each product, a comparative study focused on the comparison of organic and conventional versions, imports and regional variants was elaborated, if possible, the also a comparison of the fresh and stored product was made, as well as a comparison of different stages of processing. The results should serve as an answer to the question whether the selection of the food contributes to reducing greenhouse gas emissions. The target group are the chiefs of kitchens, school principals, cooks, diners, farmers, suppliers, as well as actors at the regional and national political level.

Evaluated systems were modelled with the cradle to gate principle, thus the product system of particular foods was terminated at the point of entry into the school canteen. The following presentation of food and related activities, as well as waste management of the product and its packaging materials were not included in the LCA. One kg of the final food was selected as a functional unit. In the case the allocation was necessary, the weight-economic allocation was used.

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4.2. Life Cycle Inventory

At this stage, it was necessary to collect the relevant data relating to the entire product system. The product system was divided into sub-processes: agriculture, processing and trade. For agriculture, inputs relating to the consumption of seeds, fertilizers, pesticides and fuel within agricultural operations for crop production, feed consumption, energy and fuel within the livestock sector were surveyed. Emissions from nitrogen fertilizer application within crop production calculated according to the methodology [50] and emissions from manure management in the livestock production, calculated according to the methodology [51], were integrated into agriculture. A general framework for crop and livestock products is shown in Figure 1 and Figure 2.

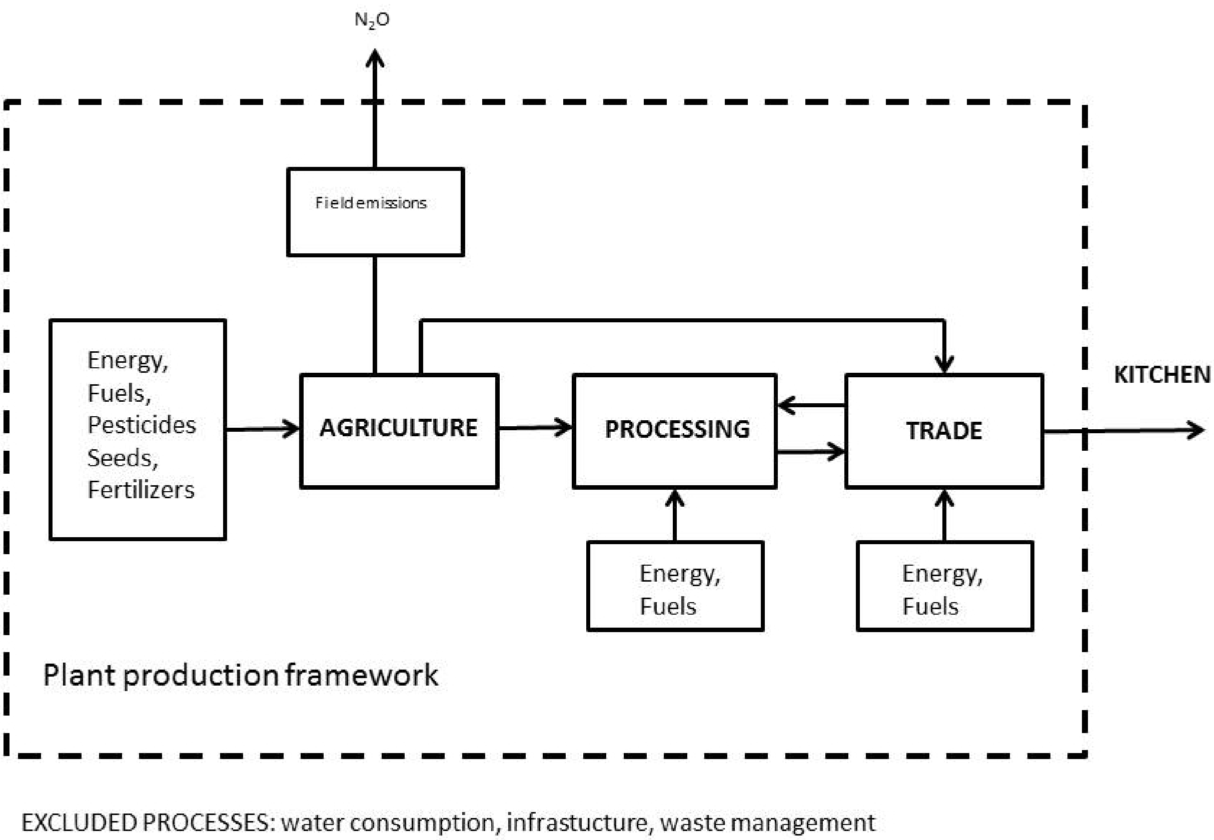

Figure 1. Framework of plant food product LCA

For processing, the data on energy consumption were collected, within the trade, it was travel distance, information on cargo and storage time of various foods. All data was obtained primarily from farmers, processors and traders, absent sufficient data, it was supplemented by data from available databases, especially the Ecoinvent database.

From a geographical point of view, regarding the data quality, the data corresponds primarily to the Czech Republic, secondarily to Central Europe. In terms of time, data corresponding to the term 2000 - 2012 were obtained, from a technological point of view, data corresponds to the widely used average technologies.

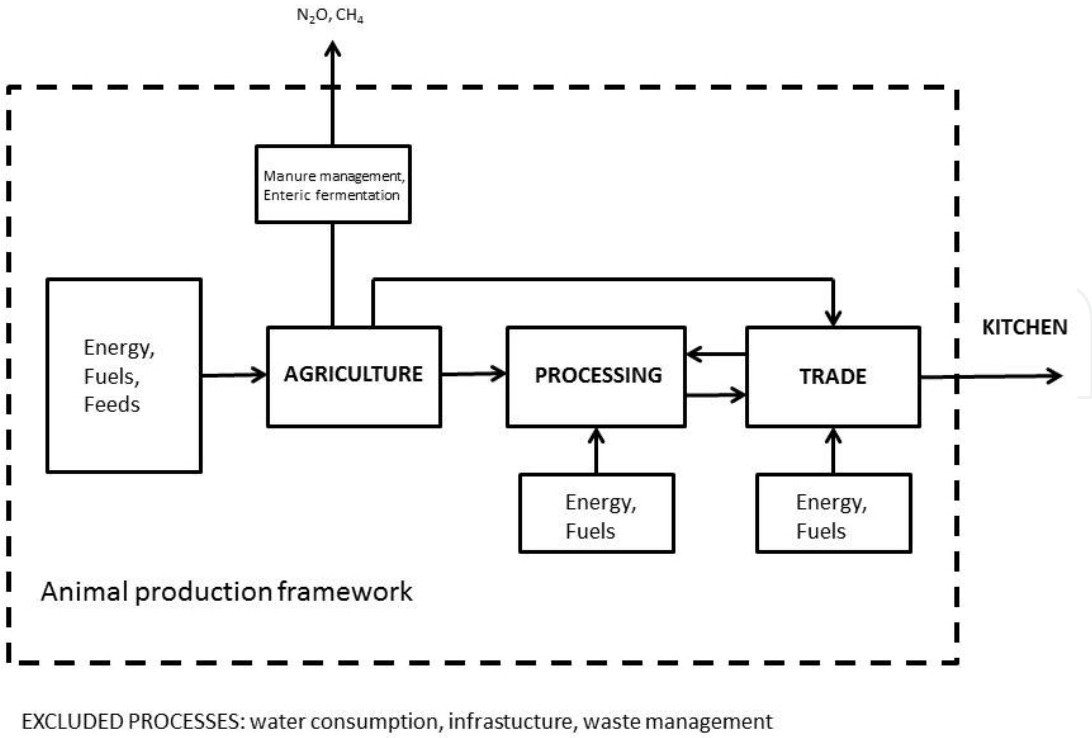

Figure 2. Framework of animal food product LCA

4.3. Life cycle inventory assessment

The results were calculated using the SIMA Pro software. To obtain the necessary results, the Recipe Midpoint (H) Europe method has been chosen as a characterization model. Results come from the climate change impact category and they are expressed in kg of a carbon dioxide equivalent (CO_2e).

4.4. Interpretation

Result interpretation and discussion is given below.

5. Results

Based on the analysis of the annual consumption of foods of participating catering facilities, there were 22 of the final products which constitute the largest food consumption selected.

5.1. Emission load in food production

5.1.1. Agricultural phase

A basic emission load resulting from agriculture involves the calculation of greenhouse gases in the field phase. In the context of comparing the formation of greenhouse gas emissions in

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the cultivation of selected crops and breeding of selected species within conventional and organic farming systems, the total greenhouse gas emissions with twelve agricultural products were observed. This total amount sum was divided into subgroups within crop production: agricultural engineering, fertilizers, pesticides, seed and field emission, and in the context of animal production to: feed consumption, manure management, and in the case of cattle on enteric fermentation.

In the case of crop production, the conventional farming system differs from the organic one in the total CO_2e emissions production as well as in the production within subgroups. Although the production of GHG emissions differs within particular subgroups, in total with most studied crops, the production of CO_2e is lower in the organic farming system. In the primary agricultural study, [52] monitored a set of crops including wheat, rye, potatoes, onions, carrots, tomatoes and cabbage, while the higher greenhouse gas emissions expressed as CO2e within the conventional farming system in the Czech Republic were found with all investigated crops except onions. The greatest differences were found with carrots and cabbage where the ecological variants produced almost 60% lower emissions than the conventional variant. The extension study [53] complements the study with the comparison of emission load of organic and conventional apples and rice, where the results showed almost the same burden for rice and in the case of apples, 33% lower emissions within organic farming. Another extension study [54] comparing garlic proves again 40% lower emissions when grown in the organic farming system. In conclusion, it can be summarized that in the context of plant production, eight of ten evaluated products were better as an organic variant, one raw material showed the same emissions in both variants and only one crop was better in the conventional variant. Results and emission savings are summarized in the Table 1.

Group	Product	Organic*	Conventional*	save BIO
corn products	wheat	0,4218	0,4606	8%
	rye	0,2972	0,5364	45%
	rice	0,6197	0,6266	1%
vegetables products	potatoes	0,1256	0,1446	13%
	cabbage	0,0329	0,0774	58%
	carrot	0,0411	0,0987	58%
	tomato	0,0671	0,0871	23%
	onion	0,0997	0,0828	**-20%**
	garlic	0,2480	0,4306	42%
fruit products	apple	0,0568	0,0848	33%

*in kg CO_2e/kg of products

Table 1. Emission of GHGs from the plant production (agriculture phase only)

Comparative studies show positive and negative factors of organic farming which are mainly lower yields and specific agronomic rules. It coincides e.g. with findings by [55]. The organic farming is more agricultural operations intensive as compared with the conventional one. For most crops, emissions from production of one kg are higher due to more intensive agricultural technology (especially mechanical protection against pathogens), while the difference is even increased by generally lower yields in organic farming. Emission load within the agrotechnical phase in the organic farming system is increased also by some operations related to pre-seeding soil preparation. The possibility of reducing GHG emissions by changes in agricultural technology is highlighted e.g. by [56] who identifies the main potential for reduction within tillage.

The fundamental difference between the conventional and organic farming system in terms of GHG emissions is obvious within fertilization. While organic farming uses organic fertilizers (especially manure or slurry), the use of synthetic fertilizers within the conventional farming system increases significantly the share of emissions. This is stated also by [57] who gives synthetic fertilizer decrease as one of the main tools for reducing CO_2e emissions. From an economic perspective, the nitrogen in organic farms is financially much more demanding than industrially produced nitrogen. This is a powerful incentive to try to prevent losses and learn how to use recycling technology [58]. Timing and management of nitrogen application are crucial. Soil mineralization processes should deliver components to plants when the plants are most in need [10]. In conventional farming, GHG emissions are increased also due to the use of pesticides. In organic farming, this load is completely eliminated, respectively, transferred to the agrotechnical phase in the form of mechanical plant protection. However in total, it is a relatively low proportion of total emissions. [59] can see here another opportunity to save emissions.

Within plant production, in organic farming, there is space for reducing greenhouse gas emissions per the production unit and an increase in income, while maintaining the current input structure.

To compare the emission load of livestock products, several studies were carried out again. Initial work [61] compared load from conventional and organic cattle breeding without milk production. One kilogram of organic beef produced twice higher emissions than one kilogram of conventional meat. Another study [53] compared pork. Organic pork was again worse than conventional meat in terms of emissions. On the contrary, when comparing variants of milk, organic milk was a little emission-less burdensome than conventional milk. The latest from animal studies compared the production of eggs [62], where organic eggs produce almost 40% lower emissions than conventional eggs. Results and emission savings are summarized in the Table 2.

The higher emission load in organic farming systems is mainly due to technology of rearing and fattening when in the organic farming system, young ones are fed with breast milk while in conventional breeding, they are fed with feed. Production of breast milk causes significantly more emissions then production of crops for feed mixtures. Additionally, within conventional breeding, the emission load is divided among several products (meat, milk).

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Product	Organic*	Conventional*	save BIO
milk	1,336	1,420	6%
egg	0.219	0.383	43%
beef	24,10	11,45	**-110%**
pork	6,643	5,143	**-29%**

*in kg CO_2e/kg of products(in egg study in kg CO_2e/egg)

Table 2. Emission of GHGs from the animal production (agriculture phase only)

5.1.2. Manufacturing phase

Environmentally friendly farming systems that utilize anti-erosion measures, advanced methods of nitrogen management and other measures, have the potential to sequester carbon and reduce greenhouse gas emissions [63]. This creates a positive environmental potential which may however be discarded in the following, or vice versa agricultural stage preceding, parts of the food production process which could result in a significant increase in CO_2e emissions. [64] states that within cereal production, the production of fertilizers in the pre-farming cycle makes up 35% of total emissions, while the farm stage only 27%.

Importance of pre-farming and post-farming stage can be documented by the example of potato, where [65] states the production of 0.145 kg of CO_2e in the conventional and 0.126 kg of CO_2e in organic farming system per one kilogram of potatoes. However, if we take into account also other phases (especially the processing and transport), the load resulting from potato products in relation to potatoes grows significantly. For one kilogram of peeled potatoes in the Czech Republic, it is 0.262 kg of CO_2e in conventional 0.247 kg of CO_2e in organic farming systems. However, for the manufacture of chips, it is already 2.072 kg of CO_2e in conventional and 2.271 kg of CO_2 in organic farming systems per one kilogram of finished product. And in the case of mashed potatoes, even in conventional production, it is 3.201 kg of CO_2e and in organic production 3.192 kg of CO_2e. These findings suggest that the differences between the production systems are relatively small if we compare it to the difference in CO_2e emissions between processed and unprocessed products. Another important factor is also common transport distances. Their importance is higher with the processed products that are in their life cycle more transported (besides transporting raw materials, there is still transport of semi-finished products between processing units). The transport distance is also affected by the density of processing networks and infrastructure. The results of the finished material (see Table 3) in our study [53] showed that eleven of the 22 evaluated products have better results as a conventional variety and eleven products have better result as a organic variety. This indicates a lack of potential of a manufacturing and sale network for organic products.

Group	Product	Organic*	Conventional*	save BIO
corn products	wheat	0,4593	0,4699	2%
	rye	0,3336	0,5495	39%
	wheat flour	0,6463	0,5861	**-10%**
	rye flour	0,5080	0,6737	25%
	roll	0,8100	0,7766	**-4%**
	bread	1,0431	1,0632	2%
	pasta	0,7336	0,7020	**-5%**
	rice	0,6197	0,6266	1%
vegetables products	potatoes	0,1931	0,1867	**-3%**
	peeled potatoes	0,2475	0,2624	6%
	puree	3,1918	3,2009	**0%**
	pommes	2,2714	2,0718	**-10%**
	cabbage	0,0851	0,1151	26%
	carrot	0,1158	0,1517	24%
	tomato	0,1748	0,1802	3%
	onion	0,1749	0,1285	**-36%**
	peeled onion	0,2428	0,1789	**-36%**
fruit products	apple	0,1273	0,1189	**-7%**
milk products	milk	1,4870	1,5603	5%
	yoghurt	1,7390	1,8123	4%
meat products	beef	24,5313	11,6510	**-111%**
	pork	6,7452	5,3083	**-27%**

*in kg CO_2e/kg of products

Table 3. Emission of GHGs from the final products

Besides transport distances, also the way of transportation has the influence. E.g. [63] states that significant energy savings could be achieved by rail preference which can reduce power consumption by up to half while emissions of greenhouse gases are reduced comparably. These factors, together with the production technology may, in some cases, eliminate emissions savings resulting from environmentally friendly management system. The principle of regionality which reduces unnecessary transport processes is thus superior to the principles of organic farming, since its failure may to reduce or completely eliminate the environmental potential, respectively, the emission savings resulting from organic farming,. Reducing the environmental potential can be demonstrated e.g. by the example of the production of bread

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in conventional and organic farming systems in the Czech Republic. Thanks to the low-volume technologies in production of bread in organic processing capacities, produced greenhouse gas emissions are much higher, so the positive effect of previous organic cultivating of wheat and flour production is eliminated [66]. Post-farming life cycle stages of agricultural products are very significant in terms of GHG emission production because within them, the emission savings generally made by organic farming in relation to conventional farming can be devalued. Assuming that the growing agricultural systems with arable land and permanent crops and grazing systems worldwide can sequester up to 200 kg C ha-1 year-1, the global carbon sequestration can reach 2.4 billion tons of CO_2e year -1. This minimum idea of conversion to organic farming would be able to lose 40% of global agricultural GHG emissions [10]. Environmentally friendly and organic farming systems are such an important tool for reducing greenhouse gas emissions.

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Author details

Zuzana Jelínková*, Jan Moudrý Jr, Jan Moudrý, Marek Kopecký and Jaroslav Bernas

*Address all correspondence to: jelinkova@zf.jcu.cz

University of South Bohemia in České Budějovice, Faculty of Agriculture, České Budějovice, Czech Republic

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"Gheorghe Asachi" Technical University of Iasi, Romania

INFLUENCE OF FARMING SYSTEM ON GREENHOUSE GAS EMISSIONS WITHIN CEREAL CULTIVATION

Jan Moudrý Jr.[1*], Jaroslav Bernas[1], Marek Kopecký[1], Petr Konvalina[1], Daniel Bucur[2], Jan Moudrý[1], Ladislav Kolář[1], Zdeněk Štěrba[1], Zuzana Jelínková[1]

[1]University of South Bohemia in České Budějovice, Faculty of Agriculture, Studentská 1668, České Budějovice, CZ 37005, Czech Republic
[2]University of Agricultural Sciences and Veterinary Medicine Iasi, Faculty of Agriculture, Mihail Sadoveanu Alley 3, Iasi, 700490, Romania

Abstract

The emissions of greenhouse gases (GHG) from anthropogenic activities have still been a topical and much-discussed issue. In farming, room for reducing GHG emissions may also be available in crop farming. The measures aimed at the mitigation of GHG emissions may include a change in the farming system or partial switch to more extensive farming methods, including organic farming. The life cycle of oat, rye, wheat and spelt wheat cultivation in conventional and organic farming systems in the conditions of Central Europe was evaluated by LCA method, impact category: climate. The results clearly show that there are considerable differences between conventional and organic farming systems in individual subcategories of the farm phase of the production of cereals. The CO_{2e} emissions produced in the cultivation of the monitored cereals are lower in organic farming systems, both when converted to an area unit and when converted to a production unit.

Key words: cereals, emissions, greenhouse gases, LCA, organic farming

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1. Introduction

In the course of the 20th century, the population grew from 1.6 to 6.1 billion (Lutz et al., 2013). This results in a steady rise in the consumption of natural sources and agricultural products (Foley et al., 2011). Since the population growth continues very rapidly, and the consumption of meat or other animal husbandry products as well as the consumption of energy in agriculture and food industry are on the increase, it cannot be expected that the trend of the growing environmental load would reverse spontaneously in the near future (Goodland, 1997; Schau and Fet, 2008). The global GHG emissions from agriculture amount to 5.1 – 6.1 billion tons of CO_2 equivalent (Niggli et al., 2011) [CO_{2e} in further text]. Baumert et al. (2005) determine the shares of GHG (CO_2, N_2O and CH_4) emissions produced in various branches of human activities. According to their findings agriculture accounted for a 13.5% share of the anthropogenic emissions in 2000. Friel et al. (2009) also claim that the share of agriculture in the global emissions is 10-12%, and an increase by half of those values can be expected to take place by 2030 (Smith et al., 2007).

According to IPCC report (IPPC, 2007) the share of agricultural production in the anthropogenic production of GHG emissions is 14%, and this share differs in various countries according to the intensity of the agricultural production. In general, carbon dioxide (CO_2) is the most important GHG generated as a result of human activity. It accounts for 82% of

* Author to whom all correspondence should be addressed: e-mail: jmoudry@zf.jcu.cz; Phone: +420723701768; Fax: +420387772456

all GHG emissions produced by the 27 EU member states, accounting for a 55% share in the total warming of all man-emitted gases (IPCC, 2014; Quashing, 2016). Agriculture is also a significant emission producer in the EU according to Brandt and Svendsen (2011). In the EU-27, the total share of GHG emissions from agriculture was 10.1% in 2011 (Pendolovska et al., 2013). Similar values can also be found in the UNFCCC report (2011), according to which this share amounted to 10.2% in 2009 in the EU-15. Therefore, ways to reduce greenhouse gas emissions are also searched for in agriculture.

In addition to animal husbandry, GHG emission savings may also be found in crop production, especially due to the large areal extent. Activities in the field of land use change, fertilizer use and production, fossil fuel burning and agricultural waste burning are the main sources of GHG emissions in the agricultural sector and they are presented as sources of CO_2 from agricultural production for example by (Nimkar et al., 2015). Another significant gas is N_2O, which is emitted in terms of production and utilization of nitrogen fertilizers and due to volatilization during various agricultural activities (Rees et al., 2013; Sutton et al., 2011). Last but not least, agricultural GHGs are associated with animal husbandry, especially beef cattle breeding and CH_4 production (Bellarby et al., 2013). The room for such measures is available in both non-food production, e.g. in the cultivation of energy crops (Bernas et al., 2016), and food production.

The most commonly grown groups of crops include cereals, which are very significant in terms of both the human nutrition and the size of the areas where they are grown (e.g. in the Czech Republic, the size of cereal fields constitutes more than half of the total arable land and, on a worldwide basis, wheat is one of the four crops that cover approximately 80% of the caloric consumption of mankind) (Šarapatka et al., 2008). This is also a reason why cereals constitute one of main groups in crop production, in respect of which it is possible to take mitigation measures. Cultivation of cereals in the conventional and organic farming system has its own specifics, which result in particular from a different approach to the protection and nutrition of plants in these systems of farming. Absence, or a very low rate of use of agrochemicals in organic farming often leads to an increase in the number of agrotechnical operations serving to protect plants; in terms of plant nutrition, in addition to the application of organic fertilizers, great emphasis is placed on proper selection of crops and securing of nitrogen from other sources (e.g. more frequent cultivation of leguminous plants).

The measures leading to a mitigation of GHG emissions may also include a change of the farming system or a partial switch to more extensive farming methods, including organic farming. Niggli et al. (2011) state that intensive crop production (often based on monocultures and high productivity) largely depends on external inputs, such as mineral fertilizers and chemical plant protection products. Sustainable farming procedures, such as organic farming, greatly reduce such dependence on inputs. As presented by Lal (2004a), a system sustainability can be evaluated based on inputs and outputs and their conversion to CO_{2e}. The American research "Rodale Institute's Farming Systems Trial", which was focused on long-term comparison of the effects of organic and conventional farming, confirms that introduction of organic farming in the whole USA would reduce CO_2 emissions by as much as a fourth due to the increased carbon sequestration in soil (LaSalle and Hepperly, 2008). In order to be able to assess the efficiency of a change of the farming system, it is necessary to quantify the exact environmental load or rather the production of GHG in the given farming systems.

There are several suitable methods used for the assessment of environmental impacts of agricultural activities (Finnveden and Moberg, 2005), such as the Life Cycle Assessment (LCA), Ecological Footprint (EF) or Emergy Analysis (EA – analysis of direct and indirect energy flows) (Thomassen and De Boer, 2005; Van Der Werf and Petit, 2002). Cambria et al. (2016) or Ng et al. (2016) also present a suitable method for evaluating agricultural activities. Moreover, LCA, as one of the few tools, offers a comprehensive approach to the evaluation of environmental impacts at present (Kim and Dale, 2005; Nelson and Robertson, 2008; Requena et al., 2011; Wagner et al., 1998). LCA is also a very valuable tool due to its ability to include and compare various farming systems, their individual processes and products and most of their environmental impacts (Charles et al., 2006; Haas et al., 2000; Haas et al., 2001).

The aim of this paper is to quantify and assess the environmental aspects of growing of major cereal species in the conditions of the Czech Republic and Central Europe within the conventional and organic farming system, especially in terms of the impact of organic and conventional agriculture on greenhouse gas emissions.

2. Material and methods

The life cycle of growing oat, rye, wheat and spelt wheat in the conditions of Central Europe was modelled in the software SIMA Pro (method ReCiPe Midpoint (H) Europe) in accordance to the standards ČSN EN ISO 14040 (ISO, 2006a) and ČSN EN ISO 14044 (ISO, 2006b). As a functional unit, 1 kg of grain was used. The output was the yield per hectare, the inputs included technological operations, seed quantity, fertilizer quantity, and plant protection products. The LCA framework includes the farm phase (field emissions, seeds and seedlings, fertilizers, pesticides, and agrotechnical operations).

In addition to the emissions produced from the above stated inputs, there are also field emissions (N_2O emissions) released after the application of nitrogen fertilizers. They are quantified by the methods described in IPCC (*Intergovernmental Panel on Climate Change*) (De Klein et al., 2006).

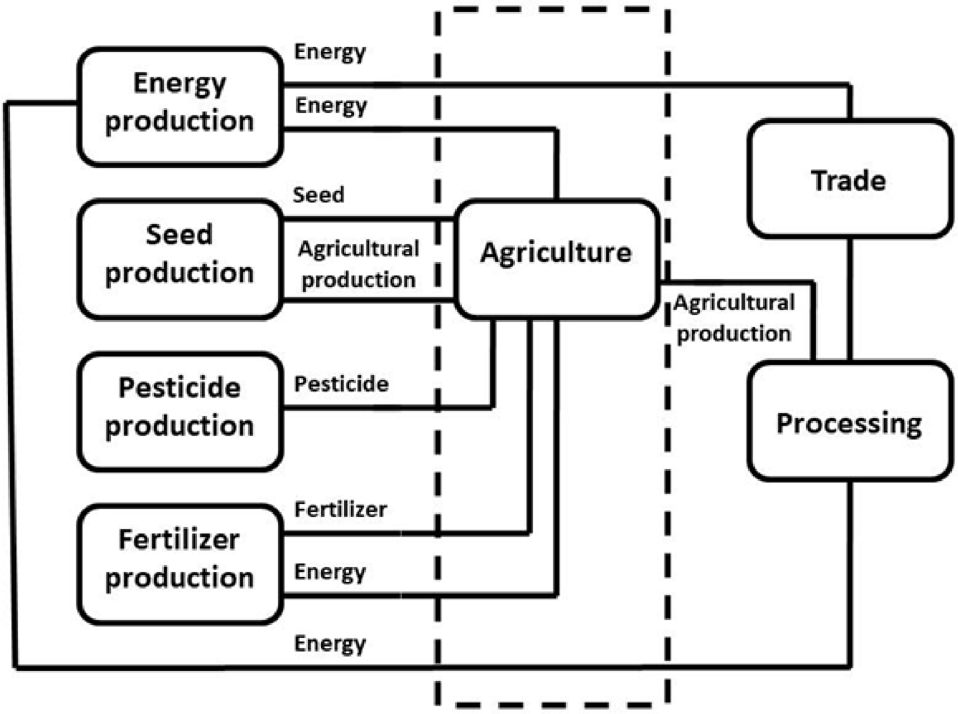

Fig. 1. Determination of the system boundaries – LCA framework

The greenhouse gases were converted to CO_{2e} based on the formula (Eq. 1):

$$CO_{2e} = 1 \times CO_2 = 23 \times CH_4 = 298 \times N_2O \quad (1)$$

The calculation of the emission load used the values obtained from the experimental cultivation of cereals in small experimental plots of the Faculty of Agriculture of the University of South Bohemia in České Budějovice (experiments were based both on an experimental plot certified in organic farming and on an experimental plot with conventional farming system) and referential operational and pilot stations, supplemented by the yield parameters from the selected set of 50 farms in the Czech Republic, the set comprising of 25 farms operating in organic farming and 25 farms operating in conventional farming system. The number of farms in the set was influenced by the total number of farms operating in organic farming system focusing on the cultivation of cereals and by the availability of the data from them. The basic data from the farms were supplemented from the Ecoinvent database (Ecoinvent, 2010).

The input data from the Ecoinvent database (2010) were adjusted to the farming conditions in the Czech Republic. The adjustments concerned mainly fuel consumption in individual agrotechnical operations. Based on the data from the selected set of farms, the most common agrotechnical procedures used in the cultivation of the monitored cereals in conventional and organic farming systems were identified. These procedures are a sequence of the most commonly used agrotechnical operations that are being carried out during cultivation, the most common agrotechnical line being developed for each monitored cereal as well as farming system. Based on these operations, the technological chains of operations used for the calculation of greenhouse gas emissions were made up.

Wheat, rye and oat were evaluated in conventional and organic farming systems; in the Czech Republic, spelt wheat is grown almost solely in organic farming systems. The average yields in the evaluated selected set grown in a conventional farming system amounted to 5.6 t/ha for wheat, 3.7 t/ha for oat and 4.0 t/ha for rye, while the average yields of the crops grown in an organic farming system amounted to 3.5 t/ha for wheat, 2.6 t/ha for oat, 2.9 t/ha for rye and 3.3 t/ha for spelt wheat.

3. Results and discussion

In the Czech Republic, cereals are the most widely grown group of crops, and are grown on approximately 50 % of arable land (Capouchová et al., 2012; Konvalina et al., 2014; Moudrý and Konvalina, 2007; Stehno et al., 2010). Given the size of the area on which they are grown, they also rank among the crops significant in terms of a possible reduction of anthropogenic emissions of greenhouse gases.

In both organic and conventional farming systems, the growing of cereals have certain specifics leading to different environmental loads or rather different greenhouse gas emissions. The greenhouse gas emissions within the production of cereals vary in different regions due to differences in species, climatic conditions, soil conditions and production system (Barton et al., 2008).

Table 1. The yield parameters of the monitored cereals

Parameter	***Unit***	***Wheat***		***Rye***		***Oat***		***Spelt wheat***
		Conv.	***Organic***	***Conv.***	***Organic***	***Conv.***	***Organic***	***Organic***
average	t/ha	5.6	3.5	4.0	2.9	3.7	2.6	3.3
SD	t/ha	1.1	0.6	1.0	0.9	0.6	0.7	0.6
CV	%	19.9	18.6	24.6	32.3	17.0	27.1	17.0
Median	t/ha	5.8	3.5	4.1	2.7	3.7	2.6	3.4
Mode	t/ha	6.6	3.6	5.3	2.4	4.2	2.6	3.7

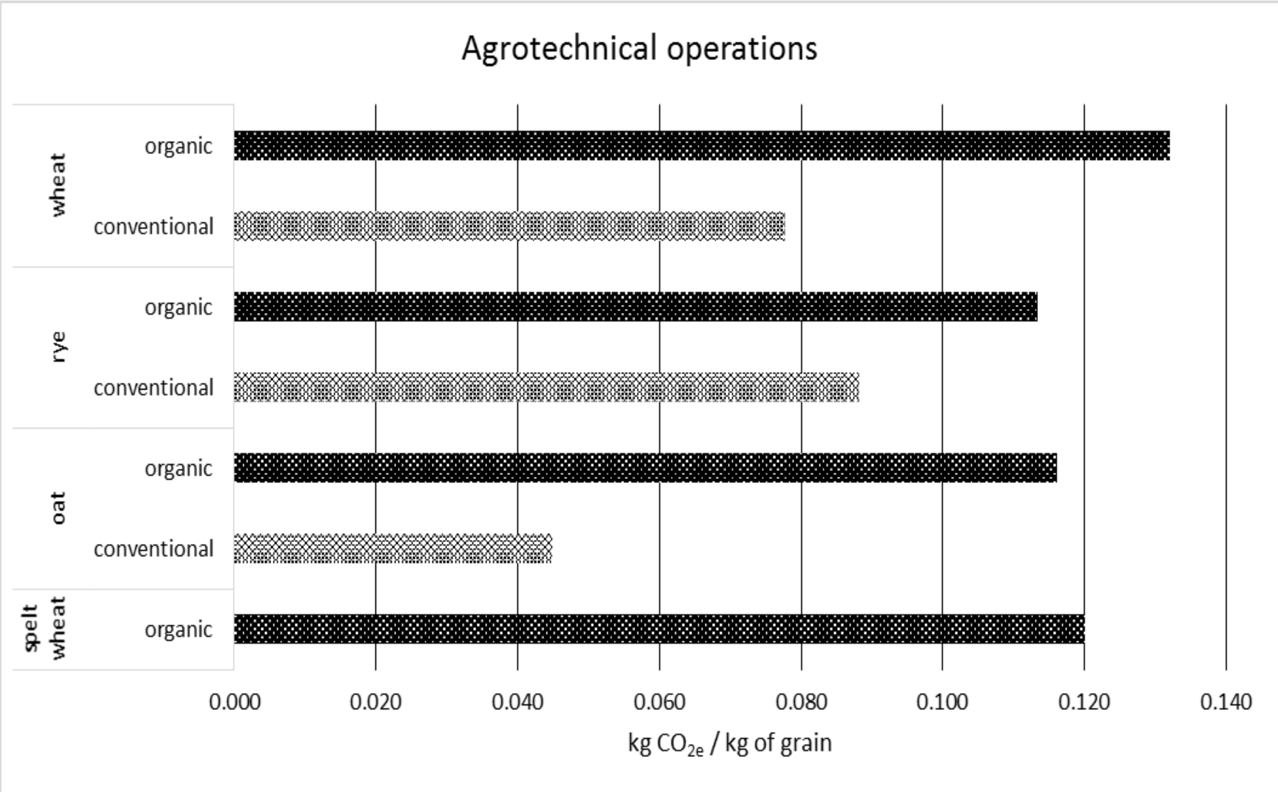

Fig. 2. GHG emissions from the basic category "agrotechnical operations"

The yield of individual crops is essential for the conversion of the emission load per unit of production. Table 1 summarizes the yield parameters of the monitored cereals in the conventional and organic farming system; the values were calculated from the yield data over the five-year period, and the average yield was used to calculate the emission load. Out of the 25 monitored conventional farms, 25 of them cultivated wheat, 19 rye, and 14 oat; out of 25 monitored organic farms, 25 of them cultivated wheat, 17 rye, 16 oat and 12 spelt wheat.

The results show that there are considerable differences between conventional and organic farming systems in individual subcategories of the farm phase of the cereals production. The production of emissions in a farming cycle is divided into the basic groups: agrotechnical operations, fertilizers, pesticides, seeds, and field emissions, and the load in those basic groups differs depending on the cultivated crop and the selected farming system.

In organic farming, a higher emission load is produced within the scope of agrotechnical operations, which is due to a higher need of mechanical operations during vegetation and a lower production effectiveness, in particular. Within the framework of the group of agrotechnical operations, the evaluated operations included stubble plowing, plowing, application of synthetic fertilizers (several times during the agricultural cycle), application of farm fertilizers, preseeding preparation and sowing, application of growth regulators, harrowing, treatment against weeds, diseases and pests, treatment against lodging, and harvesting. The conversion to the production unit, i.e. quantification of the emission load e.g. per kg of grain, in combination with the lower yields of organic farming cause that in this basic group the GHG emissions are lower for conventionally grown cereals than for those grown in organic farming systems (Fig. 2). Where the conversion involves GHG emissions produced per area unit (ha), the differences between the farming systems are considerably lower for individual cereals; as for rye, the load from the basic category "agrotechnical operations" is higher for a conventional farming system (Fig. 6).

In organic farming, the emission load from agrotechnical operations amounts to 0.132 kg CO_{2e} / kg of grain for wheat, 0.113 kg CO_{2e} / kg of grain for rye, 0.116 kg CO_{2e} / kg of grain for oat and 0.120 kg CO_{2e} / kg of grain for spelt wheat, while in conventional farming, the emission load amounts to 0.078 kg CO_{2e} / kg of grain for wheat, 0.088 kg CO_{2e} / kg of grain for rye and 0.045 kg CO_{2e} / kg of grain for oat.

A number of authors, such as Berner et al. (2008), Dorninger and Freyer (2008), Chen et al. (2013), Lal (2004b), and Teasdale et al. (2007), state changes of agrotechnical procedures as one of the ways how to reduce GHG emissions. The proposed measures are minimization, omission of plowing, limitation of the number of crossings by merging operations, but also deep application of fertilizers, incorporation of plant residues or changes in irrigation for some crops.

Another important basic group is field emissions. This fact is also confirmed by Mori et al. (2005), Tokuda and Hayatsu (2004) and Zou et al. (2005) who claim that a growing use of chemical fertilizers and manure is usually accompanied by a growing share of N_2O released from the soil. Determination of field emissions is difficult because field emissions are very varied, depending on a large number of variables, such as soil properties, climatic conditions, land management methods, etc. (Brentrup et al., 2000; Brentrup, 2003). Differences between individual farming systems are apparent even in this group, and the differences after the conversion to a production unit are due to the different yields in individual farming systems as well as due to the different fertilization and subsequent soil processes. Fig. 3 clearly shows that in this basic group, GHG emissions are higher for wheat grown in an organic farming system (0.187 kg CO_{2e} / kg of grain) than for wheat grown in a conventional system (0.137 kg CO_{2e} / kg of grain). Contrarily, the field emissions from the growing of oat and rye in an organic farming system (0.123 kg CO_{2e} / kg of grain for oat, 0.116 kg CO_{2e} / kg of grain for rye) are lower than when grown in a conventional system (0.127 kg CO_{2e} / kg of grain for oat, 0.175 kg CO_{2e} / kg of grain for rye). As for spelt wheat grown in an organic farming system, this value amounts to 0.170 kg CO_{2e}/kg of grain.

Fertilization is regarded as the most significant basic group, which also accounts for the greatest difference in GHG emissions between conventional and organic farming systems, which is consistent also with the finding by Cambria et al. (2016). According to Fott et al. (2003), agricultural emissions are mostly released from the applied fertilizers and pesticides, which is also in line with the findings of Biswas et al. (2008). In organic farming, the main cause of the reduction of emissions in the basic group “fertilizers” is the elimination of synthetic fertilizers. The production and transport of such fertilizers consume a large amount of energy, thus creating a considerable environmental load (Cormack and Metcalfe, 2000; Williams et al., 2006).

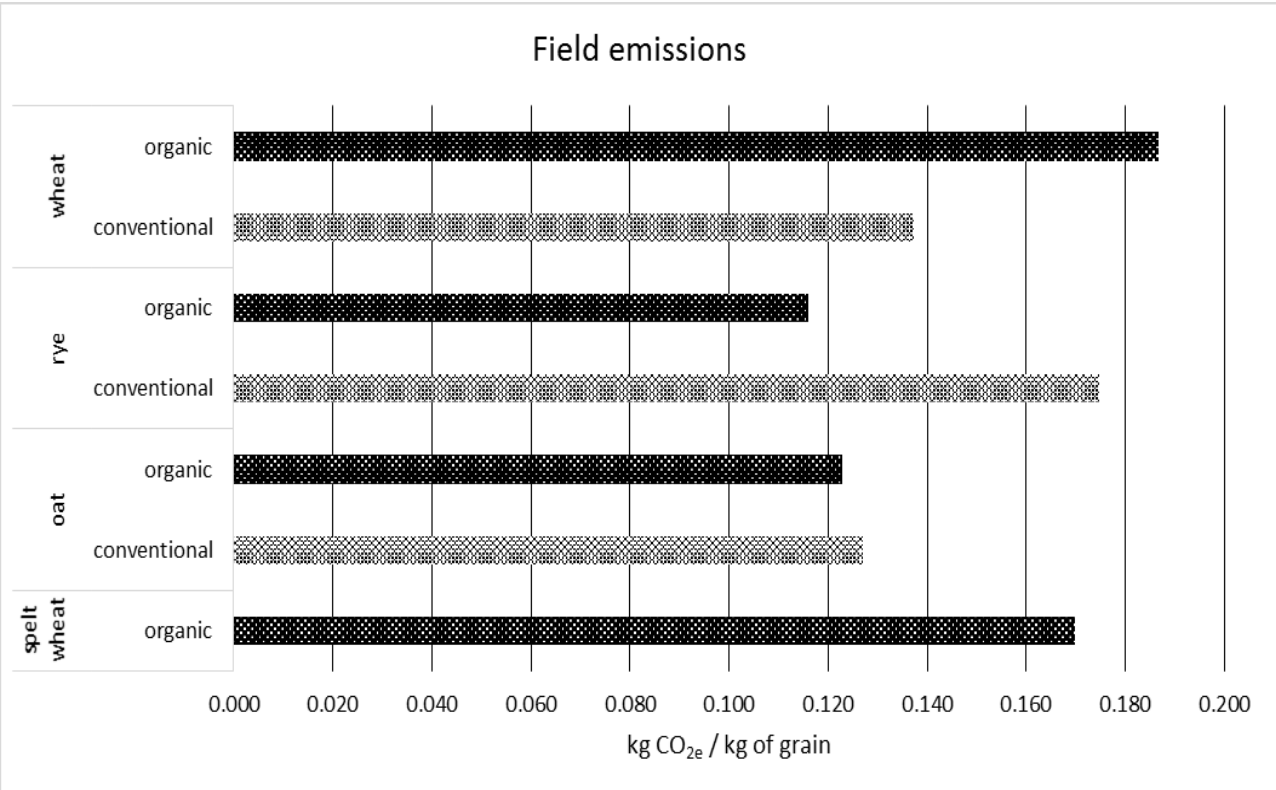

Fig. 3. GHG emissions from the basic category “field emissions”

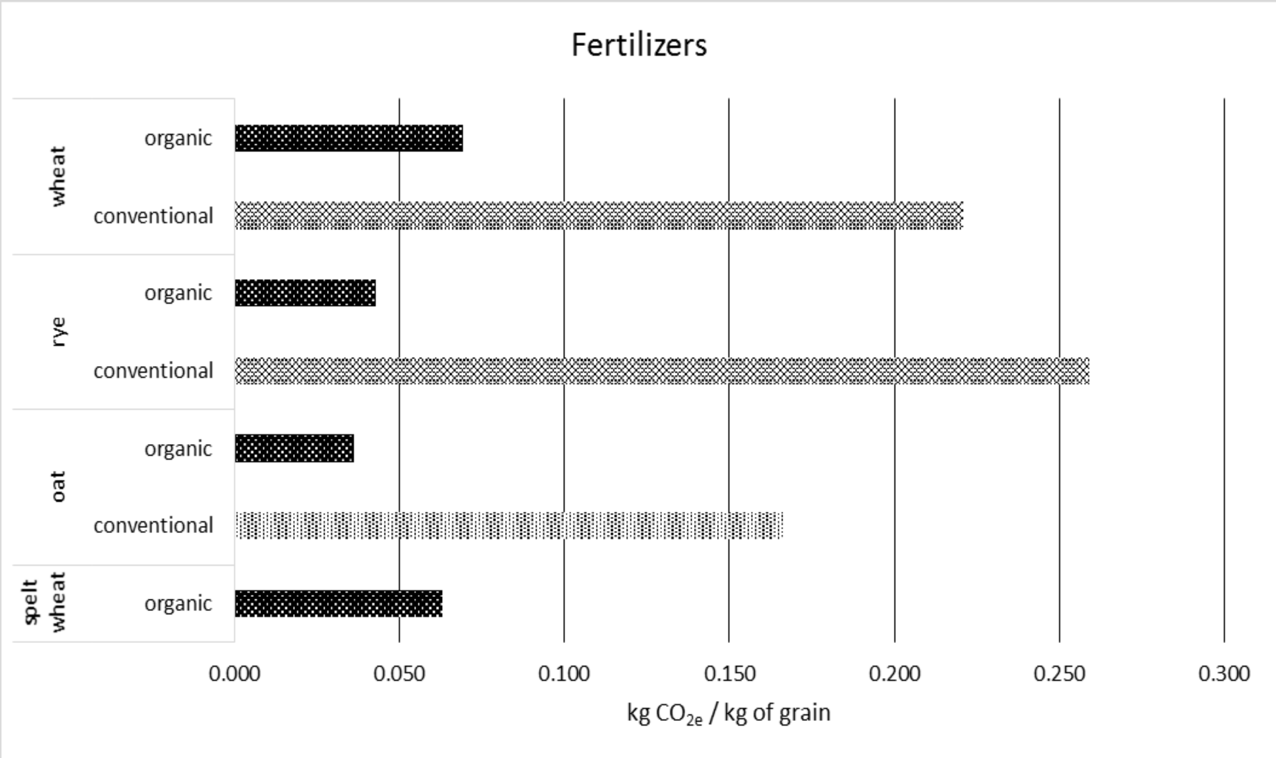

Fig. 4. GHG emissions in the basic category "fertilizers"

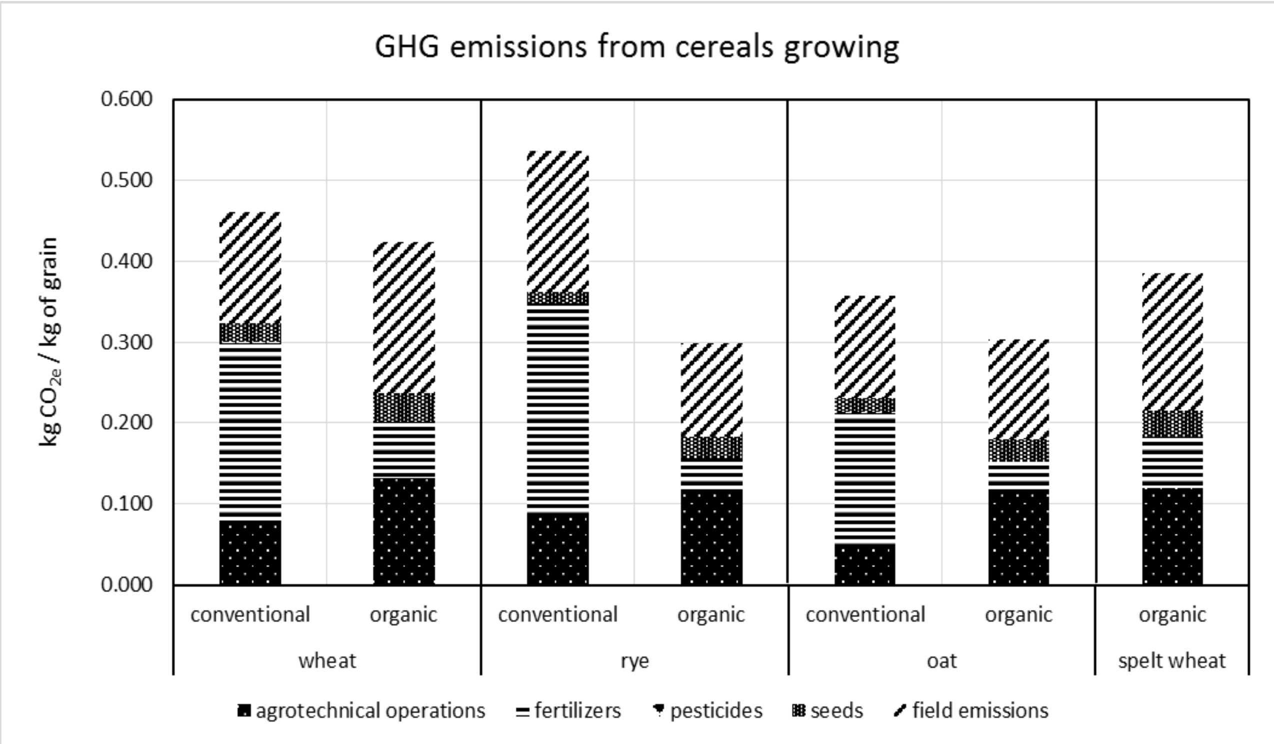

Fig. 5. GHG emissions from cereals growing – conversion to a production unit

Kindred et al. (2008) report that 11 kg CO_{2e} per kilogram of *N* are produced during the production, packing and transport of synthetic nitrogen fertilizers. In 2007, the total GHG emissions from the production and application of nitrogen fertilizers from fossil fuels amounted to 750-1080 million tons of CO_2 equivalent (1-2 % of the total global GHG emissions), while 47 years earlier, in 1960, it was less than 100 million tons of CO_{2e} (Niggli et al., 2011). Changes in fertilization, i.e. a certain degree of extensification and a correct use of organic fertilizers, may result in reduction of CO_{2e} emissions, which is in line with the statements of) Johnson et al. (2007) and Smith et al. (2008). The need for more precise nitrogen management in organic farming systems is also indicated by Kramer et al. (2006).

A considerably lower emission load generated by organic farming in the basic group “fertilizers” is evident for all the monitored cereals (Fig. 4). The highest load is produced in conventional farming as a result of application of synthetic nitrogen fertilizers. These values are 0.221 kg CO_{2e} / kg of grain for wheat, 0.259 kg CO_{2e} / kg of grain for rye, and 0.167 kg CO_{2e} / kg of grain for oat. In organic farming systems, these values are considerably lower – the emissions from fertilizers amount to 0.069 kg CO_{2e} / kg of grain for wheat, 0.043 kg CO_{2e} / kg for rye, 0.036 kg CO_{2e} / kg of grain for oat, and 0.063 kg CO_{2e} / kg of grain for spelt.

In terms of greenhouse gas emissions, the emissions from the basic group “seeds” appear to be less significant, and the emissions from the basic group “pesticides” seem to be almost negligible. As for seeds, the GHG emissions are always higher in organic farming systems due to lower yields (0.035 kg CO_{2e} / kg of grain for wheat, 0.026 kg CO_{2e} / kg of grain for rye, 0.027 kg CO_{2e} / kg of grain for oat, 0.032 kg CO_{2e} / kg of grain for spelt wheat) as compared to conventional farming systems (0.023 kg CO_{2e} / kg of grain for wheat, 0.014 kg CO_{2e} / kg of grain for rye, 0.018 kg CO_{2e} / kg of grain for oat), and the values are even considerably lower for pesticides. Pesticides are not applied in organic farming systems; in conventional systems, the emission load from pesticides is around 0.001 kg CO_{2e} / kg of grain for wheat and rye, and 0.002 kg CO_{2e} / kg of grain for oat. The environmental impact of the use of pesticides consists especially in their toxicity (De Backer et al., 2009).

As evident from Fig. 5, there are also significant differences between individual cereal species; when comparing particular species in various farming systems, the total emission load is always higher in conventional farming, even when converted to a production unit. These values amount to 0.460 kg CO_{2e} / kg of grain for wheat, 0.537 kg CO_{2e} / kg of grain for rye and 0.358 kg CO_{2e} / kg of grain for oat. In organic farming, these values amount to 0.423 kg CO_{2e} / kg of grain for wheat, 0.298 kg CO_{2e} / kg of grain for rye, 0.303 kg CO_{2e} / kg of grain for oat and 0.385 kg CO_{2e} / kg of grain for spelt wheat.

A disadvantage of organic farming is a lower production per area unit, which increases the emission load per production unit. For example, in Europe, the average yields of wheat in organic farming amount to 80 % of the conventional production (Lackner, 2008). Differences in yields in conventional and organic farming are also expressed by Mondelaers et al. (2009) who state that the average yields of organic farms are 17 % lower than those of conventional farms. On the other hand, Pimentel et al. (2005) claim that organic farming systems may achieve yields comparable with those of conventional systems for some high-production plants, such as maize. Increasing the yields in organic farming while maintaining its environmental friendliness may further increase its efficiency as a tool for reducing greenhouse gas emissions in agriculture.

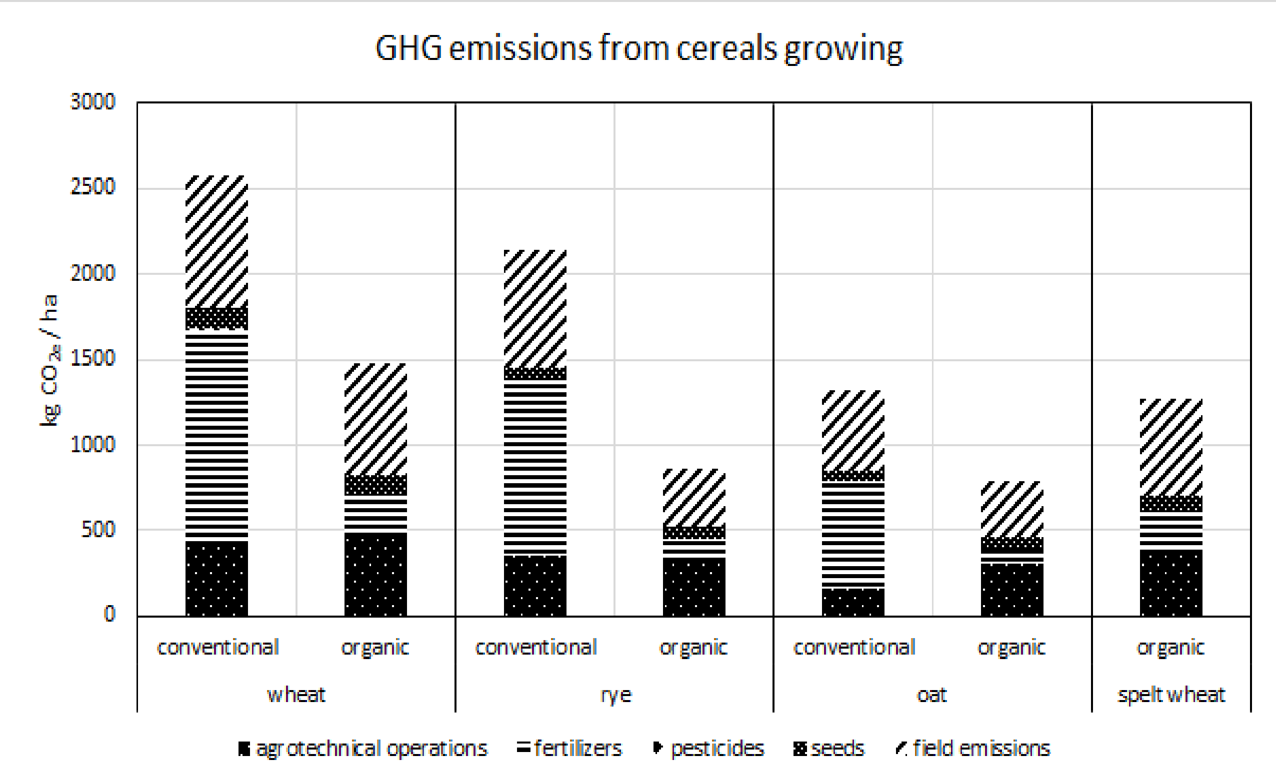

Fig. 6. GHG emissions from cereals growing – conversion to an area unit

Nemecek et al. (2005) argue that the environmental savings per area unit in organic farming are approximately double the savings calculated per production unit, which is due to the differences in yields. Knudsen (2010) also state that due to the lower yields in organic farming, the calculations of the production of greenhouse gas emissions per production unit show an increased environmental load in relation to conventional farming, so the resulting difference is lower than when converted to a unit of area.

This is in line with the findings of Mondelaers et al. (2009) who claim that due to the lower yields of organic farming, particularly in less developed countries, the environmental effect consisting in a reduction of greenhouse gas emissions is lower when converted to a production unit instead of an area unit, and in extreme cases it may even be negative. However, in both types of calculation the production of greenhouse gases remains lower in organic farming for many crops (Moudrý et al., 2013).

Considerable differences in GHG emissions after the conversion to an area unit are also well visible from Fig. 6. Given the average yields 5.6 t/ha for wheat, 3.7 t/ha for oat and 4.0 t/ha for rye, a conventional farming system produces 2577 kg CO_{2e} / ha for wheat, 2147 kg CO_{2e} / ha for rye and 1325 kg CO_{2e} / ha for oat. Similar figures (2330 kg CO_{2e} / ha for wheat, 2270 kg CO_{2e} / ha for rye and 1800 kg CO_{2e} / ha for oat) are also given by Rajaniemi et al. (2011). Given the average yields 3.5 t/ha for wheat, 2.6 t/ha for oat, 2.9 t/ha for rye and 3.3 t/ha for spelt wheat, an organic farming system produces 1482 kg CO_{2e} / ha for wheat, 865 kg CO_{2e} / ha for rye, 787 kg CO_{2e} / ha for oat and 1271 kg CO_{2e} / ha for spelt wheat.

So the evaluation of the emission load from the growing of cereals in conventional and organic farming systems in the conditions of Central Europe confirms the findings of Dorninger and Freyer (2008) who state that GHG emissions may be reduced by a correct choice of the farming system.

4. Conclusions

In crop production, a certain scope for reducing greenhouse gas emissions is also available in the growing of cereals, which are the most widely grown group of crops in many countries. The results show that the total emission load produced in organic farming systems is lower both when converted to an area unit and when converted to a production unit. Some savings may be achieved particularly by changes in the use of nitrogen fertilizers and partially by changes in agrotechnical measures.

In terms of agrotechnical operations, GHG emissions can be reduced in both conventional and organic farming, e.g. by omitting plowing and replacing it with shallow soil cultivation, another possibility is the use of tractors with lower performance and consumption, for example, during harrowing, or generally when working with lighter tools. Savings can also be achieved by lowering the number of crossings by performance of multiple agrotechnical operations at the same time.

Yields are a key factor in organic farming. Their increase can be achieved by intensification of organic farming, with higher yields being supported, for example, by precise selection of varieties in view of their suitability for specific habitat conditions, nutrient requirements and resistance to weeds, diseases and pests, and also by observing suitable sowing dates, optimal sowing and plant placement or more precise plant nutrition.

In conventional farming, as a further measure, it is recommended to restrict plant production without any link to animal husbandry, to extend sowing practices, in particular by incorporating leguminous plants, including perennial plants (alfalfa, clover), or by cultivating varieties for better use of nutrients. Reducing the need for synthetic fertilizers, especially nitrogen fertilizers, leads to a significant reduction of the emission load. Based on the results, it can be stated that a change in the farming system may help reduce the emission load in agriculture.

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Influence of farming systems on production of greenhouse gas emissions within cultivation of selected crops

Jan Moudrý Jr.*, Zuzana Jelínková, Jan Moudrý, Bernas Jaroslav, Kopecký Marek and Konvalina Petr
*Department of Applied Biotechnology, Faculty of Agriculture, University of South Bohemia in České Budějovice, Studentská 13, 370 05 České Budějovice, Czech Republic. *e-mail: jmoudry@zf.jcu.cz*

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Abstract
The study presents a comparison of an effect of greenhouse gas emission load on the environment caused within the production of crops (rye, wheat, potato, carrot, cabbage, onion and tomato) under conventional and organic farming system in the Czech Republic. For evaluation, the simplified LCA analysis focused on evaluation of greenhouse gas emission load, expressed in carbon dioxide equivalents, was used. Outputs were converted into 1 kg of agricultural production. Within the evaluation of agricultural phase, total emissions from the cultivation of crops and emissions from particular parts of agricultural phase (agricultural engineering, fertilizers, pesticides, seeds and seedlings, field emission) were surveyed. The results show that except for onion growing, there is a reduction of emissions for all studied crops.

Key words: Life cycle assessment, crop production, greenhouse gas emissions, organic farming, conventional farming.

Introduction
Greenhouse gases (hereinafter referred to as GHG) contributing to climate changes have still been much-discussed topic. In addition to natural emissions, the production of anthropogenic emission is also not negligible, i.e. emissions produced within a human activity, mainly due to energy industry as well as agriculture. Just the mentioned agriculture, as an activity with the largest area impact [24] contributes to the worldwide emission production with the share of 10-12% [9] while until 2030, we can expect an increase of even half of these values [21]. Within particular European countries, the emission share of agriculture of total GHG production was 9.1% in Austria [1], 7.7% in Germany [23] and 6.42% in the Czech Republic [15].

To a large extent, the amount of emission from agriculture is influenced also by farming systems. Conventional farming systems use more inputs in the form of fertilizers, organic and mineral fertilizers are key factors in regulation of N_2O and NO emissions from soil [17]. Just N_2O can be considered as the main greenhouse gas [26]. Cormack and Metcalfe [4] as well as Williams *et al.*[27] state that organic farming systems limit just these inputs which is consistent with the statement of Küstermann and Hülsbergen [14] that organic farming systems generally produced less emissions of N_2O and CO_2 due to lower inputs, while a similar conclusion had been previously reached also by Haas *et al.* [11] as well as Bos *et al.* [3]. The possibility how to evaluate the impact of growing of particular crops in different farming systems on GHG emissions is the use of the LCA analysis [13]. The LCA analysis based on inputs and outputs in production system evaluates their environmental impact [10], while also evaluation of GHG emissions is included. In agriculture, the LCA analysis allows an evaluation of inputs and outputs within the pre-farm, farm and post-farm phase [2]. In the contribution, the simplified LCA analysis was used for an evaluation of GHG emissions resulting from growing of particular crops within conventional and organic farming systems under conditions of central Europe.

Materials and Methods
Within the selected group of crops, GHG emissions from conventional and organic farming systems under conditions of central Europe were compared. Wheat, rye, potato, onion, carrot, tomato and cabbage were included into the group of model crops. The whole process of life cycle assessment was processed in accordance with standards ISO 140 [5, 6]. The aim of this study was to compare environmental effect of organic or conventional crop production. Therefore, results of the study are primarily intended as environmental information for consumers within qualified food selection. As a functional unit, one kg of production was chosen and results were related only to the impact category of climate change expressed by the indicator of carbon dioxide equivalent (CO_2e). Authors are aware of this limitation of the study and it has been taken into account in the interpretation of results. Life cycle modelling included all farm operations, such as agricultural engineering, use of fertilizers and pesticides. This input data was assessed on the basis of questionnaire survey. The farm phase included also emissions from application of nitrogen fertilizers which were calculated using the IPCC methodology [8]. For pre-farming operations, such as production of fertilizers, pesticides and fuel, the data from the Ecoinvent database was used.

For the study, the SIMA Pro software was used. The ReCiPe Midpoint (H) Europe methodology was used as a characterization model.

Results and Discussion

When comparing the production of GHG within cultivation of selected crops in conventional and organic farming systems, the total GHG emissions expressed as CO_2e were observed. This sum was divided into subgroups - agricultural engineering, fertilizers, pesticides, seeds and field emissions. The conventional farming system differs from the organic one in the total CO_2e emission production as well as in the production within subgroups (Fig. 1)

Although the production of GHG emissions differs within particular subgroups, in total with all studied crops except onion, the production of CO_2e is lower in the organic farming system, while main differences were found with rye, carrot and cabbage. Differences in emission load are affected by other factors, especially lower yield and specific agricultural rules of organic farming. This is in accordance with the finding of Williams *et al.* [4], who evaluated the emission load within tomato cultivation, or Wood *et al.* [28].

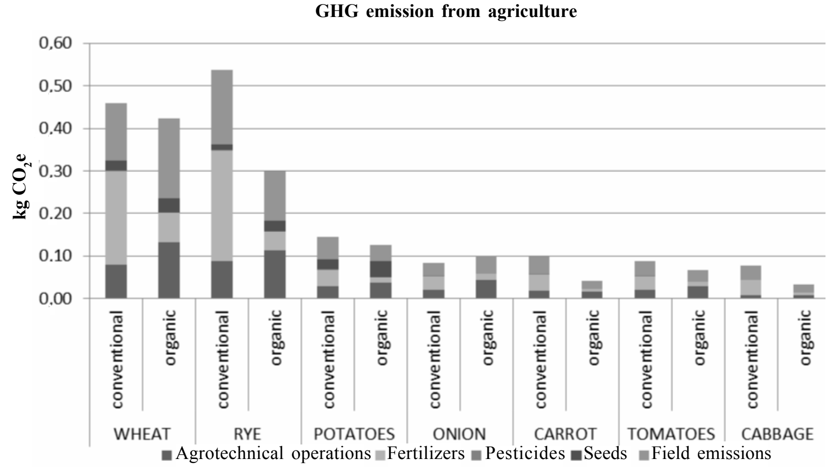

Figure 1. Total production of GHG emissions within growing of selected crops in conventional and organic farming system (in kg CO_2e per 1 kg of production).

To identify optimal GHG mitigation possibilities within cultivation of selected crops and to asses an impact of a farming system, it is necessary to assess particular sub-results within the comparison of emission load of conventional and organic products arising from agricultural operations, fertilizer use and emissions from soil processes. Fig. 2 shows the emission load resulting from agricultural operations within the field work.

Organic farming is more intensive in agricultural operations as compared to the conventional one. For most of the monitored crops except carrot and cabbage, emissions from production of one kg are higher due to more intensive agricultural technology (especially mechanical protection against pathogens), while the difference is even increased by generally lower yields in organic farming. As can be seen from Fig. 2, large differences are within wheat cultivation when CO_2e emissions produced within the organic farming systems (0.132 kg CO_2e/1kg of grains) are higher by 69.2% than emissions from the conventional system (0.078 kg CO_2e/1kg of grains). Also with cultivation of rye, there is a noticeable difference in GHG emission production, when the organic farming system (0.113 kg CO_2e/1kg of grains) produces by 28.4% more as compared with the conventional one (0.088 kg CO_2e/1kg of grains). From other investigated crops, there is a significant difference in GHG emission production with onion where the production within the organic farming system (0.042 kg CO_2e/1kg of onion) exceeds the conventional farming system (0.21 kg CO_2e/1kg of onion) by 50%, with tomatoes by 40% (organic farming 0.028 kg CO_2e/1kg of tomatoes, conventional farming 0.020 kg CO_2e/1kg of tomatoes) and with potatoes by 28.6% (organic farming 0.036 kg CO_2e/1kg of potatoes, conventional 0.028 kg CO_2e/1kg of potatoes). On the contrary with carrot cultivation, GHG emission production was lower by 5.9% within the organic farming system (0.016 kg CO_2e/1kg of carrot) as compared with the conventional one (0.017 kg CO_2e/1kg of carrot).

The fundamental difference between the conventional and organic farming system in terms of GHG emissions is obvious within fertilization. Emission load from usage of nitrogen, phosphorus and potassium fertilizers is presented in Fig. 3.

While organic farming uses organic fertilizers (especially manure or slurry), the use of synthetic fertilizers within the conventional farming system increases significantly the share of emissions. This is evident from Fig. 3 which shows that CO_2e emissions are significantly higher within the conventional farming system with all studied crops.

During fertilization of organically grown wheat, only 31.2% (0.069 kg CO_2e/1kg of grains) of the amount of CO_2e produced within fertilization of conventional wheat (0.221 kg CO_2e/1kg of grains) is released. With rye, it is even only 16.6% (organic farming 0.043 kg CO_2e/1kg of grains, conventional farming 0.259 kg CO_2e/1kg of grains). Very significant difference is within fertilization of carrot and cabbage when the values within the organic farming system are 17.9% (carrot), resp. 19.4% (cabbage) of values from the conventional system (organic farming 0.007 kg CO_2e/1kg of

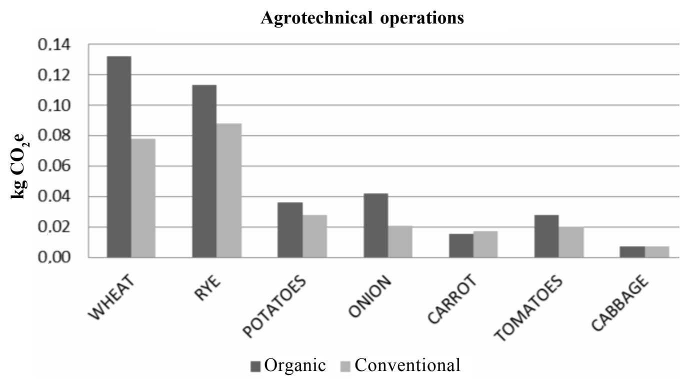

Figure 2. Production of GHG emissions from agricultural measures within growing of selected crops in conventional and organic farming system (in kg CO_2e per 1 kg of production).

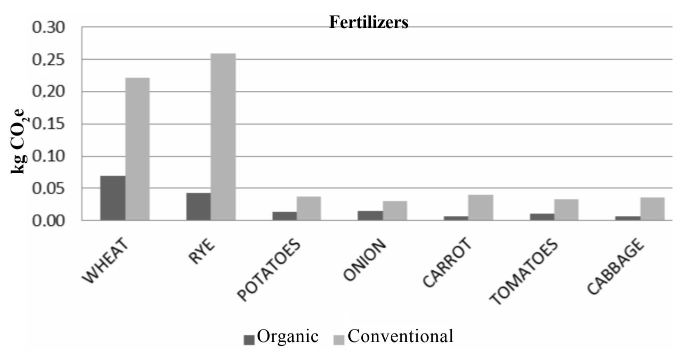

Figure 3. Production of GHG emissions within fertilization of selected crops in conventional and organic farming system (in kg CO_2e per 1 kg of production).

carrot, 0.007 kg CO_2e/1kg of cabbage, conventional farming 0.039 kg CO_2e/1kg of carrot, 0.036 kg CO_2e/1kg of cabbage). Significant differences were found within fertilization of tomato, potato and onion. Within organic farming, emissions from fertilization make up 30.3% with tomato, 37.8% with potato and 53.3% with onion as compared with values from the conventional farming system. Within the organic farming system, there is produced 0.010 kg CO_2e/1kg of tomato, 0.014 kg CO_2e/1kg of potato and 0.016 kg CO_2e/1kg of onion and within the conventional one, it is 0.033 kg CO_2e/1kg of tomato, 0.037 kg CO_2e/1kg of potato and 0.030 kg CO_2e/1kg of onion. Just changes in fertilization, i.e. certain degree of extensification and a proper use of organic fertilizers, may lead to CO_2e emission reduction which is consistent with the statement of Smith *et al.* [22] and Johnson *et al.*[12], that the proper N management can reduce N_2O emissions, while similar conclusions were drawn by Dalal *et al.* [7], Paustian *et al.* [20], Robertson and Grace [19] and Monteny *et al.* [16].

Within conventional farming, GHG emissions increased also by the use of pesticides, however, with a relatively low share of total emissions (Table 1). Still, Paustian *et al.* [20] can see here another opportunity to save emissions. Higher emissions are released within production of seed and seedlings of cereals and potato, where a higher emission intensity of organic farming is obvious. It is due to a lower yield. Lower CO_2e emissions were found with tomato, onion, carrot and cabbage, where the differences between the conventional farming system and the organic one are not apparent as in Table 1. Differences between crops are determined by the weight of seeds and seedlings.

Quite a significant share of GHG from crops cultivation is released in the form of field emissions (nitrous dioxide released after nitrogen fertilizers application). In addition, Mori *et al.* [18], Tokuda and Hayatsu [25] and Zou *et al.* [29] stated that with the increasing use of chemical fertilizers and manure, a share of N_2O emitted from soil also usually increases. Within field emissions, we cannot see a clear difference between the conventional and organic farming system, depending on the yield and amount and form of nitrogen fertilizers, the observed data of particular crops varies. This fact is shown in Fig. 4.

Table 1. GHG emissions produced within pesticides use and seed and seedlings of selected crops production in conventional and organic farming system (in kg CO_2e per 1 kg of production).

	Pesticides		Seed and seedlings	
	Organic farming	Conventional farming	Organic farming	Conventional farming
Wheat	0	0.0010	0.03500	0.02300
Rye	0	0.0010	0.02580	0.01360
Potatoes	0	0.0028	0.03790	0.02420
Onion	0	0.0023	0.00023	0.00015
Carrot	0	0.0013	0.00009	0.00006
Tomatoes	0	0.0018	0.00001	0.00009
Cabbage	0	0.0002	0.00024	0.00023

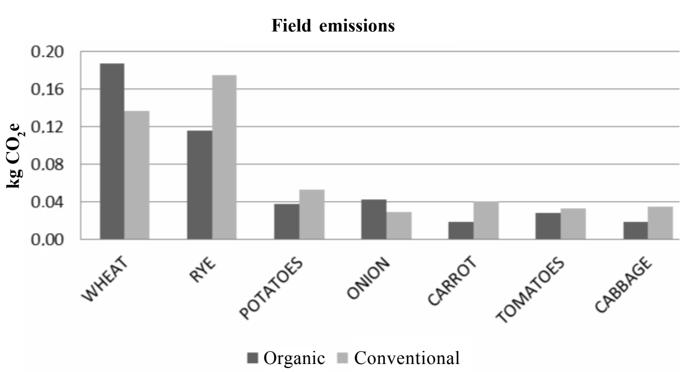

Figure 4. Production of field GHG emissions within growing of selected crops in conventional and organic farming system (in kg CO_2e per 1 kg of production).

With wheat, higher GHG emissions (0.187 kg CO2e/1kg) are detected within organic farming as compared with the conventional farming system (0.137 kg CO2e/1kg), it is opposite with rye, i.e. 0.116 kg CO_2e/1kg within the organic farming system and 0.175 kg CO_2e/1kg within the conventional one. As for other monitored crops, values within the organic farming system are higher only with onion (0.042 kg CO_2e/1kg within organic and 0.029 kg CO_2e/1kg within conventional farming). With the other crops, the trend is opposite, i.e. a lower emission load is produced within organic farming with potato (0.037 CO_2e/1kg within organic and 0.053 kg CO_2e/1kg within conventional farming), carrot (0.019 CO_2e/1kg within organic and 0.041 kg CO_2e/1kg within conventional farming), tomato (0.028 CO_2e/1kg within organic and 0.033 kg CO_2e/1kg within conventional farming) and cabbage (0.19 CO_2e/1kg within organic and 0.034 kg CO_2e/1kg within conventional farming).

Conclusions

GHG emissions within cultivation of particular crops vary depending on many factors, while the most CO_2e is released within fertilization and field emissions and also a share of agricultural operation is not negligible. With all surveyed crops except onion, where 0.083 CO_2e/kg of onion in conventional and 0.100 kg CO_2e/kg of onion in organic farming is produced, higher CO_2e emissions were found within the conventional farming system. Within cultivation of wheat, 0.460 kg CO_2e/kg of grains within conventional and 0.423 kg CO_2e/kg of grains within organic farming is released. With rye, it is 0.537 kg CO_2e/kg of grains within conventional and 0.298 kg CO_2e/kg of grains within organic farming, with potato 0.145 kg CO_2e/kg of potato within conventional and 0.125 kg CO_2e/kg of potato within organic farming, with carrot 0.099 kg CO_2e/kg of carrot within conventional and 0.041 kg CO_2e/kg of carrot within organic farming, with tomato 0.087 kg CO_2e/kg of tomato within conventional and 0.067 kg CO_2e/kg of tomato within organic farming and with cabbage 0.078 kg CO_2e/kg of cabbage within conventional and 0.033 kg CO_2e/kg of cabbage within organic farming. It is obvious, that the organic farming system is, in terms of emission, less demanding and therefore more environmentally friendly than conventional farming, where emission production is increased especially by the use of synthetic fertilizers.

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Research Article Open Access

Zuzana Jelínková, Jan Moudrý jr.*, Jaroslav Bernas, Marek Kopecký, Jan Moudrý, Petr Konvalina

Environmental and economic aspects of *Triticum aestivum L.* and *Avena sativa* growing

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Abstract: This paper deals with the assessment of cultivation of bread wheat (*Triticum aestivum* L.) and oat (*Avena sativa*) grown in Central Europe within the conventional and organic farming systems in terms of greenhouse gas emissions and economic profitability. Organic farming may be one of the tools for mitigation of greenhouse gas emissions from agricultural production. In the context of crop production, cereals rank among the most commonly grown crops and therefore bread wheat and oat were chosen. The Climate change impact category was assessed within the simplified LCA method and the production of greenhouse gas emissions expressed in CO_2e per the production unit was calculated. Economic balance of the cultivation of monitored cereals was compiled based on the yields, farm gate prices and costs. On its basis, the cultivation of wheat within the organic farming system appears to be the most profitable. From an environmental point of view, the emission load of the organic farming system is reduced by 8.04 % within the wheat production and by 15.46 % within the oat cultivation. Therefore, the organic farming system in the Czech Republic appears to be more environmentally friendly and economically efficient within the cereals production.

Keywords: Greenhouse gases emissions, LCA, wheat, oat, yields, economic profitability

***Corresponding author: Jan Moudrý jr.,** University of South Bohemia in České Budějovice, Faculty of Agriculture, Department of Agroekosystems, Studentská 166, České Budějovice, 370 05, Czech Republic, E-mail: jmoudry@zf.jcu.cz
Zuzana Jelínková, Jaroslav Bernas, Marek Kopecký, Jan Moudrý, Petr Konvalina, University of South Bohemia in České Budějovice, Faculty of Agriculture, Department of Agroekosystems, Studentská 166, České Budějovice, 370 05, Czech Republic

1 Introduction

The production of greenhouse gas emissions is still a frequently discussed issue. Berner & Berner [1] assumes that human activities also contribute to climate change. Svendsen [2] states that, within the European Union, the largest polluters are energetics, which release 27.8% of anthropogenic greenhouse gas emissions, transportation with 19.5% and industry with 12.7%. Agriculture is in fourth place with 9.2%. This share varies depending on the country, e.g. 9.5 % in Austria [3], 7.7 % in Germany [4], 15.8 % in Denmark [5] and 6.4 % in the Czech Republic [6]. One of the tools for reducing greenhouse gas (hereinafter referred to as GHG) emissions may be the change of a farming system. Organic farming usually produces lower GHG emissions due to its extensivity. The Farming Systems Trial at Rodale Institute, an American long-term research project comparing organic and conventional agriculture, states that the introduction of nationwide organic farming in the USA would reduce CO_2 emissions by up to one quarter due to increased carbon sequestration in soils [7].

It is necessary to understand the impacts of agriculture and be able to quantify them in order to efficiently implement measures to reduce GHG emissions. As stated by Lal [8], the system sustainability can be evaluated on the basis of inputs and outputs and their conversion to CO_2e. One of the most appropriate tools for this assessment is the LCA method (Life Cycle Assessment) [9-11]. According to Kočí [12], the LCA method assesses the environmental impact of a product based on the assessment of the material and energy flow, which the monitored system shares with its surrounding environment.

However, when applying an environmentally friendly farming practice, it is still necessary to maintain the ability to ensure food sovereignty and economic profitability of farming. The question of profitability is considered the major decision criterion by farmers. Lower yields are offset by higher farm gate prices within the organic farming system. This also applies to cereal production. The cultivation of which, in organic management, may be considered profitable and environmental savings are another added value.

2 Methods

Environmental impacts of wheat and oat cultivation were evaluated in terms of GHG production. GHG emissions were expressed in CO_{2e} when CO_{2e} = 1x CO_2 + 23x CH_4 + 298x N_2O. The SIMA Pro software and the Ecoinvent database were used to calculate CO_{2e} emissions. The life cycle of chosen crops were modelled in accordance with the standards ČSN EN ISO 14040 and ČSN EN ISO 14044. The impact category "Climate change" was assessed within the simplified LCA method. The method focused on the agricultural phase of oat and wheat cultivation in the conventional and organic farming systems. The inputs and outputs were referenced to the unit of one hectare and the resulting value was converted to a functional unit of 1 kg of oats. The outcome was the yield per hectare and the input included technology operations, amount of seeds, fertilizers and plant protection products. The calculation also takes field emissions into account. The input data coming from the Ecoinvent database were adjusted in accordance with the principles of farming in Central Europe. The most common agrotechnical practices were used for conventional and organic farming, and the chains of operations included in the calculation of GHG emissions in the agricultural phase of growing oats were determined according to the data obtained from a sample of 60 conventional and organic farms from the Czech Republic. Furthermore, yields and farm gate prices of wheat and oat during the period from 2007 to 2014 were found within the conventional and organic farming systems. The data acquired from the farms were adjusted in accordance with Standards of agricultural production technologies by Kavka [13,14]. The standards from 2006 were used when analyzing the period of 2007 - 2010, and standards from 2012 were used for the period of 2011 – 2014, to calculate the cost of oat and wheat cultivation. The "Standard" standard was used for the calculations. Additionally, all technological and variable costs, fixed costs and insurance against natural disasters were included into the calculations.

3 Results

The impact of the selection of a management system on the environment has not been sufficiently quantified so far for the conditions of the Czech Republic. In respect to air and climate changes, quantification of the load arisen in connection with various farming activities has been missing. Although the primary motivating factor for farmers has remained the economic efficiency, many organic farmers have also been giving increasing weight to the environmental impacts, so the quantification of the differences between a conventional and ecological system in the conditions of the Czech Republic is becoming more important for them.

In terms of the GHG emissions, there are significant differences between oat and wheat production within the conventional and organic farming systems. 0.078 kg CO_2e / kg of wheat using conventional farming practices and 0.132 kg CO_2e / kg of wheat using organic farming methods, and 0.045 kg CO_2e / kg of oats using the conventional system and 0.116 kg CO_2e / kg using the organic system is produced in the agrotechnical operation phase (table 1, figure 1, 2, 3). Higher GHG emissions produced in the agrotechnical phase of the organic farming system mainly arise from lower yields and greater need for agrotechnical inputs related with non-chemical plant protection. Fertilization is the major source of GHG emissions. When organic farming, 0.069 kg CO_2e / kg of wheat and 0.036 kg CO_2e / kg of oat was produced. Conversely, the values produced by conventional farming tend to be higher, h.e. 0,221 kg CO_2e / kg of wheat and 0,167 kg CO_2e / kg of oat. The difference is mainly caused by the application of synthetic fertilizers, especially nitrogen fertilizers used in conventional farming. Also, a modest increase in GHG emissions occurs after the application of pesticides when 0.002 kg CO_2e / kg of oat grains and 0.001 kg CO_2e / kg of wheat grains are produced. Pesticides are not used within the organic farming system. Therefore, the emission load of this phase is negligible but, from the environmental point of view, the problems rather result from pesticide

Table 1. Greenhouse gas emissions of wheat and oat production.

	Wheat		Oat	
	Conventional	**Organic**	**Conventional**	**Organic**
Agrotechnical operation	0.078	0.132	0.045	0.116
Fertilizers	0.221	0.069	0.167	0.036
Pesticides	0.001	0.000	0.002	0.000
Seeds	0.023	0.035	0.018	0.027
Field emissions	0.137	0.187	0.127	0.123

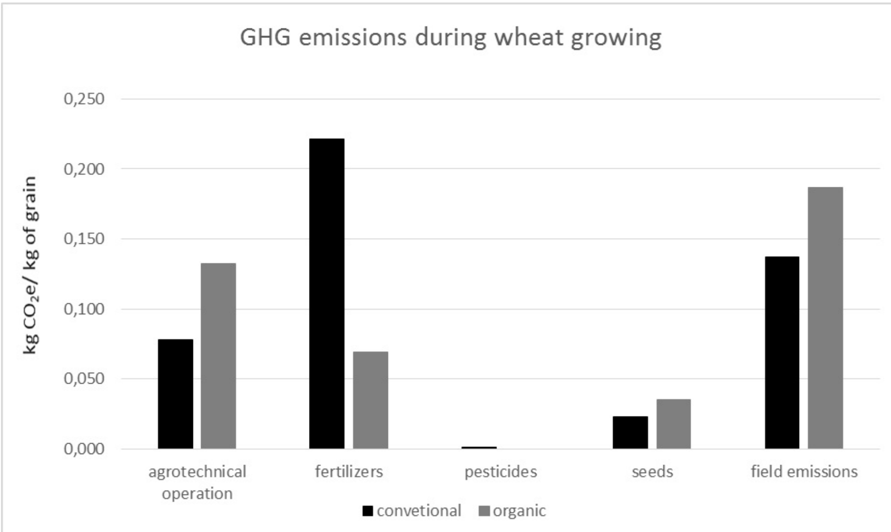

Figure 1. Greenhouse gas emissions during wheat production.

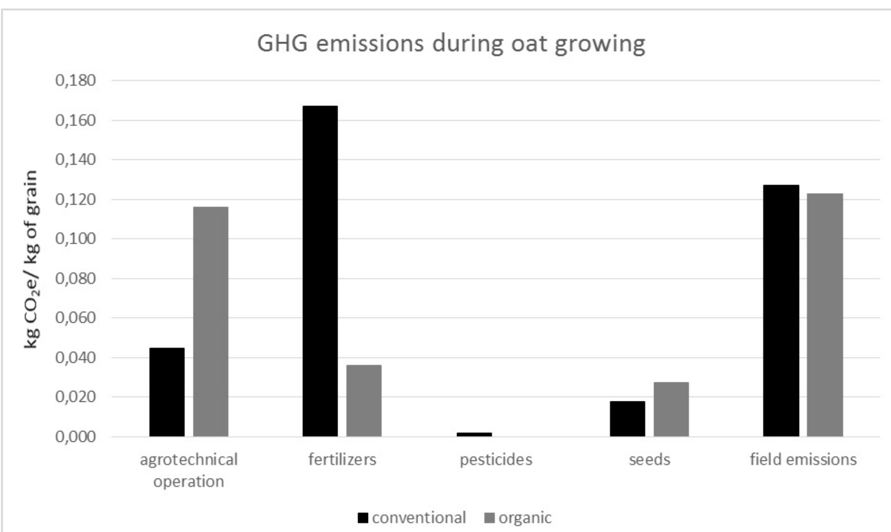

Figure 2. Greenhouse gas esemissions during oat production.

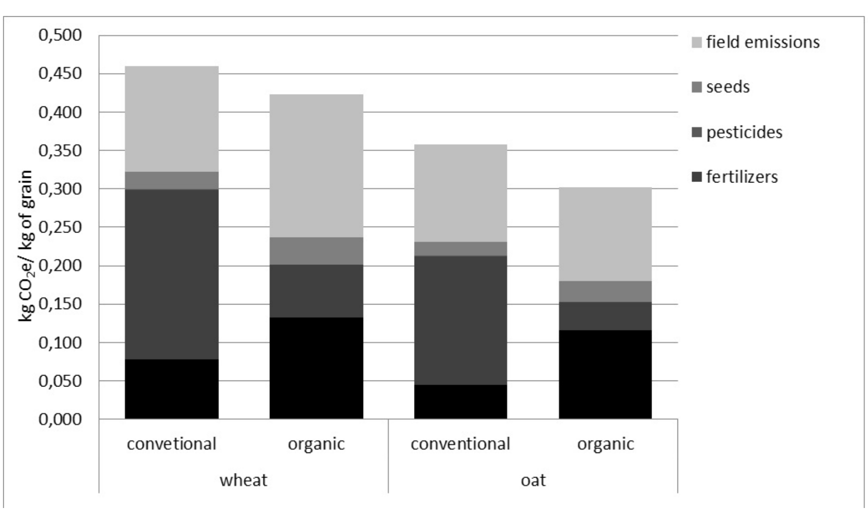

Figure 3. Greenhouse gas emissions during wheat and oat production.

residues, their impacts on biodiversity, etc. A relatively low emission load is produced in the seed phase when 0.023 kg CO_{2e} / kg of wheat grains and 0.018 kg CO_{2e} / kg of oat grains are produced using the conventional system whereas 0.035 kg CO_{2e} / kg of wheat grains and 0.027 kg CO_{2e} / kg of oat grains is produced using the organic system. A significant amount of GHG emissions are produced in the field phase. Some of the main factors are the difference in the yields and the amount and type of the fertilizers used in the conventional and organic farming systems. During cultivation of wheat, 0.137 kg CO_2e / kg of grains is stored using conventional methods compared to 0.187 kg CO_2e / kg of grains using organic methods. With oat, it was 0.127 kg CO_2e / kg of grains using conventional methods and 0.123 kg CO_2e / kg of grains using organic farming methods. Total emissions resulting from the conventional farming are higher in the production of wheat (0.460 kg CO_2e / kg of grains vs. 0.423 kg CO2e / kg of grains released within the organic system), as well as oat production (0.358 kg CO_2e / kg of grains vs. 0.303 kg CO_2e/ kg of grains produced within the organic system). Therefore, the emission load of the organic farming system is lower by 8.04 % within the wheat production and 15.46 % within the oat cultivation.

Many significant differences occur when comparing the economic aspects of cultivation of oat and wheat across farming systems. The resulting economic balance is heavily dependent on the hectare yield of grains. In the period of 2007 - 2014, the hectare yield of oat grains was 2638 kg / ha using organic farming methods and 3638 kg / ha using conventional farming methods. The hectare yield of wheat grains was 3325 kg / ha using organic farming methods and 6050 kg / ha using conventional farming methods. In the conventional system, the achieved hectare yield was higher by 28% for oats and 45% for wheat as compared with the organic system. As it is evident from Figures 4, 5, 6 and 7, the highest oat yield per hectare was 3800 kg / ha for conventional farming and 3200 kg / ha for organic farming. The highest wheat yield per hectare was 6800 kg / ha for conventional farming and 3700 kg / ha for organic farming. However, the lowest oat yield per hectare was 3100 kg / ha when using conventional farming methods and 2000 kg / ha when using the organic system, and the lowest wheat yield per hectare was 5000 kg / ha when using the conventional system and 2500 kg / ha when using the organic system.

Also, the farm gate prices of the raw materials (grain) are a significant parameter and highly variable. During the period considered, the average farm gate prices were: 5448 CZK (ca. 198 EUR) / t of grain for organic wheat, 4274 CZK (ca. 155 EUR) / t of grain for conventionally grown wheat, 4116 CZK (ca. 150 EUR) / t of grain for organic oat and 3231 CZK (ca. 118 EUR) / t of grain for conventionally grown oat. Farm gate prices for each year of the period is shown in Figure 4, 5, 6 and 7. The average farm gate prices of conventionally grown wheat and oat were both lower by 21.5% compared to the organic farming system.

The third important factor in the economic evaluation of growing crops is the total cost of production of 1 t of grain (CZK / t of production). When comparing the organic and conventional systems, the costs are generally higher within the organic farming system. The average cost was 7173 CZK (ca. 261 EUR) / t of grain with organic oat, 5920 CZK (ca. 215 EUR) / t with conventionally grown oat, 5661 CZK (ca. 206 EUR) / t with organic wheat and 4389 CZK (ca. 160 EUR) / t with conventionally grown wheat. Within the organic system, the total costs were higher by 17.5%

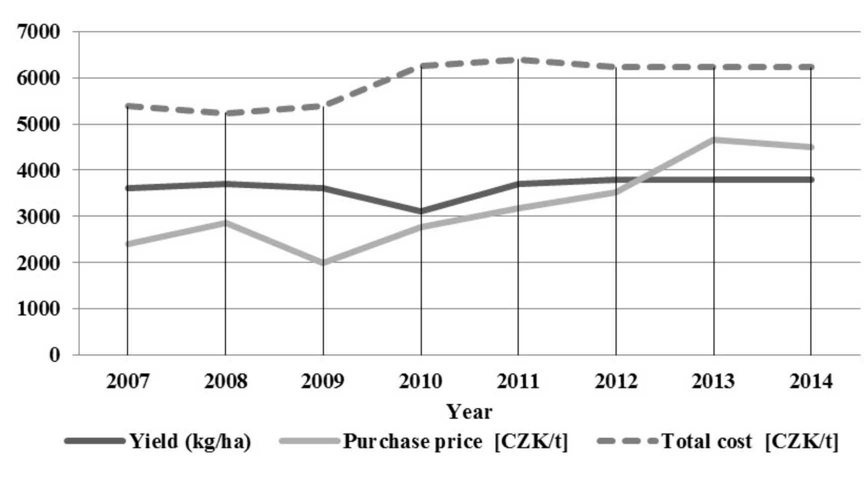

Figure 4. Yields, purchase prices and costs of oat production using conventional farming practices.

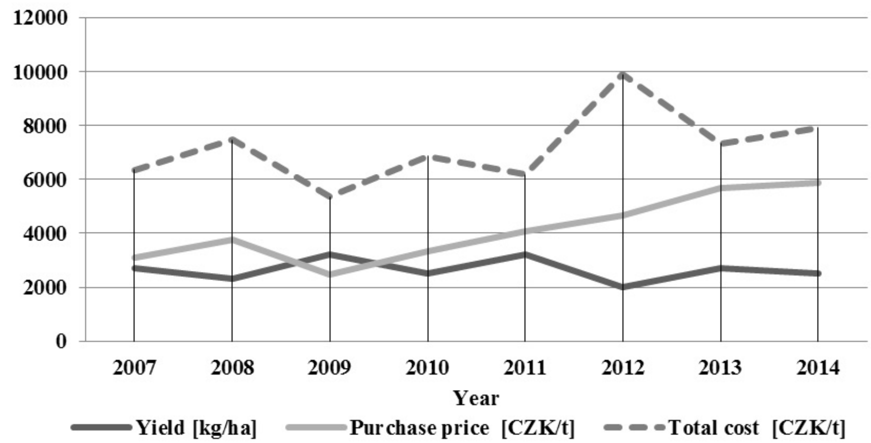

Figure 5. Yields, purchase prices and costs of oat production using organic farming methods.

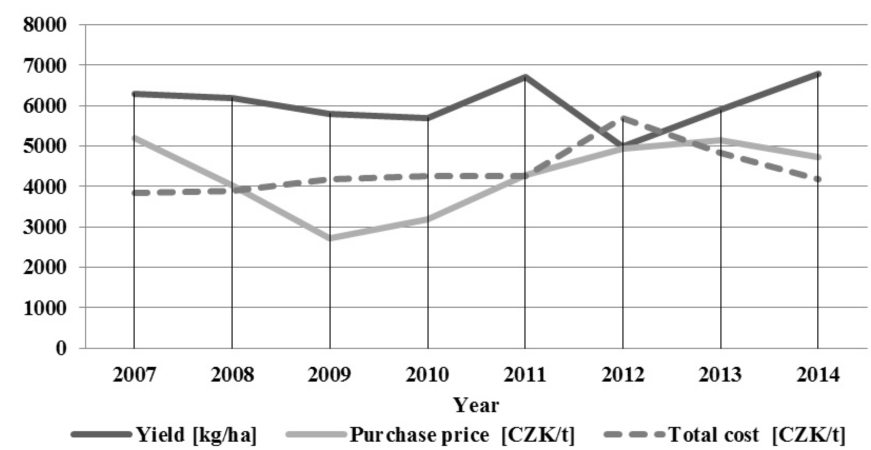

Figure 6. Yields, purchase prices and costs of oat production using conventional farming practices.

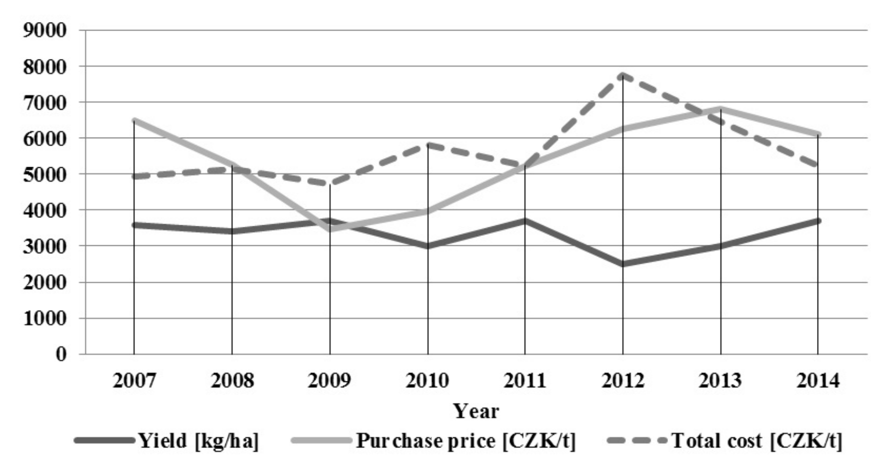

Figure 7. Yields, purchase prices and costs of wheat production using organic farming practices.

with oat and by 22.5% with wheat in comparison with the conventional system.

As Figures 4, 5, 6, and 7 show, the total cost of production of 1 t of oats and wheat exceed the farm gate price and hence the profitability is achieved after counting subsidies within both farming systems. Basic subsidies, i.e. the SAPS (Single Area Payments) for the conventional and organic farming, as well as the subsidies for organic farming (arable land) granted through the Rural Development Programme are included in Table no. 2. Adding the subsidies, growing wheat seems to be the most profitable in the organic farming system (profit 7,894.4 CZK (ca. 287 EUR) / ha), as well as in the conventional farming system (3832.5 CZK (ca. 139 EUR) / ha). Conversely, growing oats appears to be economically inefficient because the positive result is achieved only within the organic farming system (538.26 CZK (ca. 20 EUR) / ha) whereas it is unprofitable within the conventional farming system (-5254.33 CZK (ca. - 191 EUR) / ha). In practice, the results may be affected by other factors, e.g. gaining additional subsidies (e.g. the LFA - Subsidies for areas with natural or other specific constraints - which might be useful for growing at higher altitudes).

4 Discussion

Wheat, one of the most important food crops, and oats, a less demanding cereal typical for the organic farming, were chosen to assess the possibility of reducing GHG emissions in crop production. Gajdošová & Šturdík [15] also describe the importance of wheat and the worldwide increase in its cultivation. Zimolka [16] states that, in terms of sown area, wheat is the dominant crop in the Czech Republic. Oats, a 'low input' cereal typical for organic farming is also described by Šarapatka & Urban [17].

A choice of the farming system as a factor influencing GHG emissions is referred to by Barton et al. [18] who state that production of GHG emissions is influenced, in addition to other factors, by the production system and its regional specifics. Also, Küstermann and Hülsbergen [19] state that organic farming systems produce less N_2O and CO_2 emissions generally due to lower inputs. A similar conclusion had been previously reached by Haas et al. [20], as well as Bos et al. [21]. Daxbeck et al. [22] claim that the conventional farming system produces a higher emission load than the organic one. A lower emission load (by about 8.04 % for wheat and 15.46 % for oat) was calculated based on a production unit. Brandt & Svendsen [23] also describe a positive impact of organic farming and state that the difference between the organic and conventional farming is very significant if emission reductions are related to the area unit. The difference is partially reduced when calculated per a production unit. Nemecek et al. [24] comes to the same conclusion and states that environmental savings per unit area are roughly double when compared with the calculation per unit of production. The total emission load resulting from the cultivation of wheat (0.460 kg CO_2e / kg of grain in the conventional system and 0.423 kg CO_2e / kg of grain in the organic system) is lower than stated by e.g. Carlsson-Kanyama and Gonzalez [25] who reported 0.63 kg CO_2e / kg of grain using the conventional system. On the contrary, Dorninger and Freyer [26] describe lower values, 0.361 CO_2e / kg of wheat grain produced using the conventional system and 0.132 CO_2e / kg of grain produced using the organic system. Differences between results are mainly due to differences in yields.

In the cultivation of oat and wheat, the largest emission savings occur in the phase of fertilization in the organic system. Smith et al. [27] states that changes in fertilization, i.e. a certain degree of extensification and a proper use of organic fertilizers, may lead to CO_2e emission reductions, which is consistent with the statement of Johnson et al. [28] who also affirm that the proper N management can reduce N_2O emissions, while similar conclusions were reported by Dalal et al. [29], Robertson and Grace [30] and Monteny et al. [31]. In addition, Tokuda and Hayatsu [32], Mori et al. [33] and Zou et al. [34] state that with the increasing use of chemical fertilizers and manure, a share of N_2O emitted from soil also usually increases (i.e. field

Table 2. Profitability of wheat and oat production in organic and conventional farming.

Crop	Costs CZK/t	Yields (t/ha)	Purchase price (CZK/t)	Subsidies (CZK/ha)	Profitability (CZK/ha)
Wheat OF*	5661	3,325	5448	8602.6	7894.4
Wheat CF⁺	4389	6,050	4274	4528.3	3832.5
Oat OF	7173	2,638	4116	8602.6	538.3
Oat CF	5920	3,638	3231	4528.3	-5254.3

* OF = organic farming ⁺CF = conventional farming

emissions). The phase of field emission is, along with the phase of fertilization, one of the most significant sources of GHG emissions and therefore changes in fertilization and a proper use of organic fertilizers may be effective measures towards the mitigation of GHG emissions in crop production, while the transition from conventional to organic farming system is also beneficial.

In agricultural practice, farmers often place emphasis primarily on the economic efficiency of operations. It results from a combination of factors: income, costs and farm gate price. Seufert et al. [35] state that cereal yields from the organic farming system are typically lower than in the conventional one. This is in accordance with the lower yields, by 28% for oats and 45% for wheat, detected within the organic farming system in contrast to the conventional farming system. Šarapatka & Urban [17] state that the organic cereal yields reach about 1/2 values compared to the conventional farming in the Czech Republic. In Europe, the organic yields are on average 80% of conventional yields [36]. A difference in yields between the conventional and organic production is also described by De Backer et al. [37] and is evident from the example of leek production from conventional farming systems that reach 27% higher yields as contrasted to the organic farming system. Also Mondelaers et al. [38] report that yields of organic farms are on average 17% lower than in the conventional farming system. In contrast, Pimentel et al. [39] state that the organic production of some highly productive plants, such as maize, may achieve yields comparable with the conventional systems.

Neuerburg and Padel [40] argue that direct sale is important to organic farming because it may provide sales for a higher price. However, in practice, farmers are sometimes forced to cut the farm gate prices due to the general overproduction and high overall yields. High wheat production in the Czech Republic and neighbouring countries also leads to a high offer on the market, which has a negative impact on the general decline in farm gate prices [41]. Low farm gate prices and price fluctuation throughout the year consequently affect the overall economic efficiency of crops [42]. Generally, higher farm gate prices are more typical for organic production compared to the conventional production [43]. This is consistent with the findings when the farm gate prices of oat and wheat were by 21.5% higher for organically grown crops during the monitored period.

Costs per the production unit were higher, as well, 17.5% for oats and 22.5% for wheat compared to the conventional farming system. Higher production costs associated with the organic system are mainly due to low yields compared to the conventional system, and this may reach up to 40% depending on the season [44]. Also, Konvalina et al. [45] point out that the cost per the production unit for organic farming are higher by 10 – 30 %, which is consistent with the results.

Organic farming system in the Czech Republic appears to be more economically efficient in the production of both wheat and oats, however, the factors influencing profitability are highly variable and change annually. From an environmental point of view, the positive impact of the organic farming system was supported due to lower GHG emissions when growing both crops. Most organic farming in the Czech Republic has a form of cattle breeding without market production of milk on permanent grasslands, and in a number of cases this activity is economically unsustainable and fully dependent on subsidies. It follows from the results that the development of farming on arable land, where the site conditions allow, and growing certain cereals, in particular, may strengthen the economic self-sufficiency of organic farmers in the conditions of the Czech Republic and contribute to a reduction of GHG emissions. They may also be reduced by the farmers using conventional farming procedures, particularly through a reduced application of synthetic nitrogen fertilizers and their partial replacement by alternatives, e.g. in the form of organic fertilizers or precise dosing.

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Conflict of interest: Authors declare nothing to disclose.

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Review

Agroecology Development in Eastern Europe—Cases in Czech Republic, Bulgaria, Hungary, Poland, Romania, and Slovakia

Jan Moudrý Jr. [1,*], Jaroslav Bernas [1], Jan Moudrý sr. [1], Petr Konvalina [1], Apolka Ujj [2], Ivan Manolov [3], Atanaska Stoeva [3], Ewa Rembiałkowska [4], Jarosław Stalenga [5], Ion Toncea [6], Avram Fitiu [7], Daniel Bucur [8], Magdalena Lacko-Bartošová [9] and Milan Macák [9]

1 Faculty of Agriculture, University of South Bohemia in Ceske Budejovice, Studentska 1668, 37005 Ceske Budejovice, Czech Republic; bernas@zf.jcu.cz (J.B.); moudry@zf.jcu.cz (J.M.s.); konvalina@zf.jcu.cz (P.K.)
2 Faculty of Agricultural and Environmental Sciences, Szent István University Gödöllö, Páter Károly u. 1, H-2100 Gödöllö, Hungary; Ujj.Apolka@mkk.szie.hu
3 Faculty of Agronomy, Agricultural University Plovdiv, Mendeleev Blvd. 12, 4000 Plovdiv, Bulgaria; manolov_ig@yahoo.com (I.M.); astoeva@au-plovdiv.bg (A.S.)
4 Faculty of Human Nutrition and Consumer Sciences, Warsaw University of Life Sciences, Nowoursynowska 159 C, 02-787 Warsaw, Poland; ewa_rembialkowska@sggw.pl
5 Department of Systems and Economics of Crop Production, Institute of Soil Science and Plant Cultivation, State Research Institute, ul. Czartoryskich 8, 24-100 Puławy, Poland; stalenga@iung.pulawy.pl
6 National Agricultural Research Institute Fundulea, Innovation and Technical Assistance Centre for Ecological Agriculture, Nicolae Titulescu 1, 915200 Fundulea, Romania; toncea@ricic.ro
7 Agricultural Faculty, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, CaleaManastur 3-5, 400372 Cluj-Napoca, Romania; afitiu@yahoo.com
8 Faculty of Agriculture, Ion Ionescu de la Brad University of Agricultural Sciences and Veterinary Medicine of Iasi, Aleea Mihail Sadoveanu 3, 700490 Iasi, Romania; dbucur@uaiasi.ro
9 Faculty of Agrobiology and Food Resources, Slovak University of Agriculture in Nitra, Tr A. Hlinku 2, 94976 Nitra, Slovakia; magdalena.lacko-bartosova@uniag.sk (M.L.-B.); milan.macak@uniag.sk (M.M.)
* Correspondence: jmoudry@zf.jcu.cz; Tel.: +420-387-772-456

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Abstract: Agroecology is a discipline of science that is based on several disciplines, primarily ecology and agronomy. Although the first mention of agroecology was more than 100 years ago, it has recently been more intensely developed throughout Eastern European countries, beginning in the 1990s. Basically, such interest developed due to the intensification of agriculture in the second half of the 20th century, which was based on the premise of agricultural research, and related specifically to production. Agroecology is also strongly associated with sustainable agricultural activities, especially organic farming, which began to develop in Eastern European countries around 1990. Due to the unique environment of Eastern European countries, and a combination of several disciplines within them as well as other factors, agroecology in these differing countries can be perceived as somewhat different from one another. This overview focuses on the current state of agroecology in the Czech Republic, Poland, Hungary, Bulgaria, Romania, and Slovakia.

Keywords: agroecology; Eastern Europe; organic farming; development

1. Agroecology as a Scientific Discipline

Agroecology stands at the interface of several disciplines, its name being based on two fundamental disciplines: ecology and agronomy. The primary focus of ecology is on natural systems, while the focus of agronomy lies in the research and application of scientific knowledge relevant to agricultural practice [1–4]. Agroecology focuses on research into the use and functioning of fields and generally farmed ecosystems. Agroecology is the holistic study of agroecosystems, including all of their environmental and human elements [5]. It deals with relationships among plants, animals, microorganisms, and agricultural soil, as well as its relationships to these organisms in the landscape [6]; it also evaluates the impact of agrotechnology on the ecosystems of farmed land. The main objective is to optimize farm and landscape management practices [7]. Different definitions originate from one common root, which everyone agrees upon: sustainability is a global strategy to preserve the world, including the conscious use of resources that can satisfy the current generation's needs in a way that does not diminish the next generation's chances [8–12]. This definition also implies that in the course of agricultural production, reasonable management of natural resources is needed while balancing economic and environmental sustainability. Furthermore, the preservation of the environmental quality has to be considered while producing healthy foods for the modern, conscious society [13,14]. In general, it can be stated that the primary user and converter of the natural landscape is agriculture itself; therefore, the protection of nature should be harmonized with agricultural activities [15]. Conversely it is also true that the success of agricultural activity, especially its efficiency, is determined by the natural conditions, i.e., the existence and the condition of natural resources [16]. With this knowledge in mind, it can be stated that compliance with the basic objectives of sustainability does not seem to be complicated, even though it is not easy to judge which production systems and methods are 'appropriate'. Traditional agricultural systems, such as those identified as Globally Important Agricultural Heritage Systems (GIAHS), offer a wealth of knowledge, principles, practices, and biodiversity that cannot be replaced by modern science [17]. Several approaches, including integrated pest management, a polycultural farming system, conservation agriculture, and agroecology combine traditional agriculture practices with modern science [17].

Although the first works indicating the complexity of interactions in agroecosystems come from the first decade of the 20th century, in general, efforts to practically solve problems in agriculture related to ecological and environmental issues have overtaken research in many cases. This can be traced, for example, to the organic farming movement [18], which began to develop after the First World War. In the German-speaking countries, natural farming is emerging, returning to a more rigorous application of biological knowledge in agricultural practice.

Soon after that, biodynamic agriculture, with its starting point being the anthropophysical image of man and nature, was introduced in the 1920s in the R. Steiner Agriculture Course [19,20]. Of these practicable forms of farming, where the ecological approach was obvious, other systems developed and became the basis of current organic farming. Although we can label some of the elements in some of the first systems as unscientific, the current organic farming system can already draw on new findings from agroecological research, and has a number of specialized research centers building on the methodology and results of agroecology. However, if we return to the development of the first ecological systems, then the originally more isolated ecology and agrochemistry sciences, one of which was focused more on theoretical questions and nature, and the other on applied approaches and human beings, have begun to find a common path since the 1920s, with the development of plant ecology, including the cultivated ones [1]. From the scientific circles dealing with these problems, we can hear the terms of ecology in agriculture or agroecology. If we follow the development of these two scientific disciplines just after the Second World War, then ecology continued in its scientific direction, while in agronomy we observed a number of applied approaches that, to a greater extent, influenced not only our own productivity of agroecosystems, but also the individual components of the environment. We can mention, for example, new mechanization or the development of the use of agrochemicals [21]. In this environment, there is once again the intermingling of the interests of individual scientific disciplines that encounter each other in plant ecology, and we can again encounter the names of agricultural ecology or agroecology. The scope of this new scientific discipline has been gradually expanding, with the development of population ecology, an ecosystem approach, or the development of environmental protection research. The environmental movement in the 1960s, when humanity began to become more aware of the problems of environmental contamination, with the effects on health and nature, was heavily influenced by the book Silent Spring [22]. Agroecology at that time also began to attract attention at a number of scientific conferences, such as for example, at the first International Organic Congress in 1974, the Report on Agroecosystems Analysis was built [1,23]. From the 1970s, we can talk about both the increased interest of ecologists in the study of agricultural systems as well as the efforts of agricultural experts to extend their research by ecological and environmental approaches [24–26]. It is also the period in which the first monographs titled Agroecology are published, see Gliessman and Wezel et al. [27,28]. Contemporary agroecology has thus gradually developed a number of theoretical schools in the world, and in practice, it helps to develop agricultural systems to meet the principles of long-term sustainability, as presented in its definition in 1993 by FAO-UNESCO. It is a system for protecting and preserving soil, water, plant, and animal genetic resources; it dedicated to not degrading the environment, and its mechanisms and processes must be manageable, economically self-sufficient, and socially acceptable [1].

2. Agroecology in Selected Eastern European Countries

2.1. Agroecology in the Czech Republic and Slovakia

From a historical point of view, between 1918 and 1992, the Czech and Slovak republics formed one state unit (Czechoslovakia); consequently, the issue of agroecology in this review is evaluated for both states within one chapter. In the Czech Republic, agroecology can be described as an area that has seen relatively significant growth, especially after 1989, in connection with the development of the organic farming sector. By analogy with the definition of ecology, we can define agroecology as a doctrine of interactions between economically significant organisms and their environment. Agroecology thus studies agriculture, including forestry, from the point of view of ecology. Agriculture is not only seen as production; the criteria for the functioning of agricultural systems include sustainability, food security, economic viability, the conservation of resources, and social acceptability. Therefore, initiatives and projects supporting changes in agricultural practices and education, supported by individual ministries (Ministry of Agriculture, Ministry for Regional Development, Ministry of the Environment, Ministry of Education, Youth and Sports), research organizations, and farmers themselves, exist today. Agroecology, as a practice, motivates farmers to become part of an environmentally-friendly system (with increased emphasis e.g., on correct crop rotation, composting, soil protection, increasing biodiversity, using alternative sources, etc.). However, environmental management tools are not exclusively covered by the organic farming sector, but have rather become part of subsidies that are also used by conventional agriculture entities. Nevertheless, the agroecology in the Czech Republic is mainly related to the principles of organic farming, which originated in this country from 1990, when the foundations of the whole system were laid with the cooperation of the Ministry of Agriculture of the Czech Republic, the Libera Association, and the PRO-BIO Association (associations of organic farmers). A fundamental shift in the development of organic farming as well as agroecology itself was the year 1990, when the first funds were released to support the emergence of organic farms. Subsidies have been provided up to 1992, and have been apparently the main reason for the increase in areas to about 15,000 ha. The decision of the Ministry of Agriculture of the Czech Republic to cancel subsidies caused the stagnation of areas in the period between 1993–1996, but at the same time, it had a positive influence on the qualitative development of organic farming. A number of organic farms have only ceased their activities because of subsidies. In 1998, financial support for organic farmers was renewed in the Czech Republic. In 1994, it was decided to introduce a single trademark for organic food, especially for marketing reasons and the public visibility of production. International aid was also of great importance for the promotion and support of organic farming. This was a methodical support of a worldwide movement of organic farmers, which included financial and educational support, book publishing, information systems for organic farming etc. Today, organic farming in the

Czech Republic is a stabilized agricultural system that is supported by the state, and is also the most important area for agroecology development from an area perspective.

Agroecology as a field of science has also been developed in the Czech Republic (former Czechoslovakia) through a number of educational and professional publications on agricultural production, ecology, plant protection, landscape assessment, and also publications bearing the name agroecology itself (see Table 1). Research and education in agroecology began after 1960 at the Faculty of Agronomy, Agricultural University in Nitra, within Czechoslovakia, and the Complex Agricultural Research Station (CARS) in Michalovce (since 1965), which is located in the East Slovak Lowland. CARS was a predecessor of The Research Institute of Agroecology in Michalovce. In the field of education and research, Slovakia has a tradition in the development of agroecology within local universities and research centers. It houses Slovak Agricultural University in Nitra, which has a Faculty of Agrobiology and Food Resources and agroecology within the study programme (first and second cycle, BC and MSc levels); there is also the University of Prešov Faculty of Humanities and Natural Sciences' Department of Ecology, which has a course on agroecology; there are also research institutions, such as the above-mentioned Research Institute of Agroecology in Michalovce and a research institute dedicated to plant production in Piešťany. The research and teaching of some particular aspects of agroecology in the sense of the application of ecological principles to agricultural systems and their practices is broadly carried out only at the Slovak University of Agriculture in Nitra and in the research institutes for crop and animal production. According to the academic distinctions of the various approaches to agroecology made by Buttel [29], the relevant initiatives in Slovakia belong mainly to the category of agronomic ecology. The basic approach in this branch is derived mostly from agronomy, including the traditional agricultural production sciences.

In both states, which have now been independent for more than 15 years, some non-governmental organizations (NGOs) have been working as agents of agroecological principles. In Slovakia, for example, one of these is a civil association called CEPTA, otherwise known as the Centre for Sustainable Alternatives. The civil association CEPTA was founded in 2005 as an association of people who engage in different activities such as environmental protection, nature protection, support of civil participation, healthy lifestyles, and sustainable alternatives to present consumer lifestyles. The main activities and campaigns of this association include: the greening of traditional agriculture and rural development; the reduction of pesticides in food and the environment, and increases in food security; the support of local and regional production–consumption chains and direct selling; the development of waste production prevention and the creation of a sustainable economic environment for the separation, recycling, and recovery of waste; air quality protection, such as soot removal from urbanized environments; negative effects elimination from intensive biofuels production; the development of cultural and educational activities and free time activities for young people; and the promotion of sustainable economics off the back end of nuclear power.

In the Czech Republic, universities serve as carriers of agroecological principles and environmental education tools for the general public. Agroecology is taught as a field of study at the University of South Bohemia, through the Faculty of Agriculture, and at Mendel University in Brno, through the Faculty of AgriSciences. Practical agroecological approaches include more points of view, not just the ecological basis applied to the agricultural system. In this developed and sophisticated discipline, there is also an environmental and socially sensitive approach to agriculture. The principle of agroecology in the Czech Republic and Slovakia is based, among other things, on the premise that natural ecosystems are a model for long-term sustainable farming systems and on the intention to cooperate with nature. The significant growth of agroecology within the Czech Republic, especially after 1989 in connection with the development of the organic farming sector, is linked to initiatives and projects supporting changes in agricultural practice and education that originated and originate thanks to ministries, research organizations, and farmers themselves. The term agroecology can be used in multiple ways: as a science, as a movement, and as a practice. Broadly stated, it is the study of the role of agriculture in the world. Agroecology provides an interdisciplinary framework to study the activity of agriculture.

Agriculture does not exist as an isolated entity, but rather as part of an ecology of contexts. Agroecology in Slovakia is understood only in the context of ecology and environmentalism, and its full nature has not yet been recognized. Thus, agroecology is the study of ecological processes that operate in agricultural production systems with an emphasis on the application of ecological principles to agricultural systems and practices.

Table 1. Agroecology in selected professional literature of the Czech Republic and Slovakia (until 1999).

Ref.	Year	Authors	Title (in Original Language)	In English
[30]	1973	Zlatník, A.; Pelikán, J.; Stolina, M.	Základy ekologie	Fundamentals of Ecology
[31]	1976	Andonov, I.	Vliv agroekologických podmínek množení na technologickou hodnotu osiva jarního ječmene	Influence of agroecological conditions of propagation on the technological value of spring barley seed
[32]	1980	Kováč, A.; Šimko, J.; Belohorec, R.	Študium tvorby a redukcie faktorov úrodnosti lucerny siatej pestovanej na hmotu a semeno v rôzných agroekologických podmienkach	Study of the formation and reduction of fertility factors of lucerne grown on matter and seed in various agroecological conditions
[33]	1983	Pluhař, J.	Vliv některých agroekologických faktor*ů* na výskyt chorob a šk*ů*dc*ů* obilnin.	Influence of some agroecological factors on the occurrence of diseases and pests of cereals.
[34]	1986	Slavíková, J.	Ekologie rostlin	Plant ecology
[35]	1988	Duvigneaud, P.	Ekologická syntéza	Ecological synthesis
[36]	1989	Dykyjová, D.	Metody studia ekosystém*ů*	Methods of ecosystem study
[37]	1990	Veverka, K.	Zdravotní stav rostlin ve vztahu k výživě a hnojení. In Agroekologie a výživa rostlin	Plant health in relation to nutrition and fertilization in agroecology and plant nutrition
[38]	1991	Vergner, I.; Berták, R.	Základy alternativního zemědělství	Fundamentals of alternative agriculture
[39]	1992	Petr, J.; Dlouhý, J.; et al.	Ekologické zemědělství	Organic farming
[40]	1993	Kohout, J.; Škoda, V.; Zitta, M.	Obecná produkce rostlinná	General plant production
[41]	1994	Kulich, J.	Rizikové prvky v agroekologických podmienkach Hornej Nitry	Risk elements in the agroecological conditions of Horná Nitra
[42]	1996	Barták, M.; Kocourek, F.; Vrabec, V.	Obecná agroekologie	General agroecology
[43]	1996	Barták, M.; Šarapatka, B.; Kocourek, F.	Speciální agroekologie	Special agroecology
[44]	1996	Moldan, B.	Indikátory trvale udržitelného rozvoje	Indicators of sustainable development
[45]	1996	Remtová, K.	Trvale udržitelný rozvoj a strategie ochrany životního prostředí	Sustainable development and environment protection strategy
[6]	1997	Křen, J.	Systémový prístup k rastlinnej produkci	System approach to plant production
[46]	1997	Moudrý, J.	Přechod na ekologický zp*ů*sob hospodaření	Conversion to organic farming
[47]	1998	Kohák, E.	Zelená svatozář. Kapitoly z ekologické etiky	Green halo. Chapters on ecological ethics
[48]	1999	Demo, M.; Bielek, P.; Hronec, O.	Trvalo udržateľný rozvoj. Život v medziach.	Sustainable Development. Life within the limits.
[49]	1999	Dotlačil, L.; Stehno, Z.; Faberová, I.	Care on plant genetic resources of agricultural crops in the Czech Republic—Status in 1998	Care on plant genetic resources of agricultural crops in the Czech Republic—Status in 1998

These studies support the science, practice, and movement to eliminate the underestimation of agroecology via national and international projects.

2.2. Agroecology in Hungary

Agroecology is still in its infancy in Hungary. There are initiatives and projects promoting changes in agricultural practice and education, but these changes are very slow. Agricultural actors and stakeholders know in theory what would be good practice, but economic interests are against it. The economic viability of agroecological practice and its long-term effects should be better highlighted and supported by the government.

The concept of agroecology is becoming more and more well known in Hungary. Research, educational projects, international collaborations, and scientific conferences deal with the subject. There are associations and companies that are providing agroecology-related services. One good example is the National Society of Conservationists (Magyar Természetvédők Szövetsége, Üllői út 91/b, Hungary) [50] that was established in 1989. Their overall objective is to protect nature as a whole and promote sustainable development. They have 113 member associations, with almost 33,000 members across Hungary. A large number of the member groups are small, local organizations whose main activities include environmental education, awareness raising, participation in uncovering and solving local environmental problems, environmental advisory work, and nature conservation tasks. Among the society's educational publications, there is a specific issue related to agroecology (https://mtvsz.hu/kiadvanyok) that summarizes the concept of agroecology for a wider audience (not only for scientists). Another good example is the Agrofutura project [51], which has been dealing with agroecological issues for a long time, and has proven well-established technologies. The Agrofutura was founded in 2013 as an agricultural advisory, service, and manufacturing company. Agrofutura works with young scientists, mechanical engineers, and practicing farmers. They use technologies, which are based solely on biological farming. They work in balance with the humans–animals–plants–nature environment. They provide programs and services on subjects such as "Animal Welfare" and "Soil Humus Management". Both are based on teaming with the microbes. An important part of their activity is the education of farmers and families in order to support their real independence, self-care, and freedom. Hungary has recently been actively involved in important agroecological events. Last year (2016), the Regional Symposium on Agroecology for Sustainable Agriculture and Food Systems in Europe and Central Asia [52] was held in Budapest, which was organized by the FAO (World Food and Agriculture Organization, Rome, Italy). During this event, the Hungarian Minister for Agriculture confirmed that: "Agroecology is key in ensuring sustainable agriculture, [the] protection of biodiversity, sustainable natural resource management, and supporting rural development". The main goal of the symposium was to bring together the knowledge and experience already available among experts and to find solutions for the most urgent global challenges. FAO is an advocate and supporter of international cooperation. The symposium was also aimed at identifying government initiatives and starting to identify key entry points for agroecology in national policies and common European policies. Organic farming is still considered to be the best practice of agroecological farming. In Hungary, the appearance and spread of organic farming began in the eighties. At that time, it started as a movement in the form of networks. In 1987, the Biokultúra Association was established, providing the official organizational model of operation. The association not only unites the players in the organic movement and represents the interests of the members, it also performs educational and consultation tasks while providing scientific representation for the agricultural sector. Science also has an important role in the appearance of agroecology in Hungary. Several scientific projects related to agroecology were initiated, while educational research aimed at mapping out possible changes in relation to teaching methodologies of agroecology.

In general, agroecology—as a discipline—studies agriculture from an ecological perspective that addresses the stability and optimization of the agricultural system as a whole. Agroecological farming is based on the well-established knowledge of traditional farming, which can possibly lag behind monoculture-based farming, but its sustainability is far more productive and energy-efficient [53]. Agroecology is a way of understanding the relationship between agroecosystems and the environment discipline [54]. In Hungary, agroecology—as a practice—encourages farmers to become part of the ecological system to strengthen processes that are inherent in nature and incorporate them into production (e.g., crop rotation, composting, soil cover, increasing biodiversity, alternative energy use, etc.). These elements are not included exclusively in the rules of organic farming; they also became a part of the direct payment (e.g., greening) in the case of conventional farming. Agroecology is also known in other countries as a movement, which does not present a significant polarity in Hungary. Meanwhile, in the bottom–up initiative, everyone agrees that agroecology can be the basis for food self-sufficiency; this may also affect public policy. The agroecology movement's participants (farmers, animal breeders, rural communities, consumers, NGOs, trade unions, local food movements, teachers, etc.) have concrete action ideas, but they vary and are not yet uniform. The movement of La Via Campesina is not very well known in Hungary, it forms part of the 'history' of the development of agroecology, but is not relevant within Hungarian circumstances.

Certain projects and initiatives have an important role in the current zeitgeist related to agroecology in Hungary. One of the most significant projects started in 2002 within the framework of the Hungarian National Research and Development Program. The consortium of the project, "AGRO-ECOLOGY" [55] (Environmental relationships of agro-ecosystems and the possibilities of their control), has undertaken the elaboration of an up-to-date agroecology synthesis. The soil science, water regime, agrometeorological, crop production, plant protection, biodiversity, and regional research studies outlined in the project included: the assessment of the elements of agroecosystems, the determination and analysis of the relationships and interrelationships with their functioning mechanisms; the description, characterization, and quantification of the environmental effects of different agroecosystems; the analysis of the effect of environment elements on different agroecosystems; the evaluation of the mass and energy transport processes in agroecosystems, and the soil–water–near surface atmosphere–plant system; the assessment of the factors affecting, determining, influencing or modifying their mechanisms and determining the possibilities of their control; and the elaboration of the basis of an up-to-date agroecological information system operating through interactive thematic expert systems. In 2003, the Hungarian Government and the Hungarian Academy of Sciences launched a joint research project entitled "Global climate change, its impacts in Hungary and responses" (VAHAVA project) [56]. The acronym comes from the abbreviation of the Hungarian key words "Change–Impact–Response" (VÁltozás–HAtások–VÁlaszadás). Since the National Environmental Program of Hungary was already dealing with the national tasks of controlling the emissions of greenhouse gases, consequently, the VAHAVA project focused primarily on the problems of vulnerability and adaptation in relation to the anticipated impacts of the climate change. The VAHAVA project [56] formulated two strategic objectives: (1) to get the Hungarian people and economy prepared to face the occurrence of potentially increased extreme weather, such as hydrometeorological events, and to bear warmer and drier time periods with their expectable impacts; and (2) to develop the organizational, technical, infrastructural, and financial conditions that would be needed for the timely response of their society to these harmful impacts. Both scientific research and projects focusing on new educational approaches were initiated after 2000. Szent István University was a partner of ISARA Lyon in the elaboration of their Agroecology MSc course; the University of Debrecen initiated its PhD program in 1993 with the name Crop Production, Agroecology. Why is education necessary for a better understanding of agroecology? Dover [57] defines and describes an ecological approach to agriculture that differs from the industrial approach that has dominated agricultural research and development for decades. Francis et al. [58] also emphasizes that much of the education in agriculture has moved from practical, hands-on field activities and internships to focus on theory in formal learning settings (mainly in classrooms). This is also true for Hungary. The growing need for productive and sustainable agriculture calls for a new view of agricultural development that builds upon the risk reduction and resource conservation aspects of traditional farming, and draws on the advances of modern biology and technology. In the suggested strategy of Dover [57], in order to attain sustainable agriculture, the importance of the research and education must be highlighted. In order for the development of ecological agriculture to grow roots, scientists need to train a whole new generation. Therefore, multidisciplinary comprehensive ecological–agricultural training is needed in agricultural universities that will develop a new generation of agroecologists who are capable of dealing with whole systems and provide agroecological knowledge for future policy makers [59,60]. On this basis, the SAGITER project (2013–2016 Project title: Agroecological Knowledge and Ingenuity of Terroirs) [61] focused on progress toward a sustainable agriculture education that can be achieved by combining both scientific and non-specialized knowledge. The project aim was to rebalance the asymmetrical vision of the world in which the scientific knowledge is regarded as rational and therefore "right", and the popular knowledge as irrational and therefore "wrong". Scientific approaches need to be combined with vernacular knowledge. The question is how the transmission of layman knowledge can operate in a corpus designed for science, and which methodologies need to be adapted in order to allow transmission to the concerned audience. It is also a question how the people who use the agroecological knowledge were able to acquire it, and how we can transfer everyday knowledge through training. In the SAGITER project [61], Szent István University from Hungary participated in the promoting/upgrading process of the agroecological knowledge, and the ingenious systems that are implemented from time to time on the territories. Of course, one single project could not result in a complete change in the knowledge transfer method applied at universities in Hungary, but practical method collection, which was elaborated during the three-year duration of the project, and related to knowledge transfer designed for educators, can surely support them during teaching. Methodology collection and can also reinforce the better understanding of the complexity of sustainable agriculture by providing a better view of the whole picture (even for the teachers!). The primary expected outcome of the project was still the awareness of the importance of the knowledge that cannot be acquired by university textbooks or the educational foundation of future responsible actions.

2.3. Agroecology in Bulgaria

In Bulgaria, there is some misunderstanding about the term agroecology, even among scientists and university teachers. Many of them equate the terms agroecology with organic farming. The increasing intensification of agriculture requires a deeper study of its impact on the environment. The results of these studies can serve as a basis for improving and expanding agroecological measures applied in agriculture. The first steps in the field of agroecology in Bulgaria were made in the 1990s. In 1987, the Agroecological Center was established as a structural unit of the Agricultural University-Plovdiv. It was founded with the aim of coordinating the efforts of researchers, students, farmers, and consumers to carry out research and provide education for the development of organic agriculture in Bulgaria. The priorities of the Agroecological Center are education and scientific research in the field of organic farming and agroecology [62,63]. Agroecological policy in the field of environmental protection is one of the most established mechanisms of the policy within the framework of the Common Agricultural Policy (CAP) for both the European Union (EU) and Bulgaria. In the beginning (after 1987), it was mainly aimed at mitigating the environmental impact of the intensification of agriculture and understanding the positive effects of extensive agriculture. Since 2000, many agroecological programs have been designed and implemented in Bulgarian agriculture through the seven-year rural development programs (RDPs). In 1993, the first scientific–practical conference, the "Ecological Problems of Agriculture" (AGROECO'93), was organized by the Agricultural University in Plovdiv [64] and the Union of Scientists in Bulgaria. Since then, such a conference has been held every second year. These conferences cover the ecological aspects of agricultural production. Crop production, soil and waters, plant protection, and animal production are the major topics for the focus points of the conference. The articles presented at the conference have been published in the “Scientific works”, which is an annual agricultural book by the University of Plovdiv [64].

The Ministry of Agriculture, Food, and Forestry department’s “Rural Development” and “Crop Production and Organic Production” programs, [65], the National Agricultural Advisory Service [66], the State Fund’s “Agriculture” program [67], and the Ministry of Environment and Water [68] administer the agroecological policy. The State Fund “Agriculture” program provides financial support for these state aids under the supervision of the Common Agricultural Policy (CAP) and the Rural Development Program. The national agricultural advisory service provides free advice, information, training, and other services in the field of agriculture and the implementation for agroecological measures. Direct payments of European agroecological programs were started in Bulgaria by the SAPARD pre-accession program in 2000, and were continued in the following program periods 2007–2013 and 2014–2020 by green payments [69,70]. According to the 2014–2020 Bulgarian RDPs, two measures (M) cover agroecology: M10 (Agroecology and climate) and M11 (Organic Farming). Both measures relate to European programs supporting agroecology in Bulgaria that are targeted to: organic farming; the integrated production of agricultural products; expanding farming systems by reducing fertilizers and pesticides application, rotating crops, and taking actions to prevent or reduce soil erosion; the maintenance of genetic resources (local breeds threatened with extinction, plants threatened by genetic erosion); theconservation of biodiversity; actions to improve the landscape, including but not limited to the conservation of the historical characteristics of agricultural land (maintenance of traditional orchards and mountain livestock farming); and water, such as creating buffer strips, headlands, and wetland management. Many informal associations, foundations, and NGOs support agroecology and develop projects connected with different aspects of agroecology nowadays. The first and leading foundation in the field of organic agriculture is Bioselena [71], which was established in 1996 by the Research Institute of Organic Agriculture FiBL, Switzerland. The main task of Bioselena is to develop and support sustainable and organic agriculture, biodiversity preservation, and environment protection. One of the main goals of the Bulgarian Biodiversity Foundation (BBF, Sofia, Bulgaria) [72] is integrating biodiversity into key economic sectors through the implementation of European and world practice. The foundation is active in preserving natural resources, changing people’s attitudes towards protected areas and protected species, increasing recognition of the subsequent opportunities and benefits of protected areas, and working for their long-term protection. The Bulgarian Society for the Protection of Birds (BSPB) [73], which is based on years of research and analysis on globally endangered bird species such as the imperial eagle, Egyptian vulture, and migratory geese that winter in Bulgaria, makes proposals to state organizations for accepting agri-environmental activities and measures to protect endangered bird species. Most of the members of the Association of Agroecological Farm Producers (AAFP) [74] are farmers who apply agroecological measures of RDP. The main goals of the AAFP are to support and inform agroecological farmers about compliance with the requirements for the implementation of agroecological activities; increase farmers’ knowledge of the environmental benefits of agroecology; and support state structures through participation of the association in working groups, committees, expert councils, etc., in the preparation of legislative initiatives related to agroecological activities. The association “Ekofarm”, together with the Agricultural University popularizes organic farming and agroecology through round tables and seminars in different towns and regions of the country [75]. The NGO organizations develop and work on different projects connected with agroecology and the environment. Some of the projects are in cooperation with other international institutions. For example, the “Assessment and mapping of the state of grass ecosystems and their services in Bulgaria” project was developed by the BSPB in cooperation with the Norwegian directorate for nature management (DN). The “Conservation of the Saker Falcon in northeastern Bulgaria, Hungary, Romania and Slovakia” project was developed in cooperation with 14 organizations from the countries that are included in the project. The main beneficiaries of agroecological payments are farmers. There are qualification requirements in order for them to receive these payments. Farmers should have finished a vocational secondary school or university with agricultural qualifications. Another possibility for the farmers is to complete the educational (training) course in agroecology and get certification, which allows them to apply for financing from state programs and varied programs requiring these qualifications (agroecology). The Agricultural University in Plovdiv is the first state university in Bulgaria where different courses connected with the topic of agroecology have been organized. The faculty of Plant Protection and Agroecology has two main professional fields: Plant protection and Ecology, and Environmental Protection. Courses in Agroecology and Agroecology and the management of agroecosystems are part of the Bachelor and Master degree programs. The Faculty of Agronomy at the University of Forestry in Sofia teaches a course in Agroecology. Other institutions offering courses in Agroecology are centers for continued education, which were established as supporting units at universities (e.g., Agricultural University, Plovdiv; University of Ruse, etc.) or centers for professional education. For example, the Centre for Professional Training or the Foundation of Organic Agriculture (FOA) "Bioselena" [71] is licensed for training the professional "Farmer". It offers training in Agroecology and Organic Farming. Other similar centers for vocational training include "Harmony", "Zenit", etc. Research in the field of agroecology is conducted at the Agricultural University of Plovdiv, the University of Forestry, and at the research institute of the Agricultural Academy and Institute of Soil Science, "Nikola Pushkarov".

As a drawback, it can be noted that the number of larger projects targeting agroecology in the country are still small. State institutions, universities, and scientific organizations must initiate deeper projects related to the influence of the environmental issues in agriculture. One of the recent agroecological projects that was developed with the participation of Agricultural University is "Sustaining agricultural change through ecological engineering" (STACCATO, 2014–2018), financed by European program Biodiversa [76]. The project plans to quantify the dependence of ecosystem functions and the services they generate on environmental pressures in representative agriculturally dominated landscapes within Europe. The focus is on local as well as regional land use intensity and biodiversity, and the potential impacts of future climate and land-use change. Ecosystem functions and services such as nutrient cycling and crop production, biocontrol, and pollination and identity with cultural landscapes will be studied. Studies are planned in representative regions across Europe on landscapes that are shaped by annual crops and semi-natural grasslands.

2.4. Agroecology in Romania

In Romania, the history of agroecology is relatively short and started in 1977–1978. As a science, one teacher team from the Agronomy Institute of Cluj-Napoca laid the foundation of its agroecology through the publication of many courses, papers, and books. Later on, the theoretical spirit of agroecology was disseminated in Timișoara, Bucharest, and other Romanian agricultural university centers. These pioneers of agroecology defined agroecology as a branch or domain of general ecology that is dealing with the multidisciplinary study of influences exercised by environmental factors to crops and domestic animals (agricultural autecology), as well as the ecological research of structure and dynamics of agroecosystems (agricultural synecology). They also established the object and laws of agroecology. Therefore, as a scientific discipline, agroecology was conveyed by individuals with a range of expertise in ecology or biology, especially in the physiology of plants and agronomy, as well as in circumstances related to local and global problems of industrial agriculture because of neglectful of fundamental laws of living. The agroecology was extent then, in the 1984–2000s, and was more or less concomitant as a practice by delimitation and characterization of the homogeneous ecological territories (TEO), which were the basic units of the Romanian agroecosystems, and as movement by the foundation of four representative NGOs: the Organic Farmers Association of Romania (BIOTERRA), Calea Victoriei 21–23, Bucuresti [77], the Romanian Association for Sustainable Agriculture (ARAD) [78], the Agroecology Association (Agroecologia) and the National Federation of Ecological Agriculture (FNAE), str Manastur 3–5, Cluj-Napoca [79]. Another important step for agroecology development in Romania was the defining of sustainability as a feature of the (agro)ecosystems, and the development of its indicators. These included (bio)diversity, vulnerability, and resilience, as well as indicators of other (agro)ecosystem features such as: the complexity and unity of its integrality; and the productivity, efficiency, stability and equity of its functionality. The Romanian agroecosystems were delimitated and characterized in the framework of the national research program "Zonal Intensive agroecosystems" between 1985–1989. Also, the foundation of the first NGOs that focused on agricultural ecology took place between 1987–2000 following the development of the IFOAM and elaboration of the first international and national legal frameworks for agricultural products and foodstuffs obtained organically from European regulation 2092/91 and O.U.G. 34/2000, respectively.

Today, the object of agroecology is more diversified, from initial activities regarding crop production and plant protection, agricultural practices, and movement to the environmental, social, ethical, and development aspects of all food systems. In this context, the stakeholders in agroecology are diverse and active in education (Agricultural universities), agriculture production (organic farms), research and innovation (Research, Innovation, and Technical Assistance Center for Ecological Agriculture of NARDI Fundulea) [80], the promotion of small-scale family and traditional farming (Agroecologia Association and Mihai Eminescu Trust), 10 Cojocarilor Street Sighișoara [81], civil society, including peasants (Eco-Ruralis, Cluj-Napoca, Romania) [82], etc. The shareholders are a smaller agroecology group that is active in research, innovation, education, and rural civil society.

In Romania, there are three categories of players who convey agroecology. (1) First, there are professors and scientists, who are supporters of agroecology and promoters of small-scale family farming, etc., who use terms such as agroecology, agricultural ecology, and agroecosystem frequently and with full knowledge. (2) Second, there are professors who reject, without further explanation, the terms of agroecology and agroecosystem, and use only the terms agricultural ecology, or agricultural (artificial) ecosystems. (3) Third, there are some of the authors and lecturers from the "Ecology and Environmental Protection" discipline in agricultural universities and faculties who dedicate only a few hours (one to two) for agricultural ecology and agricultural ecosystems. Be aware of the opposition that is evident within applied agroecology because of two parallel terms: "eco", when discussing agriculture systems, and "bio" when referring to products; this is despite the official term in Romania, which is protected and assigned by the EU, and is "Agricultură ecologică". In this case, it is normal that the terms agroecology, agroecosystem, and ecological agriculture cause confusion among scientists and the public. In regards to vision, agroecology is the basic science of sustainable agroecosystems for the unilateral treatment of all types of farming systems. This vision is realistic and based on recent communications from the EU's "Future of Food and Agriculture" report, which outlines both the main and new priorities of the future EU agricultural policy. These are: (1) intensifying protection of the environment (soil, water, air, and biodiversity) as well as the climate; (2) increasing the focus on knowledge and innovation (smart agriculture); and (3) promoting a bioeconomy. In this context, some measures and clearing up the message about agroecology is necessary:

- The definition of agroecology has to be completed with environmental, social, and ethical aspects of the agroecosystems, which are now missing;
- The laws of agroecology have to be reviewed and disseminated to agroecosystems and rural development;
- Firmly establishing agroecosystem features and their indicators is a crucial aspect of investigation for evaluating and anticipating solutions for farm design and management, as well as land use policies;
- Developing basic standards of agroecology is the main tool for the implementation of agroecology in practice.

In Romania, there are numerous initiatives that support the development of agroecology (see Table 2), and also older publications about agroecology topics (see Table 3).

Table 2. Initiatives supporting the development of agroecology in Romania.

Symposiums (1978) on elements of agroecology
Symposiums of Romanian Academy (1978): "Artificial ecosystems and their importance for humanity" and "Agriculture and Food"
National Symposiums (1980–1994): "Ecology and Protection of Ecosystems"
Ecology and environment protection lectures (1986–present)
Annual BIOTERRA conferences (2000–2017)
R&D Project: Legume-supported cropping systems for Europe "LEGUME FUTURES", 2010–2013; WP 4–Socio economics: 4.2. Generation and evaluation of crop management and rotations, and 4.3. Farm level evaluation of legume-based cropping practices and policy instruments;
R&D Project: Replicable business models for modern rural economies, or "RUBIZMO", 2018–2021
European Union (EU) Communication/2017: "Future of Food and Agriculture", 2017

Table 3. Agroecology in selected professional literature of Romania (until 1999).

Ref.	Year	Authors	Title (in Original Language)	In English
[83]	1977	Puia, I.; Soran, V.	Umanitate și agroecosisteme	Humanity and agroecosystems
[84]	1978	Puia, I.; Soran, V.; Klemm, H.; Popescu, V.; Erdelyi St., Tatau, V.	Elemente de agroecologie	Elements of agroecology
-	1980–1984	Ionescu, A.; et al.	-	Proceedings of symposiums "Ecology and Ecosystems protection"
[85]	1984	Puia, I.; Soran, V.	Agroecologie: ecosistem si agroecosistem	Agroecology: ecosystem and agroecosystem
[86]	1986	Coste, I.	Ecologie Agricola	Course of agricultural ecology
[87]	1998	Puia, I.; Soran, V.; Rotar, I.	Agroecologie, Ecologism, Ecologizare	Agroecology, Ecologism, Ecologization
[88]	1999	Toncea, I.; Alecu, I.N.	Ingineria sistemelor agricole	Engineering of agricultural systems

2.5. Agroecology in Poland

The beginning of agroecology in Poland is closely linked to the development of organic farming. First, organic and biodynamic farms and farmer associations were established at the end of the 1980s; these formed the base for the development of agroecology in the successive years. Currently in Poland, the following practices can be linked with agroecology: organic and biodynamic farming; agri-environmental schemes; and permaculture, as well as agroforestry.

Organic and biodynamic farmers constitute the main pillar of players whose activity can be linked to agroecology. In 2016, there were 22,435 organic farmers in Poland managing about 537,000 ha of agricultural land. This constituted about 3.7% of the total Polish agricultural area (IJHARS 2017) [89]. There are no precise statistics on biodynamic farms in Poland, but their number is rather small. Farmers implementing biodiversity conservation-oriented packages of agri-environment schemes (AES) belong to another important group of players linked to that particular form of agroecology. In 2015, there were about 650,000 ha of grasslands under this type of AES, this was about 20% of all of the permanent grasslands in Poland. Permaculture is another example of practical agroecology. There were about 40 different permaculture initiatives across Poland, representing both the practice (farms) and the movements (Permakultura 2017) [90]. There are no statistics on agroforestry in Poland; however, there are already some examples of farmers implementing this type of agroecological practice.

The organic movement is quite strong in Poland. There are numerous NGOs that are strictly connected with organic agriculture in Poland. The following table (Table 4) lists them in chronological order.

Table 4. Non-governmental organizations (NGOs) strictly connected with organic agriculture in Poland.

Association of Food Producers with Ecological Methods EKOLAND (created in 1989). The oldest Polish organization dealing with organic farming.
Ecological and Cultural Association "Ziarno" (created in the late 1980s). Inspired by the biodynamic farmer Julian Osetek. Education and promotion are the main goals of this association.
Polish Society of Organic Farmers (PTRE), ul. Jacka Kaczmarskiego 27, Warszawa, is a Polish society or collective of farm producers possessing certified organic farms. Created in the early 1990s.
Union of Associations of Subcarpathian Chamber of Organic Farming is an organization created in 2005 that brings together five associations of organic farmers, producers, and processors from the region.
Association "EkoLubelszczyzna" was created in 2006, in the interests of its members to implement the strategy for the economic cluster "Organic Food Valley".
Lesser Poland Association of Organic Farmers Nature was founded in 2007 to help organic farmers in the province with the promotion and sale of organic foods on the market.
The Trade Union of Organic Farmers of St. Francis from Assisi is a nationwide organization bringing together farmers who run farms organically. Created in 2007.
The Association Forum of Organic Agriculture named by M. Górny and created in 2009. The goal is to distribute organic farming practices among agricultural producers and processors and promote organic products. Another important aim is to inspire and encourage science that supports the development of organic farming in Poland.
Kuyavian–Pomeranian Association of Organic Producers (EKOŁAN). Promotion of organic farming and its products is the main goal. Created in 2012.
National Association of Processors and Producers of Organic Products 'Polish Ecology'. The mission of the association is to inform consumers and increase trade possibilities. Created in 2015.
Polish Chamber of Organic Food is a group of traders within the organic food industry that brings together its most important representatives. Their mission is to promote healthy lifestyles by educating Polish society about what is organic food, which relates to the process of its production, and how is it different from conventional food. Particular emphasis is placed on the label of certified food. Created in 2017

Through analyzing the list above, one can conclude that at the start, there were only three associations that were historically connected with the beginning of the development of organic farming in Poland. The following eight associations were created much later, from 2005 through 2017, in parallel to the dynamic development of organic farming and processing. The main goal of all of these organizations is to bring together the organic producers and other stakeholders in order to increase opportunities for promotion and product trade. Another important aim is to increase the awareness of the consumers about the high properties of organic food. Here, we refer specifically to the Ziarno and Forum of Organic Agriculture named M. Górny, which is the most scientific organization amongst those listed. Many researchers who have conducted studies related to organic production belong to this association. The two last organizations have a strong economic aim: Polish Ecology and the Polish Chamber of Organic Food. There are at least four non-governmental organizations focused on permaculture. These are mainly foundations directed by educational activities for different players. As far as agroforestry is concerned, in 2015, a Polish Agroforestry Association was registered, and started activities that aimed to increase social awareness on the value of trees in an agricultural landscape and promote the practice of agroforestry across Poland (Agroforestry 2017) [91].

In recent years, interest in agroecology has been observed in the higher education sector. For example, the Agricultural University of Kraków's Department of Agroecology has been working in this area for many years. Furthermore, a master's degree specialization in Agroecology was developed within the Faculty of Biotechnology and Horticulture at the University of Rzeszów. Moreover, at Rzeszów University of Technology, the subject Agroecology was introduced within studies on environmental protection. A special e-learning course for students on Agroecology was realized in the Warsaw University of Life Sciences between 2009–2013 within a project financed from EU structural funds. Additionally, last year, Opole University offered a postgraduate study in Agroecology specifically for those running or planning to run an organic and/or agritourism farm. A very important institution strongly involved in agroecology research is the Institute for Agricultural and Forest Environment (IAFE) at the Polish Academy of Sciences in Poznań (former name: Research Centre for Agricultural and Forest Environment). The institute, among others, has been engaged in research on farmland biodiversity patterns and its dependency on habitat and landscape structure. Several research institutions and universities in Poland have been involved in organic farming research in recent years. Although many detailed topics have been the subject of this research, their link with agroecology is rather poor, and is often related to organic farming education.

Several bottom–up, mainly educational initiatives or movements supporting the idea of agroecology have been initiated in Poland over the last 30 years. This sector of practice is also strong, as there are still many organic and AES farmers all over Poland. Organic farming research has been quite comprehensive covering different areas of knowledge; however, in most of the research, there is a lack of a clear link to agroecology.

Some examples of initiatives that are considered as illustrating the aforementioned situation and dynamics follow. They can be: existing or transitioning systems, events, training courses, research agendas, websites, etc. The Ecological and Cultural Association ZIARNO in Grzybów in the central part of Poland is a very good example of a movement linking organic farming, permaculture, and innovative education under the umbrella of agroecology. In this region, beginning in 2014, an Ecological Folk High School that was based on Grundtvig folk universities for the innovative education of adults was successfully implemented. The association is also very active in supporting sustainable local development [92]. Another interesting example of practical agroecology linking practice, movement, and science in one place is the biodynamic farm in Juchowo in the northwestern part of Poland. This farm breeds milking cows and covers almost 2000 ha of land for arable crops, vegetables, and permanent grasslands. There are different social activities in the farm, including education, which is mainly for children (green schools), research (experiments on comparing different soil tillage systems), and social therapy, especially for disabled people [93].

3. Comparison of Agroecology in Selected Countries of Eastern Europe

The main impulse for the development of agroecology in the Eastern European countries under review is the negative impact of intensive large-scale agriculture on the environment and the depletion of natural resources; however, the demand for quality foods is also important. Conventional agriculture does not always secure the ability of the soil or the entire agroecosystem to maintain the production levels over a long period. The growing population prompts the need for productive as well as sustainable agriculture. While maintaining a sufficiently strong production function, such agriculture should be in harmony with nature, preserve resources, and utilize the positive impacts of environmentally friendly measures.

In agricultural practice, the support of agroecological principles has been gaining ground more slowly. Familiarization with various problems and the negative impacts of intensive conventional agriculture on the production and its quality and on the environment increase the interest of farmers in scientific information and their willingness to apply the outputs of agroecological research. Motivation is also stepped up by pressure from the general and professional public, the media, and end customers. Openness to agroecological research on the part of politicians and farmers in Central and Eastern Europe is also due to the support of sustainable farming within the scope of the common agricultural policy.

In the Eastern European countries under review, agroecology is addressed especially by research and educational institutions (Figure 1). A strong role is also played by movements and non-governmental organizations (NGO), which are regarded, in overall assessment, as the second strongest actors participating in the development of agroecology. The influence of the state, or rather government authorities, is lower, and the lowest influence is exerted by farmers themselves. Only in Bulgaria and Hungary is the role of government authorities higher, and comparable with the influence of movements and NGOs.

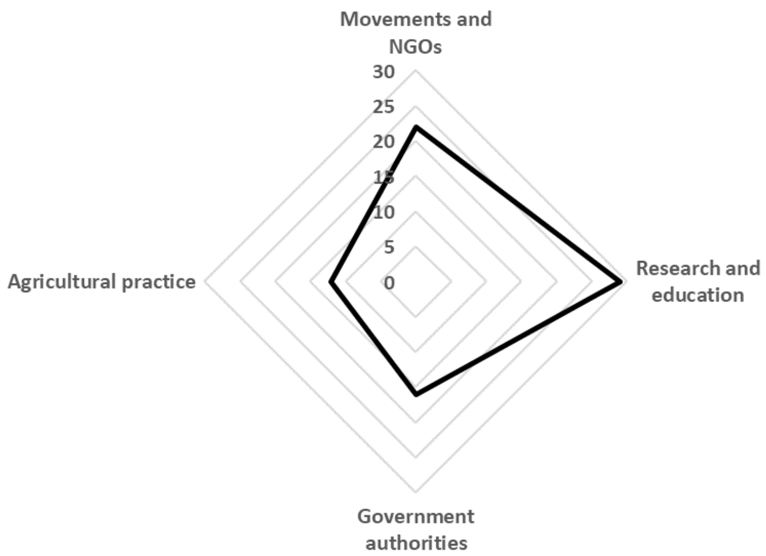

Figure 1. Influence of main actors on the development of agroecology.

The farmers themselves have not yet been perceiving agroecology as a separate discipline much. Certain aspects have been fulfilled in organic farming, but the overall demand for the development and support of agroecological measures that are bottom–up driven by the farmers themselves is very low. Therefore, the perception of agroecology by government authorities has also been rather low so far, and various elements of agroecology are addressed as part of the agenda related to the development of organic farming and environment protection. However, the influence of government authorities has been gradually growing, e.g., in Hungary where, in Budapest, in 2016, the Food and Agriculture Organization (FAO, Rome, Italy) organized the Regional Symposium on Agroecology for Sustainable Agriculture and Food Systems in Europe and Central Asia, at which the Hungarian Minister of Agriculture declared the need for a cooperative approach among government authorities and efforts to develop agroecology. The symposium also identified governmental initiatives and began to identify key inputs for agroecology in national policies and in common European policies. In Bulgaria, but also in the Czech Republic, Poland, and Romania, there have been growing efforts by government authorities to support agroecology in recent years, in particular by the application of European agroecological programs for the support of agroecological procedures. In Slovakia, the importance of agroecology for sustainable food production has not yet been sufficiently understood by governmental authorities, which results in poor support for targeted procedures. It is expected that, apart from further development in the fields of science, research, and education, the interest of NGOs in the field of agroecology will also grow in the future and, in consequence, direct agricultural practice will begin to play a more important role.

What has a significant effect on the development of agroecology is the sphere of research and education. In most of the Eastern European countries under review, there are study programs (fields) in Agroecology available at universities (Table 5). In the Czech Republic, the study field named Agroecology may be studied on all levels (Bachelor, Master, PhD); in Romania, these degrees are also available, but the study fields are called Ecology and Environment Protection and cover subjects such as Organic Farming and Ecology. Since 1993, the PhD degree may be obtained in Hungary (programs: Crop Production, Agroecology). The Bachelor study field called Agroecology also appears in Slovakia, where it is supposed to be accredited in 2018. A Master study program is available in most cases, but in a number of countries, Agroecology is also included in another study field with a different name, which is e.g., the case in Bulgaria, Poland, or Slovakia, where Agroecology is included as a separate subject in other study programm, or in Hungary, where there is no study field called Agroecology, although there are 54 Bachelors, 52 Masters, six undivided Master, and 16 VET (Vocational Education and Training) programs currently accredited in the country.

Table 5. Education and research in agroecology.

		BG	CZ	HU	PL	RO	SK
Existing study programmes at universities/colleges	Bc.	No	Yes	No	No	Yes	Yes *
	MSc.	Yes	Yes	No	Yes	Yes	Yes
	Ph.D.	No	Yes	Yes	No	Yes	No
Number of universities/colleges offering a study program in Agroecology		2	3 ***	1	1	16 **	1
Are there any lower-tier schools offering a study program in Agroecology?		Yes	No	No	No	No	No
Are there any research institutions (or their separate departments) directly addressing Agroecology?		No	No	No	No	No	Yes

* The study field will be accredited in 2018; ** The study fields have different names but their contents are identical; *** In one case the study field has a different name, but its content is identical.

At lower education levels, the Agroecology program is available only in Bulgaria, where it is taught in a majority of the secondary schools that feature agriculture (Table 5). In the other countries under review, the topic is included in other programs that are focused in particular on sustainable forms of agriculture, organic farming, environment, ecology, etc.

Except for Slovakia, where there is the Agroecology Research Institute in Michalovce, in none of the countries under review was there any research institution or its separate department directly focused on agroecology (Table 5). Agroecology or its parts are mostly included in other topics, e.g., at the Institute of Soil Biology of the Academy of Science of the Czech Republic (CZ), the Agricultural Academy in Sofia, the Agricultural University in Plovdiv, the University of Forestry in Sofia, Trakia University in Stara Zagora (BG), the Institute for Soil Sciences and Agricultural Chemistry and Centre for Agricultural Research in the Hungarian Academy of Sciences; the National Agricultural Research and Innovation Centre and the Agro-Environmental Research Institute (HU), and the National Research and Development Institute for Soil Science, Agrochemistry, and Environmental Protection (RO). In the past, in Poland, there was the Department of Agroecology at the Institute of Ecology of the Polish Academy of Science. In the Czech Republic, this sphere was addressed by the Institute of eco-agrotechnics, but those institutions do not exist anymore.

In practice, agroecology receives support in all of the countries under review, mostly from the programs connected with the European subsidy schemes, which address various topics falling under agroecology (Table 6). For example, in Poland or the Czech Republic, this concerns agro-environmental measures/programs, in particular. In Slovakia, the Ministry of Agriculture and Rural Development of the Slovak Republic also funds the Research Institute of Agroecology in Michalovce as part of the National Agricultural and Food Center.

Agroecology, or topics falling under this field, is supported in the field of research (Table 6) in the Czech Republic, Hungary, Poland, and Romania. In Bulgaria and Slovakia, the topic of agroecology may appear as part of calls of subsidy agencies, but there have not yet been any programs focused substantially on the support of agroecology or its parts. In the Czech Republic, agroecological topics are regularly announced e.g., in the program Earth under an agency of the Ministry of Agriculture; in Hungary, topics falling under agroecology form part of the Environmental Program of Hungary; in Romania, they are e.g., part of the Small Grants Program (SGP) of Global Environment Facility (GEF) (e.g., sub-program Smart Innovative Agroecology in Terms of Climate); and in Poland, there is support of organic farming as well as agri-environment schemes' (AES) scientific programm.

Table 6. Support of agroecology development.

	BG	CZ	HU	PL	RO	SK
Are there any national programs to support agroecology in practice?	Yes	Yes	Yes	Yes	Yes	Yes
Are there any national programs to support research in agroecology?	No *	Yes	Yes	Yes	Yes	No *
Apart from the Ministry of Agriculture, do other ministries address agroecology?	Yes	Yes	Yes	Yes	Yes	Yes

* The topic of agroecology may appear in some calls of subsidy agencies.

In all of the countries under review, agroecology is addressed in particular under the responsibility of the Ministry of Agriculture, but some other ministries (Table 6), mostly the Ministry of the Environment (BG, CZ, PL, RO), are also involved everywhere. Agroecology is also marginally addressed in the Czech Republic by the Ministry of the Interior or by the Ministry of Education, Youth and Sports; in Slovakia by the Ministry of Education, Science, Research and Sports of the Slovak Republic; in Romania by the Ministry of Waters and Forests and by the Ministry of National Education; and in Hungary by the Ministry of the Interior and by the Prime Minister's Office.

Although the influence of movements and NGOs on the development of agroecology is regarded to be quite high in the countries under review, we cannot find any NGOs focused primarily on agroecology (Table 7). The two exceptions are: Hungary, where there is an NGO addressing agroecology as the main topic, namely Agrofutura, which has been dealing with these issues over a long period and, apart from the support of research, also educates farmers; and Romania (e.g., Solidarity and Hope Foundation Iasi's Center for Agroecology). However, agroecology or its parts are considerably addressed by movements and NGOs that are aimed particularly at the environment, ecology, or organic farming (Figure 2). The topics that the movements and NGOs regard as the most important are ecology (CZ, HU, RO, SK), the environment and human impacts on the environment, organic farming (BG), and the related food quality, or the aforementioned topics are in balance (PL), and agroecology is included in them rather than being a separate topic.

Table 7. Movements focused on agroecology and consultancy.

		BG	CZ	HU	PL	RO	SK
Are there any NGOs focused directly on agroecology?		No	No	Yes	No	Yes	No
Are there consulting organizations focused directly on:	Agroecology	Yes	No	Yes	No	No	No
	Ecological farming	Yes	Yes	Yes	Yes	Yes	Yes
	Conventional farming	Yes	Yes	Yes	Yes	Yes	Yes
	Ecology	Yes	Yes	Yes	Yes	Yes	Yes
What is mostly addressed in consultancy?		CF	E	CF	CF	E	CF

CF = Conventional farming; E = Ecology.

Considering that the involvement of farmers in agroecological issues has been rather low so far, agroecology is also only marginally covered in consultancy (Table 7). Consulting organizations specialized in agroecology operate in Bulgaria (Association of Agroecological Farm Producers—AAFP, Sofia, Bulgaria) and Hungary. In other countries, the aspects of agroecology are covered by consultancy mainly in the fields of ecology (environment) and organic farming, and to a lesser extent in the consultancy for conventional farming.

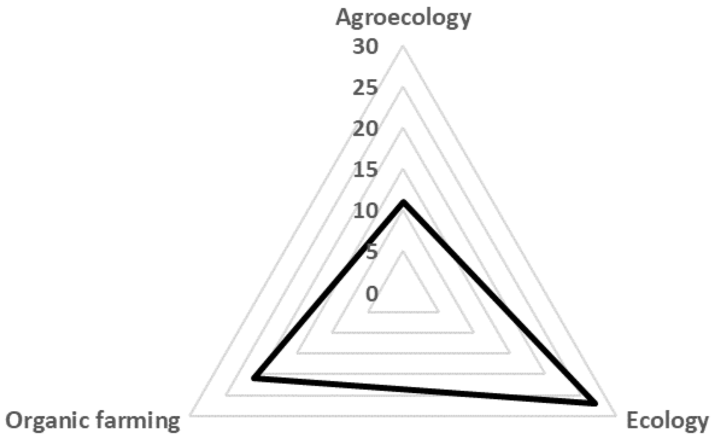

Figure 2. Focus of environmental movements and NGOs.

Consultancy as a whole is mostly aimed at conventional farming (BG, HU, PL, SK) or the environment and ecology (CZ, RO); ecological farming is covered less in consultancy (also because of its considerably lower extent).

The development of agroecology largely depends on the approach of farmers. In the countries under review, the agroecological principles are practically fulfilled rather unwittingly in organic farming, and the perception of agroecology as a separate field is low. In the Eastern European countries under review, agroecology often began to be mentioned and developed earlier than ecological farming, which began to appear more massively after the break-up of the Eastern Bloc and the change of the regime in individual countries at the end of the 1980s and beginning of the 1990s. Agroecology as a scientific field responds in particular to the environmental problems of agricultural practice and, from this point of view, it is closely linked to agriculture. However, at the same time, agricultural practice (including ecological one) makes insufficient use of the agroecological research outputs for its development, thus making this link one-sided to a certain degree.

This is also connected with a quite low perception of agroecology as a separate field by farmers (Table 8). In all of the countries under review, agroecology is a rather unclear concept for a majority of farms, and its elements are systematically developed only by a minority of farms (mostly ecologically managed ones). The impact of education is also visible here; e.g., in Slovakia, agroecology graduates have a considerably larger knowledge than most of farmers and also use such knowledge in practice. A lower knowledge of agroecological principles possessed by a majority of farmers is also evident from the perception of the introduced cross-compliance in the EU, which is understood by a majority of farmers rather as another of the series of regulations that have to be fulfilled in order to get subsidies. Only a small portion of farmers fully understands the environmental benefits and their positive impact on farming itself.

Table 8. Agroecology and agricultural practice.

	BG	CZ	HU	PL	RO	SK
Do farmers perceive agroecology separately from ecological farming? *	2	2	2	2	2	2
Has the introduction of cross-compliance in the EU raised the awareness and interest of farmers in agroecology?	No	No	No	No	No	No

* Evaluation scale 1–5 (1 = almost none 2 = minority 3 = half 4 = majority 5 = almost all).

Given certain similarities in the current state of agroecology in the Eastern European countries under review, the expected development of agroecology is also predicted to be quite similar. Agroecology will continue being developed as a scientific field linking production and environmental aspects of agriculture, and agroecological research has to be coordinated, institutionalized, and closely interconnected with education. The inclusion of agroecological topics in agricultural education on professional and university levels will enhance the agroecological knowledge of professionals and farmers, and it will also be important to educate the broader public. The support of agroecology by government institutions is an important factor and a tool to achieve sustainable farming. The form of support of ecological farming should be extended to the targeted support of agroecological procedures and conventional production as well. Assertion of agroecology in practice will be slower and conditioned by the understanding of its principles both by the government authorities and the farmers.

4. Conclusions

The development of agroecology is closely linked to the development of organic farming in Eastern European countries under review. Between the 1950s and the 1990s, there were considerable differences among the individual countries of Eastern Europe. The collectivization, specialization, and intensification of agriculture have progressed the most in the former GDR, Czechoslovakia, and Hungary. In these countries, research has focused primarily on an increase in production, and the environmental impact has been more pronounced than in other countries of the Eastern Bloc. It has been, and still is agroecology that deals with this impact. Although both educational and research activities within the framework of agroecology appear even earlier, it is only in the 1990s that their massive development takes place. Due to a lesser emphasis on finding a balance between the organic and production components of agriculture before 1990 compared to Western European countries, it is thus more necessary to implement the principles of agroecology in practice and mitigate the impact of intensive agriculture, which is oriented almost exclusively on economic efficiency. The conservative approach of a significant part of farmers that still hinders their relationship with nature, especially in production areas, and technical, technological, and biotechnological progress has been more focused on the production side of agriculture and its intensification rather than on compatibility with agroecology, although it can be well used to fulfill its principles. It can be assumed that, within conjunction with other outputs in the sphere of biotechnology, biophysics, etc., the importance of agroecology as a scientific field dealing with the balance between production and non-production functions of agroecosystems will grow.

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Szarvasi-1 and Its Potential to Become a Substitute for Maize Which Is Grown for the Purposes of Biogas Plants in the Czech Republic

Jaroslav Bernas *, Jan Moudrý Jr., Marek Kopecký, Petr Konvalina and Zdeněk Štěrba

Department of Agroecosystems, Faculty of Agriculture, University of South Bohemia in České Budějovice, Branišovská 1457, 370 05 České Budějovice, Czech Republic; jmoudry@zf.jcu.cz (J.M.J.); kopecm01@zf.jcu.cz (M.K.); konvalina@zf.jcu.cz (P.K.); zsterba@zf.jcu.cz (Z.Š.)

* Correspondence: bernas@zf.jcu.cz; Tel.: +420-387-772-401

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Abstract: The domestic biogas market has been developing rapidly, and legislation (The Act) supporting the use of renewable energy sources has come into force. In light of this act and investment support from national programs co-financed by the European Union (EU), the total number of biogas plants has recently increased from a few to 600. The total capacity of electricity generation of those 600 installed plants exceeds 360 Megawatts (MW) (as of mid-2018). Such dynamic growth is expected to continue, and the targets of the National Renewable Energy Action Plan are projected to be met. The use of waste material, which was urgently needed, was the original aim of biogas plants. However, in certain cases, the original purpose has transformed, and phytomass is very often derived from purpose-grown energy crops. Maize is the most common and widely grown energy crop in the Czech Republic. Nevertheless, maize production raises several environmental issues. One way to potentially reduce maize's harmful effects is to replace it with other suitable crops. Perennial energy crops, for example, are possible alternatives to maize. A newly introduced species for the conditions of the Czech Republic, *Elymus elongatus* subsp. *ponticus* cv. Szarvasi-1, and some other well-known species—*Phalaris arundinacea* L. and *Miscanthus* × *giganteus*—are suitable for Czech Republic climate conditions. This paper presents the findings of the research and evaluation of environmental, energy-related, and economic aspects of growing these crops for use in biogas plants. These findings are based on 5-year small-plot field trials. The energy-related aspects of producing *Elymus elongatus* subsp. *ponticus* cv. Szarvasi-1, *Phalaris arundinacea* L., and *Miscanthus* x *giganteus* are reported on the basis of experiments that included measuring the real methane yield from a production unit. The economic analysis is based on a model of every single growing and technological operation and costs. The environmental burden of the individual growing methods was assessed with a simplified life cycle assessment (LCA) using the impact category of Climate Change and the SimaPro 8.5.2.0 software tool, including an integrated method called ReCiPe. The research findings show that Szarvasi-1 produces 5.7–6.7 Euros (EUR) per Gigajoule (GJ) of energy, depending on the growing technology used. Szarvasi-1 generates an average energy profit of 101.4 GJ ha^{-1}, which is half of that produced by maize (214.1 GJ ha^{-1}). The environmental burden per energy unit of maize amounts to 16 kg of carbon dioxide eq GJ^{-1} compared with the environmental burden per energy unit of Szarvasi-1, which amounts to 7.2–15.6 kg of CO_2 eq GJ^{-1}, depending on the yield rate. On the basis of the above-mentioned yield rate of Szarvasi-1, it cannot be definitively recommended for the purpose of biogas plants in the Czech Republic.

Keywords: Szarvasi-1; biogas; environmental aspects; economy

1. Introduction

Central Europe and the Czech Republic are characterized by intensive farming, and there has been an overproduction of produced commodities (raw materials and foodstuffs), as well as problems with their sale. Energy generated from biogas shows that this industry has the potential to stabilize the farming sector. Biogas can be made from agricultural products, waste, or animal excrements [1]. The term "biogas" means a mixture of gases generated by the anaerobic fermentation of wet organic matter carried out with equipment (reactor, digester, etc.) called a biogas plant (BGP) [2]. Considering the current conditions in the Czech Republic, biogas is used mostly for the combined generation of energy in so-called co-generation units with a reciprocating combustion engine. The year-long use of biogas stations requires a continuous supply of organic matter to the fermenter. Therefore, input plant material has to be conserved (ensiled). Forage crops (*Dactylis glomerata*, *Arrhenatherum elatius*, *Phalaris arundinacea*, etc.) are frequently used as input material [3]. Mužík and Kára [4] stated that most of the plant material used for the generation of biogas is produced by agriculture. Farm animal excrement, side products of crop production, and energy crops are especially common. Species originating the input material (e.g., maize, grass, or manure) have turned out to be the decisive factors determining the impacts of a biogas unit on the environment [5,6]. Plant biomass represents more than 50% of all biogas substrates. Maize silage and other types of phytomass (made mostly from perennial grass) represent up to 80% of the plant biomass. Converted to energy content, plant phytomass input represents up to 80% of the energy content of all substrates [7]. Grasslands have become more significant for the generation of energy. Fallow grasslands can be used for the production of energy crops, and perennial grasslands produce sufficient phytomass. They are considered a very promising solution. As this research shows, there are two possibilities for phytomass use: burning dry phytomass or processing wet phytomass by anaerobic digestion to produce biogas [8].

The number of biogas stations has recently increased considerably in the Czech Republic. The original intent was to use organic waste material in these stations; however, the phytomass of energy crops is mostly used as the primary raw material. Maize is the most frequently used energy crop in the Czech Republic. The production of maize contributes heavily to anthropogenic emissions and poses many environmental problems. Replacing maize with other energy crops has shown promise for reducing environmental impacts. Perennial energy crops are considered good alternatives to maize. *Miscanthus* × *giganteus* (hereinafter referred to as "M × G"), Reed Canary Grass (*Phalaris arundinacea* L.) (hereinafter referred to as "RCG"), and *Elymus elongatus* subsp. *ponticus* cv. Szarvasi-1 (hereinafter referred to as "Sz-1") are three such crops. The last is a new species introduced to the Czech Republic. Biemans et al. [9] emphasized that the large-scale introduction of regionally unknown energy crops requires knowledge of their environmental impacts. Dauber et al. [10] asserted that not only the energy-related and economic aspects, but also the environmental aspects of growing energy crops must be considered. In order to consider the environmental aspects of energy crops, analyses such as a life cycle assessment (LCA) can be employed [11,12]. This paper′s objective is to summarize the findings for *Elymus elongatus* subsp. Ponticus cv. Szarvasi-1, a new energy crop in the Czech Republic, and to consider possibilities for its use on the basis of its environmental, energy-related, and economic aspects.

2. Materials and Methods

2.1. The Life Cycle Assessment Part of The Study

2.1.1. Goal and Scope Definition

The goals of this study are to quantify the environmental burden of the growing cycles of particular energy crops to determine their energy efficiency and to evaluate the economic aspects of growing energy crops. The results of this research may be used to motivate environment-friendly farming systems and as a source of information for agricultural subjects that focus on phytomass and its energetic use. Four crops were analyzed and evaluated, in accordance with LCA norms, to quantify their environmental impacts and to identify the key environmental process. All four crops are considered suitable for biogas processing [13,14].

System Boundaries

This paper describes a technological process for growing energy crops. This process has been set up on the basis of primary (field trials carried out on the University of South Bohemia's land in České Budějovice) and secondary data (the secondary data are from a database called Ecoinvent v3 [15], reference books, and the technical and technological norms for agricultural production). The Ecoinvent v3 database includes data from Central Europe. Primary data were gathered from 2013 to 2017, and secondary data were gathered from 2000 to 2018. The intensity of fertilization and agrotechnological methods were established according to ordinary intensive agricultural technologies [16–25]. Technologies for Sz-1 and RCG were also set up, too. Agrotechnological operations were also incorporated into the model system: from pre-seeding preparation, through harvesting the main product, to the transport of farming machinery, as well as the number of seeds used, the production and use of crop-protecting agents, the production and use of fertilizers, and the harvest and transport of the main product from the harvest site. Infrastructure processes and waste management were excluded from this research. As far as this research and paper are concerned, the transport distance from the factory to the field did not exceed 10 km.

Functional Unit

A functional unit related to a production unit and an area unit was chosen for the purpose of this research. The production unit is expressed as 1 GJ of energy generated by the electrical energy produced from the biogas produced by the anaerobic fermentation process in a co-generation unit; the area unit is expressed as 1 ha of a monoculture of the selected energy crops. The environmental impacts of the processes being researched were not divided into two or more processes (all of the upper plant material was considered the final product in this research), and there were no allocation methods employed.

Sources of Inventory Data

Field trials with the selected energy crops were established for this research. The trials were sources of primary data for LCA and the assessment of energy-related and economic aspects when the life cycle was studied. The station's characteristics are described in following Tables 1 and 2.

Table 1. Temperature and precipitation characteristics—České Budějovice (modified from [26]).

Year	Average Temperature (°C)		Precipitation (mm)	
	Year	Season	Year	Season
2012	9.3	15.3	798.1	567.7
2013	9.1	15.3	685.4	469.5
2014	10.2	15.1	595.9	428.7
2015	10.5	16.9	487.7	233.8
2016	10.5	15.7	680.9	447.7
2017	9.7	16.4	630.3	438.8
Average (2012–2017)	9.9	15.8	646.4	431.0
Long-term average (1961–1990)	8.2	14.2	582.8	366.2

Season (i.e., growing season) includes April, May, June, July, and August.

Table 2. The station characteristics (modified from [26]).

Parameters	
Altitude (MAMSL)	380
Agricultural production region	Cereal production
Soil texture class	Sand-loamy class
Soil type	Pseudogley Cambisol
Soil pH	6.4
Long-term average temperature (°C)	8.2
Long-term seasonal rainfall (mm)	366.2
Global Positioning System (GPS) coordinates	48° 57′ 07″ N; 14° 28′ 17″ E

Investigated Crops

(1) Szarvasi-1 and Reed Canary Grass

Reference stands of the investigated grass species (RCG and Sz-1) were established in accordance with growing technologies (System boundaries). The existing perennial grasses were removed with glyphosate before the reference crops were established. The soil was loosened with a mid-deep plow to 14–18 cm depth and leveled with a cultivator within the framework of pre-seeding preparatory works. Mulch was put onto the land, which was treated with glyphosate in August 2013 before autumnal seeding. Mineral fertilizers were added to the soil before seeding, one year before the crop stand was established. The initial dose of mineral fertilizer per plot (125 × 800 cm) was 300 g of triple superphosphate (hereinafter referred to as SF3), 200 g of ammonium sulphate (hereinafter referred to as AS), 100 g of ammonium nitrate (hereinafter referred to as AN), and 625 g of potassium salt (hereinafter referred to as PS). The initial dose was identical for all plots (Table 3). The fertilizer doses were adjusted according to the purpose of use of every single crop stand. However, doses of fertilizers were different in the productive years (Table 4). For grasslands cultivated for the purpose of BGP, fertilizer was applied in two phases between two dates of mow. The mineral fertilizers AS, PS, and SF3 were applied in spring, before the growing season started, and AN was applied just after the first date of mow. Seeding was carried out on 30 August 2013 using a seeding machine to ensure seeding was accurate and precise. The seeding rate was 5 g of seeds per 1 m^2 for RCG and 2.5 g of seeds per 1 m^2 for Sz-1 (mean germinability of RCG = 39% and mean germinability of Sz-1 = 89% [27]). All plots were rolled after seeding.

Table 3. Methodology of fertilization in a year when the crop stand was established.

	Used Nutrients (kg ha^{-1})					
	Nitrogen (N)		Phosphorus (P)		Potassium (K)	
	Pure	Fertilizer and Its Amount	Pure/Oxide	Fertilizer and Its Amount	Pure/Oxide	Fertilizer and Its Amount
Sz-1	67	AS 200, AN 100	48 (135 of P_2O_5)	SF3 300	30 (37.5 of K_2O)	PS 62.5
RCG	67	AS 200, AN 100	48 (135 of P_2O_5)	SF3 300	30 (37.5 of K_2O)	PS 62.5

Doses of fertilizers were identical every year when the crop stands were established. Sz-1 and RCG see Section 1; AS, AN, SF3, PS see section "Szarvasi-1 and Reed Canary Grass".

Table 4. Methodology of fertilization in productive years.

	Used Nutrients (kg ha^{-1})					
	Nitrogen (N)		Phosphorus (P)		Potassium (K)	
	Pure	Fertilizer and Its Amount	Pure/Oxide	Fertilizer and Its Amount	Pure/Oxide	Fertilizer and Its Amount
Sz-1	100	AS 300, AN 150	10 (28.2 of P_2O_5)	SF3 62.5	30 (37.5 of K_2O)	PS 62.5
RCG	100	AS 300, AN 150	10 (28.2 of P_2O_5)	SF3 62.5	30 (37.5 of K_2O)	PS 62.5

(2) *Miscanthus* × *Giganteus*

The M × G stands were established using accepted practices (section "System Boundaries"). The density of planted rhizomes was 0.5 m × 1 m (Table 5). Mid-deep plowing to 14–18 cm depth was carried out in autumn 2012 (40 tons of manure per hectare were plowed into the soil). Pre-seeding preparatory works were carried out with a cultivator, and the soil was leveled in the spring. Crops were seeded and the soil was rolled and leveled. The newly emerged crop stand of *Miscanthus* × *giganteus* was treated with herbicide in order to protect it from dicotyledonous weeds. Weed control was applied once more during the growing season. This consisted of mechanical inter-row treatment. It is highly recommended to keep M × G crop stands free of weeds in the first year of establishment [25]. Doses of fertilizers were adjusted according to the purpose of use of every single crop stand. For the crop stand grown for the purpose of BGP, fertilizers were applied in two phases between two dates of mow. The intensity of maize fertilization is shown in Table 6.

Table 5. Overview table for *Miscanthus* × *Giganteus*.

Year of Seeding	Density of Rhizomes (m)	Fertilizers	Depth of Plants Seeded (cm)	Area (sq. meters)
2013	0.5 × 1	Mineral	8–10	100

Table 6. Methodology of fertilization of *Miscanthus* × *Giganteus* applied in productive years.

	Used Nutrients (kg ha^{-1})					
	Nitrogen (N)		Phosphorus (P)		Potassium (K)	
	Pure	Fertilizer and Its Amount	Pure/Oxide	Fertilizer and Its Amount	Pure/Oxide	Fertilizer and Its Amount
M × G	70	AN 260	40 (112.5 of P_2O_5)	SF3 250	70 (87 kg of K_2O)	PS 145

The intensity of fertilization of M × G was derived from typical intensive farming methods. M × G crop stands are not usually fertilized in the first crop stand establishment.

(3) Maize (as a Reference Crop)

Maize reference crop stands were established each spring starting in 2013. Buckwheat, spring barley, or oat was the previous crop. The potential influence of previous crops was not taken into account in this study. The plot was prepared before seeding: 20 tons of manure per hectare was applied in autumn and plowed into the soil (mid-deep plow). The plot was leveled with a cultivator within the framework of pre-seeding preparatory works. Seeding was performed with a sowing machine for accuracy and precision. The seeding rate was 30 kg of seeds per hectare. A silage herbicide was applied to the plot. SF3 mineral fertilizer was applied in a dose of 200 kg per hectare during the sowing itself; urea (hereinafter referred to as U) was also applied in a dose of 200 kg per hectare (46% of N); PS was also applied in a dose of 104 kg per hectare. The density of the crop stands was 75 × 13 cm, and seeds were 5 cm deep in the ground. The crop stand was treated chemically with herbicide during the growing season to protect it from dicotyledonous weeds. Another dose of nitrogen was supplied (125 kg of U per hectare) at the phase of the fifth or sixth leaf. The intensity of maize fertilization is shown in Table 7.

Table 7. Methodology of fertilization of maize.

	Used Nutrients (kg ha^{-1})					
	Nitrogen (N)		Phosphorus (P)		Potassium (K)	
Maize	Pure	Fertilizer and its amount	Pure/oxide	Fertilizer and its amount	Pure/oxide	Fertilizer and its amount
	150	U 325	30 (85.5 of P_2O_5)	SF3 190	50 (62.4 of K_2O)	PS 104

The intensity of fertilization of maize was derived from typical intensive farming methods.

Harvest

The interval between dates of mow (and harvest dates) and the dates of mowing were adjusted according to the purpose of use of the phytomass (previous parts of the methodology). Perennial energy crop stands (Sz-1, RCG, and M × G) grown for the purpose of BGP were always mowed and harvested two times per year when dry matter content was 28–38%. Maize crop stands were always harvested once (in September), and the harvest depended on dry matter content (the optimal percentage is 28–35%).

Software Data Inventorization

The cradle-to-gate principle, which is based on calculating the life cycle of a product from material supply to the end of the production (growing) process, was selected for the purpose of this research. The phases of use and removal of the product were not included in this study. Inventorization data from the Ecoinvent database [28] and SimaPro 8.5.2.0 program were used in this study (Table 8). These data were modified and enriched with data gathered from field trials and reference books (Section 2.1.1). SimaPro 8.5.2.0 software with an integrated database called Ecoinvent v3 [28] was used to develop models of the production systems. The inventoried data and details of the collection of the data are described in Section 2.1.1.

Table 8. Inventory table: inputs and outputs of life cycle.

		Standard Conventional Farming Technology			
Output	Unit	Sz-1	RCG	M × G	Maize
	GJ	average energy gain (GJ ha^{-1})			
Input	Unit				
Inputs from technosphere		Sz-1	RCG	M × G	Maize
Ammonium nitrate (as N)	kg	x	x	x	x
Ammonium sulphate (as N)	kg	x	x		
Application of plant protection products by field sprayer	ha	x	x	x	x
Combined harvesting	ha	x	x	x	x
Fertilization by broadcaster	ha	x	x	x	x
Glyphosate	kg	x	x	x	x
Grass seed	kg	x	x		
Herbicide at plant	kg	x	x	x	x
Maize seed for sowing	kg				x
Manure, solid, cattle	kg			x	x
Miscanthus rhizome for planting	p			x	
Nitrogen fertilizer (as N), urea ammonium nitrate production	kg				x
Planting	ha			x	
Potassium chloride (as K_2O)	kg	x	x	x	x
Solid manure loading and spreading by hydraulic loader and spreader	kg			x	x
Sowing	ha	x	x		x
Tillage, harrowing by rotary harrow	ha	x	x	x	x
Tillage, harrowing by spring tine harrow	ha	x	x	x	
Tillage, plowing	ha	x	x	x	x
Tillage, rolling	ha	x		x	x
Transport, tractor, and trailer, agricultural	tkm	x	x	x	x
Triple superphosphate (as P_2O_5)	kg	x	x	x	x
Inputs from nature					
Land occupation	ha	x	x	x	x
Inputs in the air					
Carbon dioxide (from fertilizers)[IPCC]	kg	x			
Dinitrogen monoxide (from fertilizers)[IPPC]	kg	x	x	x	x

Inventory of input and output data; × = input from Ecoinvent 3 database; calculated in accordance with the IPCC (Intergovernmental Panel on Climate Change) methodology (Section "Determination of Field Emissions").

2.1.2. Life Cycle Impact Assessment

A simplified life cycle assessment method is an instrument for emission load calculations and is defined by specific norms [13,14]. The results of this research are related to the impact category of climate change, which is expressed in carbon dioxide equivalents.

SimaPro 8.5.2.0 software and ReCiPe Midpoint (H) V1.13/Europe Recipe H., an integrated method, were used for emission load calculations. One GJ of final product (dry matter) energy and an area unit (1 ha) were used as functional units. The technological processes of growing the selected crops were set up on the basis of primary data (field trials carried out on plots at the University of South Bohemia) and secondary data (data gained from the Ecoinvent v3 database, reference books, and technical and technological norms for agricultural production—see System boundaries). Data related to Central Europe were determined from the database. Primary data were collected from 2013 to 2017 and secondary data were collected from 2000 to 2017. The intensity of fertilization and agrotechnological methods were determined on the basis of typical intensive farming technologies. All of the agrotechnological operations—from pre-seeding preparatory works to the number of planted seeds, production and application of herbicides, production and application of fertilizers, transport of agricultural machinery, harvest and transport of the main products—were incorporated into the model system. The calculated emissions included not only those produced by the above-mentioned processes but also field emissions produced (especially dinitrogen monoxide ones). Emissions are mostly caused by nitrogenous fertilizers (farm or industrial ones) [29,30]. The Intergovernmental Panel on Climate Change (IPCC) methodology was used to calculate the quantity of emissions [31–33].

The results of the five-year growth of maize, RCG, Sz-1, and M $\times$ G for energy-generating purposes are summarized in this paper. According to the methodology applied and data gathered during the study period (dry matter yield rate, inputs and outputs of cycle of growth), the life cycles (from pre-seeding soil preparation to harvest, transport, and silage of the harvested material) of the above-mentioned crops were determined, and the environmental impacts were calculated. As mentioned above, the results of this research are related to the impact category of "climate change", which is expressed in carbon dioxide equivalents (CO_2 eq = 1 $\times$ CO_2; 2 $\times$ CH_4; 298 $\times$ N_2O). The metric is based on the efficiencies of greenhouse gases [34,35]. The potential impact of N_2O and CH_4 emissions (they are produced by crops grown on arable land) on global warming (one-hundred-year interval) is 298 times and 23 times higher than the potential impact of carbon dioxide [36].

Determination of Field Emissions

The application of mineral and organic nitrogenous fertilizers results in the release of so-called direct and indirect emissions of dinitrogen monoxide (expressed as carbon dioxide equivalents). The emission load was determined in accordance with the IPCC methodology called Tier 1 [31] and the Czech national report on the inventory made of greenhouse gases (the agricultural section) [37].

2.2. Biogas Efficiency Determination

Biogas (or methane) efficiency was determined in this study. On the basis of the resulting values, the suitability of each energy crop for BGP purposes was determined.

A tested substrate was incubated in BGP fermenter digestate. It did not show any abnormalities, such as acids, pH, etc. A mixed digestate of fermenters from various BGPs was used, with various "nutrition" sources for bacteria: maize, grass, beef slurry, etc. All BGPs using residual substrates, pork slurry, bird excrement, etc. were excluded from the digestate. The digestate was filtered before use with a 2-mm sieve and then incubated at 40 °C for one week. Homogenized substrate was added to it, and it was incubated in anaerobic conditions at 40 °C. Gas was caught in a flask with a scale and the quantity was determined. Entering this flask was gas bubbling through a solution of NaOH, and carbon dioxide was captured while CH_4 was produced. There was a negligible error caused by minor gases that were not captured in the hydroxide. The quantity of such gas was up to 2%.

The incubation lasted until the substrate's potential was exhausted, and the inoculum was used as a blind sample. The quantity of gas generated during this blinded test was deducted from the results for the substrate. There was measurement uncertainty expressed as the extended uncertainty with a coefficient of expansion of $k = 2$ (significance level of 95%). The above-mentioned uncertainty did not apply to any values below the limit of quantification.

2.3. Economic Efficiency

The economic analysis was based on models of all growing and technological operations and costs. This analysis included an economic assessment of the variable and fixed costs of machinery, the total costs of 1 ha, yield of the main product, costs of a unit of the main product (1 GJ of generated energy), and profit in the case of market production and use in both directions. The technical and technological norms for agricultural production and input data on growing perennial crops in practice were used as sources of information and examples.

The costs of growth include all the costs associated with growing energy crops. The costs of establishment, fertilization, harvest, field and road transport, weed control, and overhead costs are considered the main costs. Most of the expenses include the cost of work and machinery equipment.

3. Results and Discussion

3.1. Phytomass Yield and Potential Profit

Dry matter yield is presumed to be the primary figure of the total assessment. As expected, maize produced the highest average yield of phytomass (or dry matter) (14.4 tons of dry matter per hectare, on average). It produced a relatively stable yield in a short period of time compared with perennial crops. Table 9 shows the summary results achieved during the first four years of crop growth. Perennial crops produced <1/2 of the overall dry matter yield of maize during these four years. M × G was the highest-yielding perennial crop (9.6 tons of dry matter per hectare, on average). From this perspective, the period for which perennial crops and maize were compared is untimely, as perennial crops usually achieve their yield potential three years after the crop stand is established [22,26]. The yield potential is as follows: 12 tons of dry matter per hectare for RCG [24,38], 15–25 tons of dry matter per hectare for M × G [16,39–42], and <15 tons of dry matter per hectare for Sz-1 [22,43]. The fact that C4 crops (maize and M × G) are considered more efficient energy crops than C3 grasses (RCG and Sz-1) has to be taken into account; C4 crops have higher photosynthetic rates [16]. The fact that the perennial crop stands were not harvested in the first year (compared with maize) was also considered. However, when evaluating the environmental burden during our four-year cycle, the first year must also be included in this evaluation (because of energetic inputs).

Table 9. Summary of final figures: average harvest used for BGP.

Crop	Dry Matter ($t\ ha^{-1}$)	CH_4 (m^3)	Energy ($GJ\ ha^{-1}$)	Area Needed for Generating the Same Energy Gain (ha)	kg CO_2 eq GJ^{-1} 4-Year Average	kg CO_2 eq GJ^{-1} 10-Year Average
Maize	14.4	5981	214.1	1	16.0	13.3
M × G	9.6	3422	122.5	1.7	16.2	8.1
RCG	8.6	2920	104.5	2.0	16.9	7.6
Sz-1	8.6	3171	113.5	1.9	15.6	7.2

Average yield of phytomass does not include the first non-productive year—the one in which the crop stand is established (compared with the average emission load).

Yield of phytomass, harvest time [44], and silage capacity [45,46] play crucial roles in the overall yield of methane [47,48]. To test the specific efficiency of CH_4—the amount of methane produced by 1 kg of dry matter ($m^3\ CH_4\ kg^{-1}$ of dry matter)—the values were calculated. Depending on the yield in the first four years, maize can produce three-fold higher amounts of methane (or energy in GJ per hectare) than perennial crops. Statistical assessment (Least Significant Difference—LSD test) and variance analysis (ANOVA) are shown in Tables 10 and 11, which show that yield is influenced by the intensity of treatment and energy-related parameters ($p \leq 0.05$) by species (Table 10). Analysis of variance (ANOVA) shows that energy efficiency is statistically significant ($p \leq 0.001$) and influenced by species (more than 63%) (Table 11).

Table 10. LSD (Least Significant Difference) test: impact of species on average yield of phytomass (kg ha^{-1}) and on average energy efficiency (GJ ha^{-1}).

Homogeneous Groups, alpha = 0.05 Error: Intergroup. AS = 12180000, df = 44.00		**Homogeneous Groups, alpha = 0.05 Error: Intergroup. AS = 2408.0, df = 44.00**
Species	Average yield of phytomass	Average energy efficiency
Maize	14,457.71b	215.28b
M × G	9622.67a	122.30a
RCG	8582.20a	104.53a
Sz-1	8635.61a	113.56a

Rem.: AS = average square; values indicated by the same letter do not show any statistically significant differences at a level of significance of $p < 0.05$; df = degrees of freedom

Table 11. One-dimensional tests of significance for the average yield of phytomass (kg ha^{-1}) and the average energy efficiency (GJ ha^{-1}) (ANOVA analysis).

	Average Yield of Phytomass			**Average Energy Efficiency**		
Factor	df	AS	%	df	AS	%
Species (1)	3	9.38 ***	33.87	3	31,728.1 ***	63.86
Year (2)	2	8.97 *	32.39	2	2669.0 ***	5.37
1*2^{fc}	6	7.55 ***	27.27	6	14,983.3 ***	30.16
Error	36	1.79	6.47	36	297.6	0.61

Rem.: df = degree of freedom; AS = average square; * = statistically significant, $p \leq 0.05$; *** = statistically significant, $p \leq 0.001$; ^{fc} = factor combination; df = degrees of freedom.

Crops were harvested in accordance with the methodology and on the dates shown in Table 12; the dry matter content at the time of harvest was recorded (Table 13). There are many recommendations for fixing the date of mow; nevertheless, the date of harvest is not crucial for the overall efficiency of methane [43]. For example, Mast et al. [49] recommended fixing the date of the second mow of Sz-1 to at least the beginning of October.

Table 12. Dates of mow of perennial crops and maize.

Date of Mow	**I.**	**II. (Harvest of Maize)**
2013	-	15 September
2014	6 June	30 September
2015	12 June	1 October
2016	2 June	13 September

Perennial crops were harvested in two phases. Perennial crop stands were not mowed in the first year.

Table 13. Average dry matter content in phytomass at the moment of harvest (%).

	Sz-1	**RCG**	**M × G**	**Maize**
Average dry matter content in phytomass at the moment of harvest (%)	38.3	40.0	36.3	36.7

Perennial grass yields were higher in the initial years; this finding is confirmed by the statistical assessment ($p \leq 0.05$) (LSD test) (Table 14). Therefore, it is possible to determine the optimal date of Sz-1 harvest for the purpose of BGP according to lignocellulose content. Alaru et al. [50] stated that Sz-1 contains an average of 38% cellulose, an average of 27% hemicellulose, and an average of 10% lignin. *Miscanthus* (*Sacchariflorus*) contains 42% cellulose, 30% hemicellulose, and 7% lignin. Hemicellulose is hydrolyzed more easily and produces more methane and less tar than cellulose. Both are more biodegradable than lignin. The total methane efficiency depends on the lignin content: every 1% of lignin in the biomass decreases the methane efficiency by 7.49 L of CH_4 kg^{-1} (on average) [50].

Table 14. LSD test: average dry matter content (kg ha^{-1}) in perennial crops (RCG, Sz-1, M × G) during every mow.

Homogeneous Groups, Alpha = 0.05000. Error: Intergroup. AS = 3825000, df = 166.00	
Mow	average dry matter yield
1	4961 b
2	2932 a

Rem.: AS = average square; values indicated by the same letter do not show any statistically significant differences at $p < 0.05$; df = degrees of freedom.

There were no significant differences in methane efficiency [CH_4 (l kg^{-1} of dry matter)] between the dates of mow [49,51]. However, methane efficiency depends greatly on the lignin content. So, methane efficiency increases if the date of harvest is postponed. The dates of mowing were fixed in this study. Hemicellulose, cellulose, and lignin are the three main elements of biomass and they usually represent 20–40%, 40–60%, and 10–25% of lignocellulose biomass [52]. Cellulose is the most common organic compound on Earth; biomass cell walls are mostly made of it, and it typically represents 33% of plant biomass [50]. However, there is a lack of information on the optimal Sz-1 harvest date for the purpose of BGP [49].

Table 13 shows the average content of dry matter (%) in the phytomass at harvest, and it plays a crucial role in the silage process and biogas (or methane) efficiency. For perennial crops, the average content of dry matter was higher at the time of the second mowing [49]. In most cases, there is high-quality silage and the highest efficiency of biogas if dry matter represents from 28% to 35% of the biomass [51,53]. A low content of dry matter worsens the silage quality and lowers the water leakage and biogas efficiency [54]. On the other hand, if the optimal level of dry matter content is exceeded, it becomes less degradable, less storable, and of lower quality [53]. Qualitative and quantitative parameters of phytomass (or silage) determine and influence the efficiency of growth. The results of this assessment are shown in Tables 15 and 16.

Table 15. Results of assessment of silage samples.

	Sz-1	**RCG**	**M × G**	**Maize**
CH4 (l kg^{-1} of dry matter)	367.2	340.3	355.0	416.0
CH4 (l kg^{-1} of sample)	94.9	102.3	70.2	127.7
CH4 (l kg^{-1} of organic dry matter)	410.7	377.4	414.7	434.6
Burnt heat (MJ kg^{-1} of dry matter)	14.6	13.5	14.1	16.6
Calorific value (MJ kg^{-1} of dry matter)	13.1	12.2	12.7	14.9
Dry matter (g kg^{-1} of sample)	240.50	288.00	208.30	283.20
Nitrogenous elements (g kg^{-1} of sample)	23.89	22.36	20.54	19.89
Fiber (g kg^{-1} of sample)	71.40	75.85	74.08	56.02
Ash (g kg^{-1} of sample)	30.78	30.37	17.31	12.14
Lactic acid (g kg^{-1} of sample)	19.54	22.20	4.50	17.48
Acetic acid (g kg^{-1} of sample)	3.84	3.20	3.87	2.15
Butyric acid (g kg^{-1} of sample)	0.00	0.00	0.00	0.00

Values come from the analyses performed in accordance with the methodology described in Section 2.2.

Table 16. CH_4 yield depending on phytomass yield (m^3 of CH_4, Σ for 4 years).

	m^3 of CH_4, 4-Year Sum
Maize	23,922.1
M × G	10,264.5
RCG	8761.0
Sz-1	9512.7

Maize is considered the most promising crop for high methane efficiency [47,51,53], as confirmed by this research. Mast et al. [49] revealed similar methane efficiencies for Sz-1 and maize: Sz-1 = 376–311 L CH_4 kg^{-1} of organic dry matter [3340 Nm^3 ha^{-1} (28 June) and 4156 Nm^3 ha^{-1} (18 July)]; maize = 349 L CH_4 kg^{-1} of organic dry matter (6008 Nm^3 ha^{-1}). Sz-1 has potentially high methane efficiency [51], so it is presumed to be competitive with maize. It creates methane more slowly than the other crops (in the first 10 days in particular). According to Lhotský and Kajan [7], a selected species of grass (in a sample) produced 502–530 lN (norm liters) of biogas per kg of organic dry matter, and maize produced 621 lN of biogas per kg of organic dry matter. There were no dramatic differences between the biomass samples in that study. Such results show that perennial grass phytomass can be a suitable and economical alternative, and biogas can be one of its products; e.g., appropriate conditions may apply in submontane regions, where there is little arable land. Methane content plays a crucial role in biogas. Mast et al. [49] stated that CH_4 represents 52.6% of the biogas made from maize and 53.2% of the biogas made from Sz-1.

The volume weight values also determine how certain crops are used for BGP purposes. The average values of volume weight are shown in Table 17.

Table 17. Average values of volume weight.

	Sz-1	RCG	M × G	Maize
Volume weight (kg m^{-3})	577.1	505.8	527.7	752.1

3.2. Environmental Aspects of Production

A life cycle of certain energy crops was created according to the values presented in Section 3.1, the selected methodology, and the data available; the environmental load per 1 GJ of generated energy from phytomass was quantified for the purpose of biogas stations. The results of this research are in accordance with the category of Climate change expressed in carbon dioxide equivalents (CO_2 eq).

Table 18 shows the results of a four-year cycle of growing selected energy crops for the purpose of biogas stations and monitoring the environmental burden (kg of CO_2 eq) according to a production unit (GJ). The results of this research show that Sz-1 imposes the lowest environmental burden per production unit (15.58 kg of CO_2 eq GJ^{-1}). Considering this fact, phytomass yield and potential energy profit have the highest impact. On the other hand, the above-mentioned results show that RCG imposes the highest environmental load (16.88 kg of CO_2 eq GJ^{-1}) and it is a frequent crop involved in the conventional farming system. M × G (16.18 kg of CO_2 eq GJ^{-1}) has a comparable environmental load to maize (15.99 kg of CO_2 eq GJ^{-1}). Taking perennial crop stands grown for 10 productive years into account, we discovered that the production of greenhouse gas (and the environmental burden) per production unit has been changing considerably. Table 9 shows some model values. The environmental burden is quantified for a 10-year cycle, and the value of the reference phytomass yield is published in several available reference books (see Section 3.1). An environmental burden of 13.3 kg of CO_2 eq GJ^{-1} is determined for maize, taking the average dry matter yield of 15 t ha^{-1} into account; this is very similar to the results of our four-year monitoring cycle. Dressler et al. [55] showed very comparable figures to ours: 45.4–57.7 kg of CO_2 eq t^{-1} of fresh silage material, which represents approximately 0.14–0.18 kg of CO_2 eq kg^{-1} of dry matter, depending on dry matter content at the time of harvest. Bacenetti et al. [56] also showed comparable figures to ours: 78.6–82.7 kg of CO_2 eq t^{-1} of fresh silage material. The authors of [57,58] also showed similar results. However, as seen in the models of this 10-year growing cycle for RCG, Sz-1, and M × G, there are considerable differences among these three species. If RCG is grown for 10 years and produces 12 t ha^{-1} of dry matter on average, it will create an environmental burden of 7.6 kg of CO_2 eq GJ^{-1} (about 9.3 kg of CO_2 eq GJ^{-1} less than in the four-year cycle). M × G and Sz-1 have a long-time average yield of about 15 t ha^{-1} of dry matter; if M × G and Sz-1 are grown intensively for 10 years, they will impose an environmental burden of 8.1 kg of CO_2 eq GJ^{-1} and 7.2 kg of CO_2 eq GJ^{-1}, respectively. It is about one-half of the four-year cycle.

Table 18. Emission load (kg of CO_2 eq) according to the production unit (GJ).

System Subprocesses	Maize	M × G	RCG	Sz-1
Organic fertilizers	0.29	0.17	x	x
Mineral fertilizers N	4.14	5.01	5.53	5.10
Mineral fertilizers P	0.65	1.49	1.13	1.04
Mineral fertilizers K	0.13	0.33	0.22	0.20
Seed consumption	0.31	0.31	0.22	0.21
Chemical protection	0.16	0.10	0.11	0.10
Agrotechnological operations	1.93	2.72	2.19	2.02
Transport of harvested phytomass	0.84	1.02	0.87	0.84
Field emissions	7.53	5.06	6.59	6.07
Total environmental burden	15.99	16.18	16.88	15.58

All energy inputs entering the system in the first 4 years are included in the system processes.

To address the potential mitigation of the production of greenhouse gas within the framework of a typical farming process, we have to focus on the largest polluters. As the results of our research show, the production and use of nitrogenous fertilizers and their field emissions are ranked among the top polluters in farming, and the farming process produces the most emissions [30,59–63]. Therefore, addressing the cause means a reduction in fertilizer doses, a complete change in the farming system ([30,64]) or some other instruments [65]. A reduction in fertilizers has been considered crucial for reducing N_2O and NO emissions [59]. The amount of greenhouse gas emissions produced from agriculture is partly influenced and determined by the farming system, too. The conventional farming system is based on higher inputs of fertilizers (organic and mineral ones) that are considered crucial factors for mitigating N_2O and NO emissions produced in the soil [59,66]. N_2O may be considered the main greenhouse gas; the organic farming system usually produces less N_2O and carbon dioxide because of its lower inputs [67]. LaSalle [68] stated that if the organic farming system was applied throughout the USA, it would lead to higher carbon sequestration in the soil and reduce carbon dioxide emissions by one-fourth. There are more possibilities for mitigating the environmental burden, such as replacing existing cultivations and crops (e.g., maize) with some other suitable crops, e.g., certain perennial grass species that have suitable properties [26,45]. However, they are not an adequate substitute for maize from a production point of view [69]. Nevertheless, energy grass species and perennial crops in general impose fewer critical requirements for a fertilizer; therefore, they produce less carbon dioxide during their life cycle and they create fewer significant environmental impacts than all annual energy crops. For example, Hijazi et al. [5] stated that input material (e.g., maize, grass, or manure) is the crucial factor that influences and determines the final and overall impact of biogas production on the environment.

Agrotechnological interventions may also contribute heavily to the emission burden, depending on the intensity of farming; they may have an impact that falls into the climate change category, which is expressed in terms of the consumption of fossil fuels. According to Sauerbeck [70], the consumption of fossil fuels by agriculture is considered less significant when compared with the consumption of fossil fuels in total (about 3–4.5% in very developed and rich countries). Agrotechnological interventions contribute to the environmental burden: 1 GJ of generated energy is equal to 12.1–16.8%. Growing M × G imposes the greatest environmental burden from the technological point of view. Comparing conventional and organic farming systems, both of them produce similar greenhouse gas emissions, which are produced by consuming fossil fuels and using machinery. However, there is a difference caused by the use of synthetic (mostly nitrogenous) fertilizers and pesticides in conventional farming; such a farming system produces >600 kg of CO_2 eq ha^{-1} per year [71]. The transport of harvested phytomass from the field also produces emissions. The environmental burden is decisively influenced by the distance of a farm field and the amount of transported material. The transport represents 5.2–6.3% (or 0.8–1.0 kg of CO_2 eq GJ^{-1}, respectively) of the environmental burden of every single technology. It is not the primary agriculture but the transport that is supposed to be the main polluter of the air; processing the primary agricultural production, production of products, long-time storage, and preparation of food are also considered serious air polluters. A sustainable approach should, therefore, support ecological, environmental-friendly, and regional (or local) production [72,73]. For example, Dorninger and Freyer [74] stated that the regional transport by trucks and lorries in Bavaria produces only 60–76 g of CO_2 eq per kg of cereals; however, the transport from the EU (Poland or Spain in particular) to Bavaria produces 253–359 g of CO_2 eq per kg of cereals. The same amount of emissions is produced by the entire field production in total [75]. Considering all of these facts and findings, it is evident that the environmental value of a product is largely influenced by transport and distance [72]. According to Stratmann et al. [76], the primary agricultural production, processing, and transport produce about 45% of all the emissions. Changes to production processes and the establishment of more environmental-friendly approaches (transport limitations, preference in regional products) may reduce the environmental burden and emissions [77].

Chemical agents (herbicides) play a minor role (≤1%). This also applies to the other herbicides. Although pesticides have a negligible impact on the impact category of Climate change, we have to properly address this issue. Interestingly, there are almost 600 tons of active substances per 1 million inhabitants in the Czech Republic, and only 2 kg ha^{-1} of active substances fall upon the arable land (compared with 3.5 kg ha^{-1} in Germany and almost 11 kg ha^{-1} in the Netherlands) [78].

The contributions of every input and output of the monitored four-year growing cycle to the total emissions and environmental burden are shown in Figure 1.

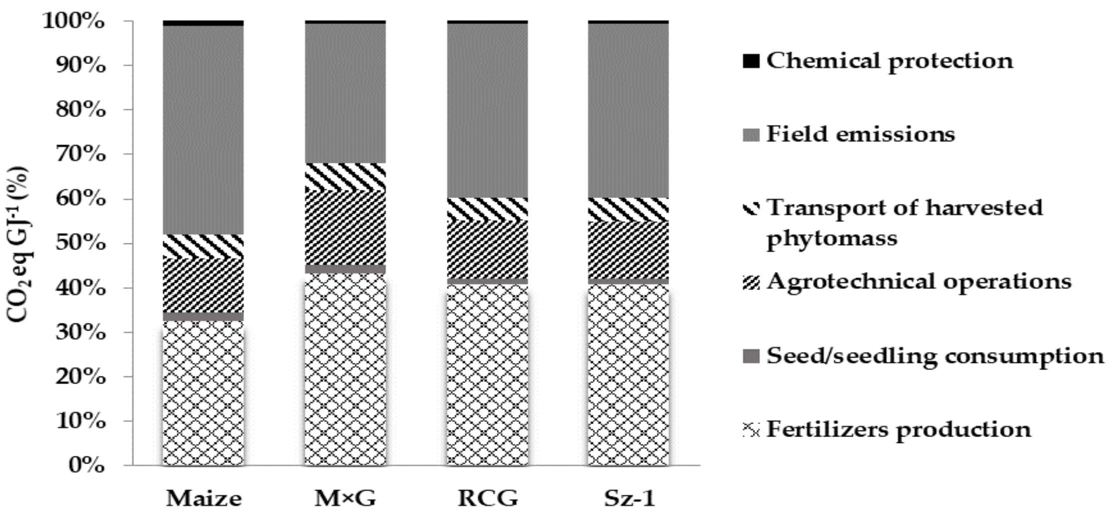

Figure 1. Contributions of every process to the total environmental burden (%).Identical contribution of RCG and Sz-1 and every process to the total environmental burden (%) is caused by identical farming technology used.

Greenhouse gas emissions per area unit (1 ha) are another monitored aspect and evaluated category. It includes all the material and energy flows for every year. Hectare yield is not included in the evaluation in this case. The category breakdown is shown by the graph in Figure 2. Agricultural production, land use, fertilizers, and energy consumption (from non-renewable resources) in particular contribute significantly to environmental degradation. Increase in biogas efficiency, environmental-friendly farming approaches, and perennial agriculture development are presumed to be the main eventualities [79,80]. Savings in GHC biogas production should be calculated not only per production unit (e.g., kg of CO_2 eq GJ^{-1}), which is how most LCA outputs are determined [81], but also per area unit and time unit (MJ/ha/year) [12]. However, many LCA inputs are usually calculated per production unit [81].

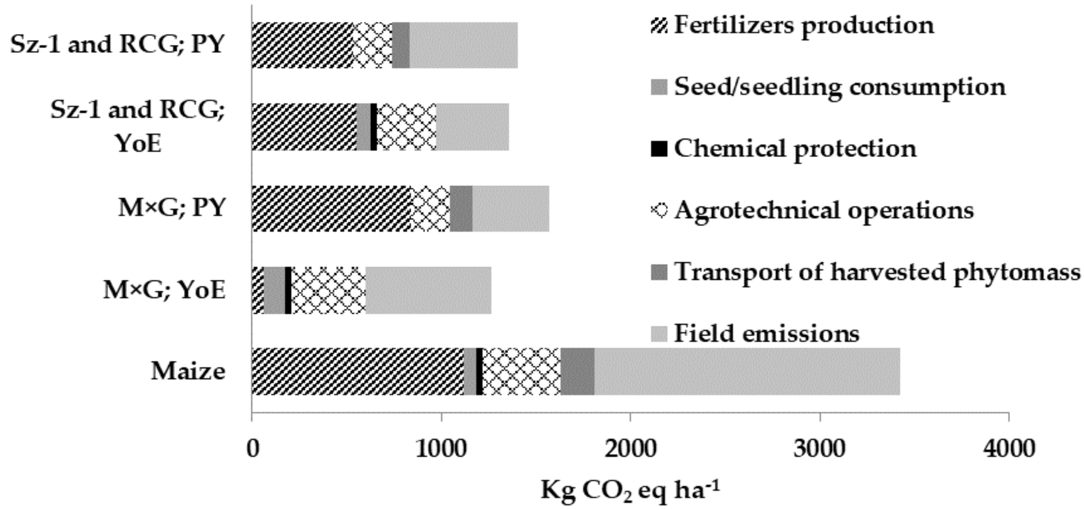

Figure 2. Emissions per area unit. PY = productive year, YoE = year of establishment.

Figure 2 shows the major differences in greenhouse gas production per area unit (1 ha) between maize, RCG, Sz-1, and M × G. To incorporate the unique farming technology used for maize into the assessment, any differences between greenhouse gases produced per area unit each year (in accordance with the methodology) were determined. As various farming technologies were employed, the environmental burden of perennial agriculture related to an area unit was divided into several years of establishment (of the crop stand) (YoE) and productive years (PY). The figures in Graph 2 show that conventional maize produces the most emissions per area unit (3422.50 kg of CO_2 eq GJ^{-1}). Considering the perennial character of the other crops, models of the environmental burden per area unit were divided into YoE and PY. An area emission burden of 1266.2 kg of CO_2 eq GJ^{-1} in YoE and 1567.7 kg of CO_2 eq GJ^{-1} in PY was quantified for the M × G crop stand establishment in this research. An emission burden of 1358.5 kg of CO_2 eq GJ^{-1} in YoE and 1406.1 kg of CO_2 eq GJ-1 in PY was quantified for the Sz-1 and RCG crop stand establishments. Field emissions are the most significant type of emission: during the first four years of our research, maize produced about 1611.9 kg of CO_2 eq ha^{-1} per year, and the perennial crops produced about 384.4–666.9 kg of CO_2 eq ha^{-1} per year, depending on the employed technology. Recalculated to carbon dioxide eq, it reflects the findings of [66,82,83] on clover grasses. Maize imposes a much higher environmental burden than the other tested crops. The environmental burden of maize per area unit is, nevertheless, comparable to the other crops. Generally speaking, and from the point of view of emission burden per area unit, growing perennial crops (Sz-1, RCG, and M × G) is more environmentally-friendly than growing maize. Some other authors have also confirmed this fact, e.g., [46,84]. These crops also provided an adequate yield that is comparable to maize (seen on the long-time horizon).

3.3. Economic Evaluation

A lot of European (e.g., [85–87]) as well as Czech (e.g., [17,40,88–90], etc.) authors have previously studied and evaluated the economic efficiency of energy crops. It is difficult to compare the results of two different research studies, as they may have applied different methods, preconditions, or frameworks. The following table (Table 19) shows the potential costs of 1 GJ of generated energy, taking the intended use of energy crops into account. Data were collected for almost five years, and the economic balance was determined according to the methodology defined for this research's purpose (Section 2.3). The economic aspect is the determinant of whether or not a certain crop is included in the cropping, as whether perennial energy crops are accepted by farmers or not depends on their financial profitability [87].

Table 19. Price of to 1 GJ of generated energy.

	Maize	M × G	RCG	Sz-1
EUR GJ^{-1}	6.1	8.6	7.0	6.4

The prices mentioned in this paper are comparable to European standard prices of EUR 5–8 per GJ of energy, as reported in 2009 [87]; nowadays, they are used as indicators of the overall assessment.

Costs per area unit (ha) of maize grown are usually higher than the costs of any other energy crops [91]. However, when comparing costs per unit of generated energy (1 GJ of energy in this case), the situation is the opposite [92] (especially because of a relatively stable and high yield). Our research shows that if phytomass were used in a biogas station, 1 GJ of generated energy would cost EUR 6.1–8.6. Such prices are adequate for the intensity of the growing cycle inputs and for the final phytomass yield (or the potential amount of energy produced). M × G seems to be quite expensive (EUR 8.6 per GJ); this is because the costs of the crop stand establishment are high in this instance, possibly amounting to EUR 2500–4500 per ha, including the preparation of the plot, the purchase of seeds, and the seeding itself [40]. In spite of this, M × G is considered a promising alternative plant. Very desirable economic results may be produced with this crop, depending on the intensity of the inputs and hectare yield [93]. According to our research, Sz-1 and maize seem to be the cheapest options despite intensive maize growing and high input costs (EUR 1150–1350 per ha). Their low costs are due to the annual phytomass yield, which is quite high (14.4 t ha^{-1} of dry matter on average).

The price of phytomass as a fuel (including transport of phytomass) is highly variable and determined by the fossil fuel market price of energy (including the impact of energy policy and environmental policy). In 2009, unrefined biomass cost EUR 4–5 per GJ in Europe. Heat and energy are mostly generated by biomass made from fast-growing trees and perennial crops [87,94]. The prices of energy phytomass have been varying from EUR 1.4 to 5 per GJ in Europe over the last 15 years [87,88,95]. Such a wide range of prices is caused by different factors, e.g., the biomass market being relatively undeveloped. The price of biomass is largely influenced by the costs of transport and processing methods. The final price of biomass is determined mostly by the input costs (wages, transport, etc.); this is generally applicable to all forms of biomass use. Such costs may be very different in different parts of the Czech Republic. Usually, every form of biomass is used in a different way, and the price of biomass reflects the various forms being used differently. Therefore, the differences in price between stations and forms of biomass are expected to be quite significant in the future [89].

A model of the economic balance was created for the purpose of our research; it is based on the market production of certain energy crops and various intensities of treatment (Table 20).

Table 20. Model economic balance based on the market production.

Phytomass Growing for the BGP (Biogas Plant) Purpose					
	Year costs per hectare (EUR per ha)	Average silage yield (t per ha)	Silage market price (EUR per t)	Potential profit (EUR per ha)	+ SAPS subsidy (EUR per ha)
Maize	1305.8	46.48	19.2–38.5	481.9	665.8
M × G	1055.5	32.13	26.9–38.5	180.2	364.1
RCG	728.2	23.52	26.9–38.5	176.4	360.3
Sz-1	728.2	24.66	26.9–38.5	220.3	404.2
Single value of EUR (Euros) 38.5 per ton is considered the market price of silage; the amount of SAPS subsidy derives from the average for 2013–2016					

Year hectare costs represent the technological costs (total variable costs + fixed costs of machinery), and for perennial crops, they are based on 10-year projection.

A subsidy from SAPS (Single Area Payment Scheme) is involved in the model economic balance; it is one of the most stable subsidies that have been provided recently (Table 21). The market price of silage is derived from the current market needs and qualitative parameters of silage material. The price of Sz-1 seeds seems to be quite problematic: it fluctuates, and it is quite high at the moment (up to EUR 27 per kg). Considering a seeding rate of 35 kg per ha, the total seeding costs would amount to EUR 942 (they would rise by 13% in the 10-year cycle).

Table 21. Development subsidies from the SAPS.

Year	SAPS Subsidy (EUR per ha)
2012	224.5
2013	233.4
2014	230.7
2015	136.3
2016	135.2
average for 2013–2016	183.9

(SAPS: Single Area Payment Scheme).

On the basis of the above results and economic models of market production, we can assess the economic efficiency of growing certain energy crops for the direct sale of phytomass and for the purpose of BGP. After finding a suitable market and sale, we can sell the harvested phytomass efficiently. The market price of harvested phytomass containing 28–36% of dry matter varies from EUR 19 to 46 per ton. Such a price reflects the species and quality, and maize phytomass is usually the most expensive. Table 20, among other data, shows the model's yearly costs per hectare; they represent the technological costs (total variable costs plus fixed costs of machinery). For the perennial crops, the calculation of the model's yearly costs is based on the 10-year projection. For the average phytomass yield indicated by this research, the economic profitability would be equal to 9.5–36.9%, and maize would be the most profitable energy crop. The economic efficiency was improved due to the SAPS subsidy, which amounted to EUR 184 per ha, on average, between 2013 and 2016.

The use of grasslands and energy crops without subventions seems to be unrealistic from an economic point of view. The use of available subventions helps a great deal and makes their production economical [96]. In 2006, there were the following subsidies for growing energy crops in the Czech Republic: single area payment scheme (SAPS), additional payment (TOP UP), LFA or NATURA 2000 subsidies, and support for energy crop growing. Nowadays, there is only SAPS, LFA, or NATURA 2000 remaining. Support for energy crop growing (the so-called carbon credit) was terminated in 2009; it is not possible to apply for this kind of payment anymore. In 2006, EUR 43.6 per ha was paid. A farmer had to produce a representative yield in order to gain this kind of support; the representative yield level was stipulated by the Ministry of Agriculture. For example, in 2009, the representative yield was 7 tons per hectare for RCG and 6 tons per hectare for M $\times$ G [97].

4. Conclusions

Recently, Sz-1—an alternative and promising energy crop—was introduced in some European countries (mostly in Hungary and Germany), and it has good yield potential. As the results of this research show, Sz-1 produces an average yield that is below a profitable level ($\geq$12 t ha^{-1} of dry matter) (6.1–8.6 t ha^{-1}, a four-year average). Qualitative analyses for Sz-1 phytomass were performed and show that biogas (or methane) can be made from it, and it produces more energy per production unit than any other energy crop grown in the Czech Republic. The profit from phytomass per area unit and overall economic assessment are crucial factors. According to the findings of this research, and despite its significant environmental benefits, Sz-1 cannot be recommended as an economically viable alternative to maize. Thus, a serious question arises: should the economic or environmental aspect be prioritized?

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Greenhouse gasses emissions during maize growing for energy purposes

JAROSLAV BERNAS, JAN MOUDRY jr., ZUZANA JELINKOVA, MAREK KOPECKY
Department of Agroecosystems
University of South Bohemia in Ceske Budejovice
Studentske 13, 370 05 Ceske Budejovice
CZECH REPUBLIC

bernasj@seznam.cz

Abstract: Due to the increasing energy consumption and depletion of fossil fuels, alternative energy sources are becoming an increasingly important topic. One of the most important renewable energy sources is the energy from phytomass. Recently, also in the conditions of the Czech Republic, there has been a significant development of production of energy crops as raw material for the biogas production in biogas plants (BGP). However, farming and particularly technical processes associated with it participate in the anthropogenic emission production. This article presents the results of monitoring of emission load resulting from the cultivation of maize (*Zea mays* L.) for energy purposes. As a tool for emission load measuring (expressed in CO_2e where CO_2e = 1x CO_2 + 23x CH_4 + 298x N_2O), the simplified LCA method, respectively its climate impact category, was used. For calculation, the SIMA Pro software and the Recipe Midpoint (H) method was used. From the results, it is obvious that the cultivation of maize for energy purposes produces the greatest amount of CO_2e emissions within nitrate fertilization (0.052455 kg $CO_2e.1kg^{-1}$ of dry matter) and field emissions (0.050359 kg $CO_2e.1kg^{-1}$ of dry matter). Maize cultivation for energy purposes shows a higher emission load as compared for example with energy grasses.

Key words: maize, greenhouse gases emissions, Life Cycle Assessment, crop production

Introduction

The current situation and trends indicate the probability of irreversible effects on the world economy and particularly on the global climate. Energy demand will be growing constantly and it will drain especially irreplaceable fossil energy sources. It is an undeniable fact that fossil fuels are limited and it is necessary to look for other sources. We could say that in case of the economical land use, there will be biomass constantly available [13]. One of the possibilities is its transformation into biogas through anaerobic fermentation in biogas plants (BGP) [21]. In 2012, there were about 320 biogas plants in the Czech Republic. There will have been about 720 of them by 2020 [9]. With the increasing number of biogas plants, also the demand for suitable substrates increases while we could assume that the maize silage will still predominate. Also the current biogas production in BGP is based predominantly on the usage of maize. However, recently, there have been certain problems relating to its cultivation [23]. In terms of biomass energy utilization (in our case, specifically grown maize), it is necessary to deal with not only issues related to economic and social topics, but also environmental issues [26]. In terms of GHG emission production (in the Czech Republic, mainly N_2O, CH_4 and CO_2), it is also an important producer within agriculture, in addition to energetics and industry [18]. For example, according to Svendsen [29], this contributes by 9.2% to the total GHG emissions within the European Union. Within the trend of sustainability, however, also the agriculture should contribute to reduction of the emission load. In the literature, there is often a question of the impacts of agricultural alternative forms on reduction of environmental load discussed [11, 12]. For example, there are very often different crops, etc. compared which brings not always relevant results [28]. Therefore, for the energy crop cultivation, there is necessary to find possibilities of emission savings elsewhere than in changing of the entire farming system. To monitor specific emission load in different farming systems, The LCA (Life Cycle Assessment) analysis can be used [10]. It evaluates the environmental impact of a product based on the assessment of the impact of material and energy flows that are exchanged by the monitored system with the environment [8]. LCA is a transparent scientific tool [30] which evaluates the environmental impact on the basis of inputs and outputs within the production system [7]. On the basis of this study, it is possible to make a model of the established production system, to identify the strongest sources of emissions from particular energy flows and to determine the total emission load within the maize cultivation.

Material and methods

The aim of this study was to develop a model of technological process of cultivation of maize and wheat and to determine the impact of the emission load on the environment through it. As a tool for calculation of the emission load, the simplified Life Cycle Assessment (LCA) method was used. It is defined by international standards - ČSN EN ISO 14 040 (CNI, 2006a) and ČSN EN ISO 14 044 (CNI, 2006b). The results of the study were related to the Climate change impact category expressed as an indicator of carbon dioxide equivalent (CO_2e = 1x CO_2 + 23x CH_4 + 298x N_2O). For calculation, the SIMA Pro software with the Recipe Midpoint (H) integrated method was used. The functional unit of the system was 1 kg of the final product (1 kg of dry matter). Technological process of cultivation of silage maize for biogas production in BGP was compiled on the basis of primary data (direct information from farmers) and secondary data (obtained from the Ecoinvent database, specialized literature and agricultural production technology standards). The database uses data geographically related to Central Europe. The range of time horizons for the primary data collection was between the years 2012 - 2014 and the years 2000 - 2014 for the secondary data. Data selected for modelling are based on the average of commonly applied technologies. To the model system, there were agrotechnical operations from seedbed preparation, seed quantity, the use of plant protection products, the production and application of fertilizers, etc., to the harvest of the main product included. In addition to the emissions resulting from the above inputs, there are so called filed emission (N_2O) released after the application of nitrogen fertilizers produced. For their quantification, the IPCC (Intergovernmental Panel on Climate Change) methodology is used [3].

Results and discussion

Climate changes are a key topic of these days. Production of greenhouse gases in the world needs to be constantly monitored and it is necessary to look for ways how to reduce their most important resources at the same time. For example, emissions from agriculture represent about 10 - 12% of the total produced GHG emissions (CO_2e) in the world representing 5.1 to 6.1 billions tones of CO_2e [20]. Within the EU-27, the total share of emissions from agriculture in total production of CO_2e is estimated at 10.1% [22] and in the Czech Republic, this share is 6.3% [6].

As stated before, results of the study were related to the *Climate change* impact category expressed as an indicator of carbon dioxide equivalent (CO_2e = 1x CO_2 + 23x CH_4 + 298x N_2O). The same concentration of different greenhouse gases has very different consequences for increasing absorption of long-wave radiation, so the certain greenhouse gases are more effective than others [19]. Nitrous dioxide (N_2O) is the most effective greenhouse gas produced by agriculture [15]. One kilogram of this gas has the same greenhouse effect as 289 kg of CO_2 [27, 15]. In addition, these gases (CO_2, N_2O, CH_4) are characterized as greenhouse gases with a direct impact on climate [14].

This paper evaluates the current model of a technological progress within the cultivation of maize for the production of biogas. Results show the amount of emission impact on the environment. Table 1 shows the values of particular system processes while the highest emission load is associated with agrotechnical operations (0.020346 kg $CO_2e.kg^{-1}$ of dry matter), N fertilizer application (0.052455 kg $CO_2e.kg^{-1}$ of dry matter) and production of N_2O field emissions released after the application of N fertilizers (0.050359 kg CO_2e.kg-1 of dry matter). Also Barros [1] states that the greatest amount of GHG emissions released into the atmosphere comes mainly from N fertilizers. Zou et al. [31] and Mori et al. [16] also state that fertilizer usage has an effect on increasing N_2O emissions from the soil.

Table 1 Production of emissions within particular system processes, own source - Bernas et al., 2014

System subprocesses	**kg $CO_2e.kg^{-1}$ of maize dry matter**
Organic fertilizers	0.003607
Mineral fertilizers N	0.052455
Mineral fertilizers P	0.007475
Mineral fertilizers K	0.002661
Total fertilizers	***0.066198***
Seed consumption	0.003203
Chemical protection	0.000763
Agrotechnical operations	0.020346
N_2O field emissions (converted to CO_2e) generating after the application of N fertilizers.	0.050359
Total production	***0.140870***

The highest CO_2e emission load comes from nitrogen fertilizer application (0.052455 kg $CO_2e.kg^{-1}$ of dry matter) and production of N_2O field emissions released after the application of N fertilizers (0.050359 kg $CO_2e.kg^{-1}$ of dry matter). On the contrary, the lowest amount of CO_2e emissions results from the use of chemical plant protection products (0.000763 kg $CO_2e.kg^{-1}$ of dry matter). This is contrary to the statement of Fott [5] who states that emissions from agricultural activities come mainly from the usage of nitrogen fertilizers and pesticides precisely. Graph 1 shows a comparison of two strongest emission sources also expressed in $CO_2e.kg^{-1}$ of maize dry matter with the emission load resulting from the remaining system processes altogether.

If we think of CO_2e production reduction within the chosen cultivation process, it is necessary to focus on the two most powerful sources (N fertilizer application and field emission arising from the application of N fertilizer). In this respect, we often deal with the question regarding reducing the dose of fertilizer and the total change of the agricultural system [4, 17]. Another way how to reduce emissions of greenhouse gases is the replacement of maize by another energy plant. Also Bellarby [2] proposes the cultivation of less loading plants as a way how to reduce (namely mitigate) GHG emissions. These may be, for example, energy grasses. These have prerequisites to lower CO_2e production during their life cycle thanks to the character of perennial plants and generally lower fertilization requirements.

Fig. 1 Network of energy flows, own source (SIMA Pro) - Bernas et al., 2014.

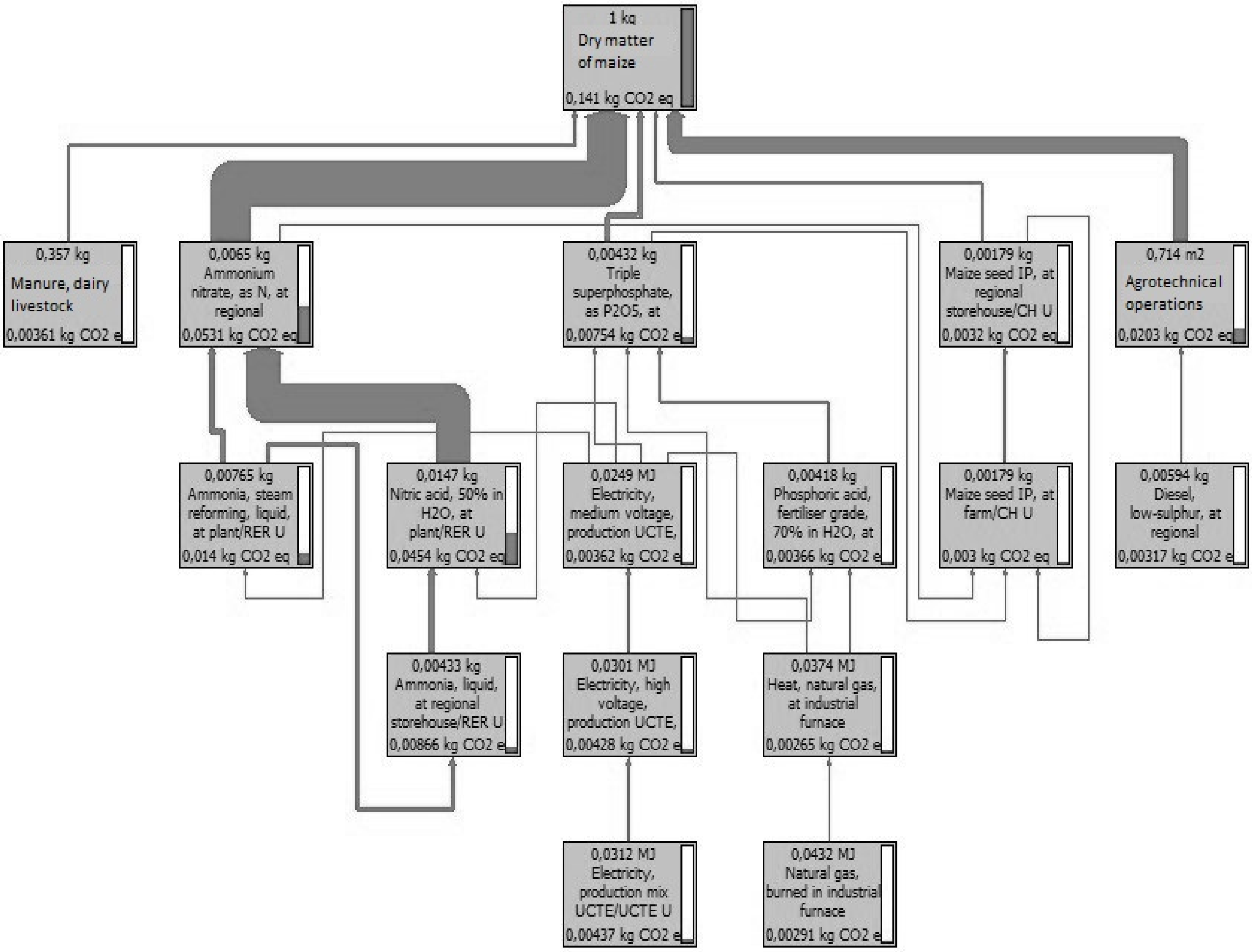
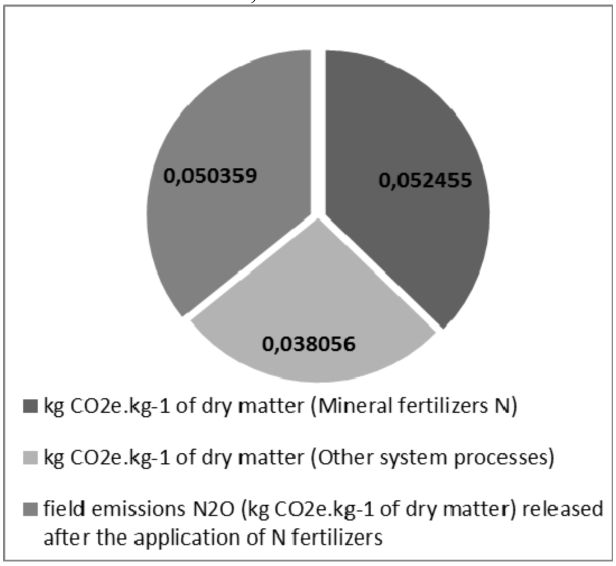


Figure 1 represents a network of particular energy flows involved in the production of 1 kg of maize dry matter. The strongest energy flow demonstrates the emission load due to the use of N fertilizers. One of the reasons why N fertilizers are the strongest producers of GHG emissions within agriculture is their constantly rising consumption. For example, Robertson and Vitoušek [25] stated that global consumption of N fertilizer increased tenfold in the period from 1950 to 2008.

Graph 1 Main sources of CO_2e emissions, own source - Bernas et al., 2014



* *Among other system processes, an application of organic fertilizers, mineral P and K fertilizers, seed consumption, chemical plant protection and agrotechnical operations were included.*

Conclusion

The results show that the total emission load of the selected cultivation cycle of maize intended for biogas production represents 0.140870 kg CO_2e.kg^{-1} of maize dry matter. From the system subprocesses, the largest emission load for the *Climate change* impact category is formed by nitrogen fertilizer application (0.052455 kg CO_2e.kg^{-1} of dry matter) and N_2O field emission resulting after the application of N fertilizer (0.050359 kg CO_2e.kg^{-1} of dry matter). The reduction of the amount of CO_2e produced within the cultivation of maize for biogas can be done by reducing the dose of fertilizer (probably at the cost of lower yields), changes of the cultivation technology or choosing another energy plants. When deciding on the introduction of another energy plants suitable for the production of biogas, it is also necessary to know the CO_2e emission load generated during its growing cycle. Based on this finding, it would be possible to carry out further evaluation and comparison.

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MISCANTHUS – POSSIBILITY OF GREENHOUSE GAS EMISSION MITIGATION

BERNAS JAROSLAV, JELINKOVA ZUZANA, MOUDRY JAN JR., KOPECKY MAREK, MOUDRY JAN
Department of Agroecosystems
University of South Bohemia in Ceske Budejovice
Studentska 13, 370 05 Ceske Budejovice
CZECH REPUBLIC

bernasj@seznam.cz

Abstract: One of the most important renewable energy source is the energy from phytomass. Recently, there has been significant development of growing energy crops as raw materials for biogas production in biogas plants (BGP). In the conditions of the Czech Republic, it is mainly maize. Maize cultivation itself and especially technical processes associated with it participate significantly in the anthropogenic emission production. One of the ways of reducing these emissions is the substitution of maize with another plant suitable for such purposes. This may be *Miscanthus x giganteus*. This article presents the results of monitoring of emission load resulting from the cultivation of maize (*Zea mays* L.) and *Miscanthus x giganteus* for energy purposes. The tool to determine the level of emission load (expressed in CO_2e where CO_2e = 1x CO_2 + 23x CH_4 + 298x N_2O) is the simplified Life Cycle Assessment (LCA) method, respectively its Climate Impact category. For the calculations, the SIMAPro software and the ReCiPe Midpoint (H) method is used. The results show that within the cultivation of *Miscanthus x giganteus* for energy purposes, the CO_2e production decreases during the second year of cultivation by nearly 40% per 1 kg of dry matter. While in comparison with maize, it is almost half production of CO_2e per the production unit depending on the yields and energy inputs.

Key Words: maize, *Miscanthus x giganteus*, greenhouse gas emissions, Life Cycle Assessment

INTRODUCTION

Climate-change-wise environmental impacts are the key issue of these days. Since the population growth continues very rapidly and also the energy consumption in agriculture increases, we cannot expect that in the foreseeable future, a spontaneous reversion of the trend of increasing environmental load will come (Schau, Fet 2008). Emissions from agriculture account for roughly 12% of the total produced emissions of greenhouse gases (CO_2e) on the Earth (representing 5.1 to 6.1 billion tonnes of CO_2e) (Niggli et al. 2009), within the EU-27, the share of emissions produced by agriculture to the total production of CO_2e is estimated at 10–11% (O'Brien 2014). It is necessary to constantly monitor the production of greenhouse gases (GHG) within agriculture and, at the same time, look for ways to reduce their most important sources (Franks, Hadingham 2012). For example, Smith et al. (2008) provides a variety of options of mitigation of greenhouse gas emissions in crop production. One of the ways can be the attempt to look for savings of greenhouse gases with most commonly grown crops. The very often grown crop, not only in conditions of the Czech Republic, is maize (Graebig et al. 2010). It is widely used as raw material for the BGP (Ahlgren et al. 2010) as an important renewable energy source (Poeschl et al. 2012). However in general terms, it is perceived as a plant representing a considerable burden for the environment (Vogel et al. 2015). In this respect, maize can be partially substituted with another plant also suitable for this usage. It can be *Miscanthus x giganteus* (Lewandowski et al. 2000) that can contribute to potential reduction of environmental impacts in the form of greenhouse gases (GHG) with its yield potential and the perennial plant character (Boehmel et al. 2008). For the monitoring of specific emission loads in different farming systems, we can use the LCA (Life Cycle Assessment) study (Contreras et al. 2009) evaluating environmental impacts of a product based on the assessment of the impact of material and energy flows that the monitored system exchanges with the environment (Haas et al. 2000). Flows of greenhouse gases produced within agriculture are highly complex and heterogeneous but proper management of agricultural systems offers opportunities for mitigation (Smith et al. 2008). It is a transparent scientific tool (Weinzettel 2008) which evaluates the environmental impact on the basis of inputs and outputs within the production system (O'Brien et al. 2014). On the basis of this study, it is possible to make a model of set production systems, identify the strongest sources of emissions from various energy flows and compare the emission load within the maize and *Miscanthus x giganteus* growing during the first three years of cultivation.

MATERIAL AND METHODS

The aim of this study was to draw up models of technological processes during practical cultivation of maize and *Miscanthus x giganteus* and to determine the emission load impact on the environment using them. The simplified method of Life Cycle Assessment (LCA), defined by the international standards of ČSN EN ISO 14 040 (CNI 2006a) and ČSN EN ISO 14 044 (CNI 2006b), was used as a tool to calculate the emission load. The results of the study were related to *the Climate change* impact category expressed in the carbon dioxide equivalent *(CO_2e = 1x CO_2 + 23x CH_4 + 298x N_2O)*. The SIMAPro software and the ReCiPe Midpoint (H) method were used for the calculations. The system functional unit represented 1 kg of the final product (1 kg of DM). Technological processes of the cultivation of maize and *Miscanthus x giganteus* intended for the production of biogas in BGP were compiled based on primary data (field experiments at ZF JU in České Budějovice), as well as secondary data (acquired from the *Ecoinvent 2010* database, literature search and normative data on agricultural production technologies). The database uses data geographically related to Central Europe. The primary data were collected between 2013 and 2015 and the secondary data between 2000 and 2015. Data selected for the modelling is based on the average of commonly applied technologies. Agrotechnical operations from seedbed preparation, the amount of seeds and seedlings, the use of plant protection products, production and application of fertilizers, etc., to harvesting the main product were included into the model system. Besides the emissions arising from the inputs mentioned above, so called field emissions (N_2O emissions) are also produced after the application of nitrogen fertilizers. The IPCC methodology (*Intergovernmental Panel on Climate Change*) is used to quantify them (O'Brien et al. 2014). The results presented in this paper are based on field experiments having been established since 2013 on the grounds of the University of South Bohemia in České Budějovice. Selected fertilization intensity and particular agrotechnical practices were set on the basis of the already used growing technologies for conditions of Central Europe (Lewandowski et al. 2000, Weger, Strašil 2009). The paper presents the results of 3-year growing of maize and *Miscanthus x giganteus* (hereinafter referred to as *M. x g.*) for biogas plants (BGP). *M. x g.* stands were harvested twice a year. Based on the chosen methodology and data acquired during their growing (yields of dry matter, inputs and outputs of the growing cycle), it was possible to compile their life cycle within the farm stage (from preliminary tillage to harvest and storage of the harvested material) and to determine the impact on the environment.

RESULTS AND DISCUSSION

As already stated, the results of the study were related to the *Climate change* impact category expressed in the carbon dioxide equivalent (CO_2e = 1x CO_2 + 23x CH_4 + 298x N_2O). CO_2, N_2O, CH_4 are characterized as greenhouse gases with a direct impact on the climate (Menichetti, Otto 2008) while each of them has different efficacy at the same concentration (Millar et al. 2010). Table 1 shows yields of dry matter and values of emission load resulting from the production of 1 kg of dry matter (hereinafter referred to as DM) in particular years. The highest yield of maize was achieved in 2014 (19.25 $t \cdot ha^{-1}$ DM) while 0.221 kg CO_2e corresponds to 1 kg of DM. On the contrary, the lowest yield was achieved in 2015 (7.29 $t \cdot ha^{-1}$ DM). This significant decline was primarily due to the extreme drought during the growing season. This year, the production of CO_2e per 0.583 kg $CO_2e \cdot kg^{-1}$ of DM has grown. The first harvest of *M. x g* was in 2014 (5.58 $t \cdot ha^{-1}$ DM) – the first production year. Normally, the newly established stands are not harvested in the year of establishment (Weger, Strašil 2009). For the calculation of emission load arising throughout the 3-year cultivation cycle (see Table 2), it is necessary to include the year of stand establishment in the calculation. Yields of *M. x g.* in the first three years of growing do not usually achieve the full yield potential (Christian et al. 2002) that can be up to 30 t · ha^{-1} DM (Weger, Strašil 2009). In the second year of cultivation (2015), the yield of DM 9.05 t · ha^{-1} was achieved (an increase of almost 40%).

Table 1 Dry matter (DM) crop and emission load per 1 kg of DM in particular years

	Year	Yield of DM (t · ha^{-1})	Emission load (kg $CO_2e \cdot kg^{-1}$ of DM)
Miscanthus x giganteus	2013	Without yield	Not assessed
	2014	5.58	0.263
	2015	9.05	0.162
Maize	2013	14.13	0.301
	2014	19.25	0.221
	2015	7.29	0.583

Legend: According to the conventional technological methods, Miscanthus x giganteus was not harvested in the year of establishment (2013)

Emission load (kg CO_2e) at the yield of 1 kg DM depends mainly on the final yields per one hectare. Therefore, it is natural that the emission load at the yield of 1 kg DM will decrease while maintaining the cultivation cycle of *M. x g.* and with the increasing yield per one hectare. This is noticeable already in 2015 when the emission load per 1 kg of DM at the yield of 9.05 t · ha^{-1} DM decreases by 38.4% as compared to 2014. At the expected yield of *M. x g.* at 15 t · ha^{-1} DM and maintaining the same growing process, the emission load per 1 kg of DM decreases by nearly 60% (as compared to 2014). *M. x g.*can be cultivated for even 16 years (Lewandowski et al. 2000) with reliable yields of 15–25 t · ha^{-1} DM. If we compare *M. x g.* and maize with an average yield of 15 t · ha^{-1} DM within a ten-year cycle at the preserved growing technology, we can conclude that the emission load from production of 1 kg of DM with *M. x g.* will be almost 50% lower than with maize.

Another situation occurs when comparing these two energy plants in the first three years of cultivation in total. In this evaluation, we must include also the first production year (year of stand establishment) of *M. x g.*, that is the most energy-intensive from the perspective of multiannual growing, in the calculation. This led to a significant increase of production of kg $CO_2e \cdot kg^{-1}$ of DM (Table 2) as compared to maize.

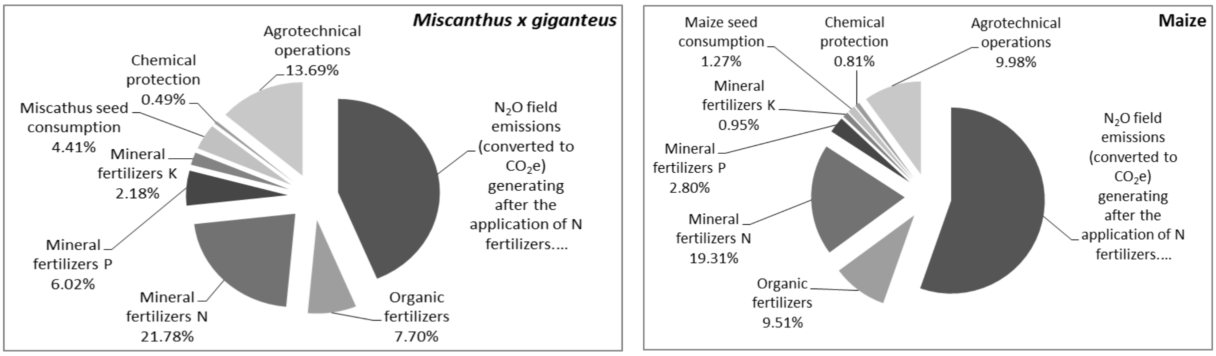
Table 2 Greenhouse gas emissions (kg $CO_2e \cdot kg^{-1}$ of DM); average in the first three years of cultivation

System subprocesses	Maize	*Miscanthus x giganteus*
Organic fertilizers	0.0298	0.0276
Mineral fertilizers N	0.0605	0.0781
Mineral fertilizers P	0.0088	0.0216
Mineral fertilizers K	0.0030	0.0078
Total fertilizers	0.1021	0.1351
Seed consumption	0.0040	0.0158
Chemical protection	0.0026	0.0018
Agrotechnical operations	0.0313	0.0491
N_2O field emissions (converted to CO_2e) generating after the application of N fertilizers.	0.1736	0.1568
Total production	0.3135	0.3586

Legend: All energy inputs in the first three years of cultivation and achieved yields of phytomass are included in system processes

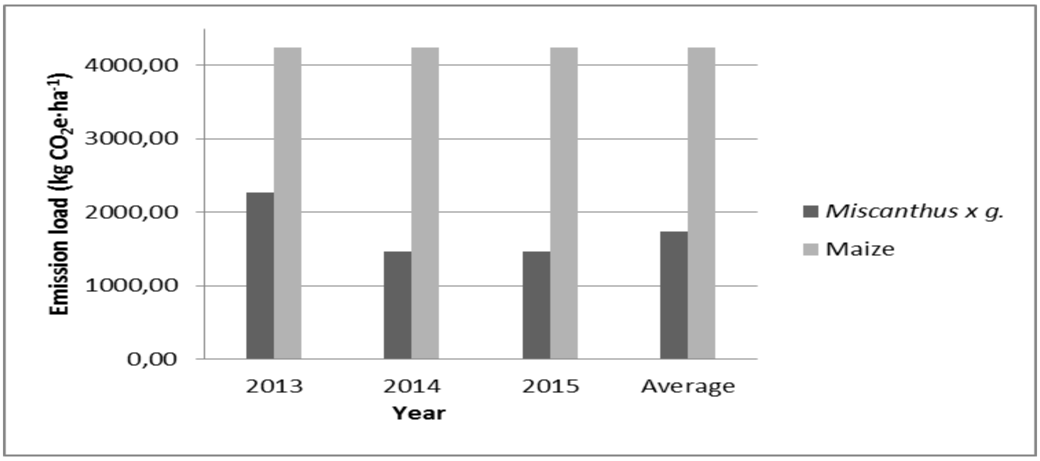
Figure 1 shows the share of particular system processes on the production of emissions (in %). It is known, that the most powerful sources of emissions released into the atmosphere come from the fertilizer use and their application to the soil (Zou et al. 2005, Mancinelli et al. 2013). Even in this case, we can say that the largest share of total production consists of the emissions generated by the use of fertilizers and so-called field emissions (N_2O emission converted to CO_2e) generated after the application of N fertilizers. The intensity of fertilization of both monitored plants was selected on the basis of established growing technologies (Lewandowski et al. 2000, Weger, Strašil 2009). The level of N fertilization was chosen similarly to Boehmel et al. (2008) who state that the optimum N fertilization level for maize is about 120 kg · ha^{-1} and for *M. x g.* 80 kg · ha^{-1}. At higher doses, the significant increase of phytomass is no longer detectable. Another monitored category was the production of greenhouse gas emissions per the unit of area (1 ha). This category includes all material and energy flows in a given year (within the farm stage). In this case, the calculation does not include the yields per hectare. Values are reported in the Figure 2.

Figure 1 Contribution of particular subprocesses (in %) to the creation of emission load



Legend: There was no harvest in 2013 (the year of the Miscanthus x g. stand establishment); this is why the emission load per the production unit was not calculated

Figure 2 Emission production (kg CO_2e) per the area unit (1 ha)



The aim of this chart is to show a significant difference in greenhouse gas production per the area unit (1 ha) between maize and *M. x g.* In the first year of cultivation, the difference was 46.5%, in the second and the third one 65.5% and on average for three years, it was 53.5%. In order to maintain uniform cultivation technologies for maize, the production of greenhouse gases per the area unit in each year is without differences. The same is true of *M. x g.* but from the second year of cultivation. In the first year of cultivation, the production of greenhouse gases (as against following years) is increased due to the relatively energy-intensive establishment of vegetation.

In general terms, this points to the possibility of reducing the production of greenhouse gases (CO_2e) by growing less energy-intensive perennial plants (Bellarby et al. 2008) even while maintaining yield potential comparable with maize. Another positive benefit of perennial plants (which *M. x g.* belongs to) is a permanent soil cover and deposition of carbon dioxide (Clifton-Brown et al. 2004, Deckmyn et al. 2004) but also the support of biodiversity (Hope, Johnson 2003). In terms of the possibility of mitigation of greenhouse gases within the cultivation of maize, questions regarding crop rotation, including intercrops in crop rotation and ploughless tillage systems are addressed (Al-Kaisi, Yin 2004). The advantage of growing *M. x g.*, besides a lower environmental impact and a high yield per hectare of phytomass, is also high energy production (Menardo et al. 2013).

CONCLUSION

The aim of this paper was to point out the possibilities for mitigation of greenhouse gas emissions CO_2e within growing *Miscanthus x giganteus*, as a plant suitable for use in the BGP and its mutual comparison with maize. The results show that with the cultivation of *M. x g.*, we can reduce greenhouse gas emissions per the unit of production (1 kg of DM) by about 50% and per the area unit (1 ha) by about 65% per year, as compared with maize. The determining factor in the calculation of emission load (CO_2e) within the farm stage through LCA is the chosen intensity of fertilization and the yield of phytomass. Additionally in the longer term, you can achieve yields per hectare of *M. x g.* that are comparable with maize and the total energy profit per the production unit. For the *Climate change* impact category, the highest emission load is associated with the application of nitrogen fertilizers, the field N_2O emissions arising from the application of nitrogen fertilizers and partially utilized agrotechnical operations. Any reduction in the amount of CO_2 produced within growing maize or *M. x g.* for BGP can be done by reducing the dose of fertilizer (probably at the cost of lower yields), by changing cultivation technology, and the inclusion of other environmentally friendly energy plants.

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ENERGY CROPS GROWING – IMPACT ON GREENHOUSE GASES EMISSIONS

J. BERNAS*, J. MOUDRY Jr., Z. JELINKOVA, M. KOPECKY, P. KONVALINA, J. MOUDRY

Faculty of Agriculture, University of South Bohemia in Ceske Budejovice, 13 Studentska Street, 37 005 Ceske Budejovice, Czech Republic
E-mail: *bernasj@seznam.cz*

Abstract. In Czech Republic, an important phytomass with energetic value is the maize. Besides other environmental impacts, maize cultivation is highly associated with anthropogenic emission production, which could suggest the substitution of maize with other energy plants (e.g. grasses – Reed canary grass (*Phalaris arundinacea* L.), *Elymus elongatus* subsp. ponticus cv. Szarvasi-1). Results of monitoring of emission load resulting from their cultivation for energy purposes were presented in this paper in the frame of a study case, where a simplified (streamlined) LCA method (Climate change impact category) was used based on the SIMAPro software (ReCiPe Midpoint (H) method). Within the cultivation of both grasses for energy purposes, CO_2e production decreases on average by more than 20% per 1 kg of dry matter in the first three years of cultivation in comparison with maize, while it is possible to produce up to 80% less CO_2e per the area unit. The lower emission load falls then on methane production.

Keywords: simplified LCA, maize, grass, biogas.

AIMS AND BACKGROUND

The original idea of biogas plants – preferential use of waste material – has not often been preserved and phytomass of purpose-grown energy crops is now often used as a primary raw material. The aim of this paper is to examine the possibility of replacing maize, as the plant grown for the BGP purposes, by another more environmentally friendly plant, while maintaining a comparable yield of phytomass and biogas yield (resp. methane) and achieving significant reductions in GHG emissions per the unit of production and area.

Climate changes and their impact are a key issue of our time and agriculture brings a significant contribution to this environmental issue. Within the EU-27, the share of emissions produced by agriculture to the total production of CO_2e is estimated at 10–11% (Ref. 1) and for example in the Czech Republic, this share is 6.03% (Ref. 2). Agriculture is one of the major producers of methane (CH_4) and nitrous oxide (N_2O) (Ref. 3) and generates a large share of total emissions affecting the global climate change[4].

[*] For correspondence.

A very often grown crop is maize[5,6], which is also widely used as raw material for biogas plants (BGP) (Ref. 7) and valuable from the point of view related to the high energy inputs (e.g. in the form of mineral fertilisers, fuel, chemical plant protection products and others). Maize can be partially substituted with other plants (e.g. perennial plants) also suitable for this purpose[8]. Such plants should have high energy and yield potential together with minimum environmental impacts[9]. Perennial energy crops have, in addition to a long life cycle[10], other positive aspects such as the permanent soil cover (protection against erosion) or higher carbon dioxide sequestration[11] and they also contribute to promoting biodiversity[12]. They are also a tool for climate change impact mitigation[13,14].

The LCA (Life Cycle Assessment) method[15] in the simplified LCA version[16,17], could be used for the environmental assessment of specific emission loads monitored in different farming systems.

A model of production systems could be developed based on the results of this study. Also, the identification of the strongest emissions sources from various energy flows and the comparison of the emission load within the maize (*Zea mays* L.), *Phalaris arundinacea* L. and *Elymus elongatus* subsp. ponticus cv. Szarvasi-1 could be performed.

EXPERIMENTAL

In order to design models of technological processes related to cultivation of maize (*Zea mays* L.) – hybrid Simao, Reed canary grass (*Phalaris arundinacea* L.) – Chrastava variety and *Elymus elongatus* subsp. ponticus cv. Szarvasi-1 and to assess the emission load impact on the environment, a methodology fully described by Baumann and Tillman[15] was used. The methodology is based on the simplified LCA method, defined by ČSN EN ISO 14040 (Ref. 18) and ČSN EN ISO 14044 (Ref. 19) standards, and the SIMAPro software and the ReCiPe Midpoint (H) method, considering the Climate change impact category expressed in the carbon dioxide equivalent (CO_2e). The system functional unit was represented by 1 kg of the final product (1 kg of DM) and the area unit (1 ha). Technological processes of the production of monitored crops intended for the production of biogas in BGP was compiled based on primary data from field experiments on the grounds of the University of South Bohemia in Ceske Budejovice, as well as secondary data acquired from the Ecoinvent 2010 (Ref. 20) database, literature search and normative data on agricultural production technologies. The study takes into consideration the primary data from 2013 to 2015 and the secondary data from 2000 to 2015. Specific agricultural procedures, including intensity of fertilisation, have been established on the basis of commonly applied intensive cultivation technologies[9,21–26], while the growing technology of *Elymus elongatus* subsp. ponticus cv. Szarvasi-1 was determined consistently with Reed canary grass (*Phalaris arundinacea* L.). In order to quantify the gas emissions (including field N_2O emissions) the IPCC methodology (Intergovernmental Panel on Climate Change) was used[27,28]. Characteristics of the test habitats are described in Tables 1 and 2.

The results presented in this study are related to the three-year cultivation of maize (*Zea mays* L.), Reed canary grass (*Phalaris arundinacea* L.) and *Elymus elongatus* subsp. ponticus cv. Szarvasi-1 for use in a biogas plant (BGP). Both habitats are harvested twice a season. Their life cycle within the farm stage (from preliminary tillage to harvest, transport and ensilage of the harvested material) and the impact on the environment was evaluated according to the Climate change impact category expressed in the carbon dioxide equivalent ($CO_2e = 1\times CO_2 + 23\times CH_4 + 298\times N_2O$). It should be noted that CO_2, N_2O and CH_4 are greenhouse gases with a direct impact on the climate[29,30].

Table 1. Annual and seasonal climate of the years 2012–2015 at the experimental site of Ceske Budejovice

Year	Average temperature (°C)		Precipitation (mm)	
	year	season	year	season
2012	9.3	15.3	798.1	567.7
2013	9.1	15.3	685.4	469.5
2014	10.2	15.1	595.9	428.7
2015	10.5	16.9	487.7	233.8
Long-term average (1961–1990)	8.2	14.2	582.8	366.2

Table 2. Habitat characteristics

Altitude (MAMSL)	380
Agricultural production region	grain-growing
Soil texture class	sandy-loam
Soil type	pseudogley cambisoil
Soil pH	6.4
Long-term average temperature (°C)	8.2
Long-term seasonal rainfall (mm)	366.2
GPS coordinates	48°57′07″ N; 14°28′17″ E

RESULTS AND DISCUSSION

The results of this study show the rate of emission load related to a Climate change impact category through selected functional units (area unit, production unit) and their various sub-processes. Table 3 shows the summary results achieved during the first three years of cultivation. In the first three years of cultivation, not even half yield of dry matter (hereinafter referred to as DM), as compared with maize, was achieved. From this perspective, it is premature to equate grass with maize, because the grass will fill its yield potential generally up to three years after the establishment of vegetation[24,26]. This is about 12 t ha^{-1} of DM with Reed canary grass[25] and up to 20 t ha^{-1} of DM with Szarvasi-1 (Ref. 24). Also the fact that C4 plants (maize) are seen as more efficient power plants than C3 grasses thanks to more efficient photosynthetic activity should be taken into account[21]. Results are influenced also by the fact that in the founding year (2013), stands of grasses (unlike maize) were not harvested. For the evaluation of emission load arising throughout the 3-year cultivation cycle (Table 3), it is necessary to include the year of grass stand establishment in the calculation.

Phytomass yield plays a decisive role in the overall yield of methane[8,31], as well as the choice of the harvest term[32] and ensilability. When testing the specific yield of CH_4 – methane volume produced from 1 kg of added organic materials (m^3 CH_4 kg^{-1} org. DM), the following mean values were obtained: Maize 423 l CH_4 kg^{-1} org. DM, Reed canary grass 355.5 l CH_4 kg^{-1} org. DM and Szarvasi-1 404 l CH_4 kg^{-1} org. DM. Depending on yields in the first three years of maize cultivation, the three times higher yields of methane was achieved when compared with grasses (Fig. 1). Particular emission loads corresponding to the production of 100 l CH_4 during the first three years of cultivation are included in Table 4.

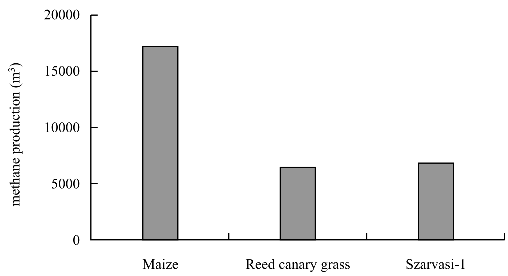

Fig. 1. Theoretical yield of methane in the first three years of cultivation (the sum of phytomass yields)
Note: This assessment was based on the CH_4 spec. yield – methane volume from 1 kg of added organic matter (m^3 CH_4 kg^{-1}org. DM)

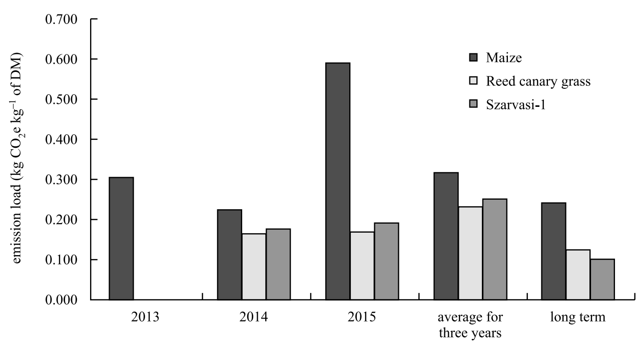

Fig. 2. Emission load in kg CO_2e kg^{-1} of DM for particular time intervals
Note: All energy inputs and outputs in particular years of cultivation and achieved yields of phytomass are included the evaluation. In 2013, the stands of grasses were established and were not harvested

Table 3. Summary results achieved during the first three years of cultivation

Name	Year	Yield of DM ($t\ ha^{-1}$)			Emission load ($kg\ CO_2e\ kg^{-1}$ of DM)	Emission load ($kg\ CO_2e\ ha^{-1}$)
Reed canary grass (*Phalaris arundinacea* L.)	2013		–		–	1.225×10^3
	2014	harvest I	5.10	**9.24**	0.167	1.558×10^3
		harvest II	4.14			
	2015	harvest I	6.64	**9.21**	0.169	1.558×10^3
		harvest II	2.57			
Elymus elongatus subsp. ponticus cv. Szarvasi-1	2013		–		–	1.225×10^3
	2014	harvest I	4.48	**9.0**	0.173	1.558×10^3
		harvest II	4.52			
	2015	harvest I	6.94	**8.21**	0.189	1.558×10^3
		harvest II	1.27			
Maize (*Zea mays* L.)	2013		**14.13**		0.303	4.279×10^3
	2014		**19.25**		0.222	4.279×10^3
	2015		**7.29**		0.587	4.279×10^3

Note: Energy grass stands were established in 2013 (30. 8.) This year, they were not harvested and emission load per yield unit (1 kg of DM) was not evaluated. Terms of the harvest were chosen as follows: 2014 – harvest I 3. 6. and harvest II 30. 9. 2014 and in 2015 – harvest I 12. 6. and harvest II 1. 10. 2015.

The highest yield of maize was achieved in 2014 (19.25 $t\ ha^{-1}$ of DM) while 0.222 kg CO_2e correspond to production of 1 kg of DM. On the contrary, the lowest yield was achieved in 2015 (7.29 $t\ ha^{-1}$ of DM) when due to the significant DM yield decrease, the share of emissions per the production of 1 kg of DM increased roughly 2.5 times (0.587 kg $CO_2e\ kg^{-1}$ of DM). In this year, the emission load per 1 kg of DM of grass is by 60–70% lower when compared with maize. A significant decline in the yields of maize was due to extreme weather conditions during the 2015 growing season (Table 1), which resulted in the second harvest of grassland (Table 3). In 2015, despite the extreme seasonal condition, higher DM yield was achieved with both grass species when compared with maize (Reed canary grass by 26% and Szarvasi-1 – 14%). This is to demonstrate one of the advantages of perennial plants, which consists in the possibility of multiple harvests. This may be partly to prevent the adverse seasonal effects of climate and losses of total annual production.

Emission load resulting within a yield of 1 kg of dry matter is dependent not only on the actual inputs and outputs of the growing cycle, but especially on the final yields. With the expected yield of 12–15 $t\ ha^{-1}$ of DM with Reed canary grass and Szarvasi-1 as well and a long growing period, the emission load per 1 kg of dry matter decreases by 50–60%, compared with maize (Fig. 2).

Table 4 shows the share of particular system sub-processes on the production of emissions. As already stated, in this evaluation, it was necessary to include also the first non-productive year (year of grass stand establishment) in the calculation. This led to a significant increase in the production of CO_2e per the production unit. Emission load at the yield of 1 kg of dry matter is by only about 20% lower with grass when compared with maize.

Table 4. Total emission load per the production unit (kg CO_2e kg^{-1} of DM, kg CO_2e 100 l^{-1} of methane) and per the area unit (kg CO_2e ha^{-1}) – average in the first three years of cultivation

System subprocesses	Maize (*Zea mays* L.)	Reed canary grass (*Phalaris arundinacea* L.)	*Elymus elongatus* subsp. ponticus cv. Szarvasi-1
Organic fertilisers	0.030	–	–
Mineral fertilisers N	0.061	0.068	0.073
Mineral fertilisers P	0.011	0.018	0.019
Mineral fertilisers K	0.003	0.004	0.004
Total fertilisers	0.104	0.090	0.097
Seed consumption	0.004	0.004	0.004
Chemical protection	0.003	0.001	0.002
Agrotechnical operations	0.031	0.048	0.052
N_2O field emissions (converted to CO_2e) generating after the application of N fertilisers	0.174	0.089	0.096
Total production (kg CO_2e kg^{-1} of DM)	0.316	0.233	0.250
Next evaluation categories			
kg CO_2e ha^{-1} per year	4.279×10^3	1.433×10^3	1.433×10^3
kg CO_2e 100 l^{-1} of methane	0.074	0.0655	0.0618

Note: All energy inputs in the first three years of cultivation and achieved yields of phytomass are included in system processes.

Gas emissions are strongly related to the soil ferilisation[33]. Boehmel et al.[9] state that N fertiliser has 41–64% share of energy consumption for annual crop (maize) production and the share of 17–45% with perennial crops. Fertilisation intensity of monitored plants was chosen on the basis of already established cultivation technologies[9,21–26] while the level of mineral N fertilisers for maize was compiled similarly as e.g. by Boehmel et al.[9] who state that the optimum mineral N fertilisation level is N 120–150 kg ha^{-1} and 80–100 kg ha^{-1} for grasses according to Usťak et al.[25]. Szarvasi-1 responds well to higher doses of N, provided, however, P and K fertilisers[24] which were applied in doses of 10 kg ha^{-1} of P and 30 kg ha^{-1} of K. At higher N doses, there is no longer significant increase in phytomass detectable. The efficiency of fertilisers decreases when increasing the dose of fertilisation because a large portion of the fertiliser is not accepted by a plant and instead of this, it goes into water or air[4]. One of the advantages of perennial grasses is that they require less nutrient and pesticides than annual crops[34].

Due to the significant impact on the GHG emission production, it is needed to monitor the fertilisation management and deal with the possibility of economical and efficient use of fertilisers. Although the total consumption of N continues to increase (from 1950 to 2008 up to tenfold) (Ref. 35), in 2005, according to the study of Erisman et al.[36], only 17% of produced 100 mil. t of N were used by crops while the rest got lost to the environment. In agroecosystems, in many cases, mineral N is the driver of productivity that has significantly increased thanks to the high input doses of soluble fertilisers and synthetic pesticides. The correct managemant of nitrogen is described in 4 IPCC assessment report[4]. The high content of unstable nitrogen in the form of compounds (NH_4, NO_3) in the soil can contribute to emissions of nitrogen oxides and thus form an essential part of agricultural emissions[4]. N_2O is formed in numerous N transformations in soils, but in most cases, the main source is denitrification and nitrification. CO_2 emissions and particularly N_2O emissions are highly spatially variable[37].

Another typical feature of N_2O emissions is their strong variability over time, including environment changes (such as temperature and rainfall) and management operations (such as fertilisers, irrigation, plowing), or the existence of various specific soil microbial communities that affect changes in the soil environment. All these characteristics make the estimation of the total flow of gas from the soil to the atmosphere difficult[37].

For this reason, the IPCC methodology was used in this study to measure N_2O emissions[27]. So called field emissions (N_2O field emissions converted to CO_2e) are (on average in the first three years of cultivation) on the level of 2351.22 kg CO_2e ha^{-1} per year with maize and 549.31 kg CO_2e ha^{-1} per year with grasses (Fig. 3). This corresponds to an amount that is stated in a study by Simek et al.[37] with grass-clover stands. Figure 3 indicated the emissions of GHG per the unit of area (1 ha), taking into consideration all material and energy flows in a given year (within the farm stage), without including the yields per hectare.

Figure 3 points out a significant difference in greenhouse gas production per the area unit (1 ha) between maize and grasses – Reed canary grass (*Phalaris arundinacea* L.) and *Elymus elongatus* subsp. ponticus cv. Szarvasi-1. It should be noted that in the first year of cultivation, this difference was > 80% and in the second and the third, it was > 70%.

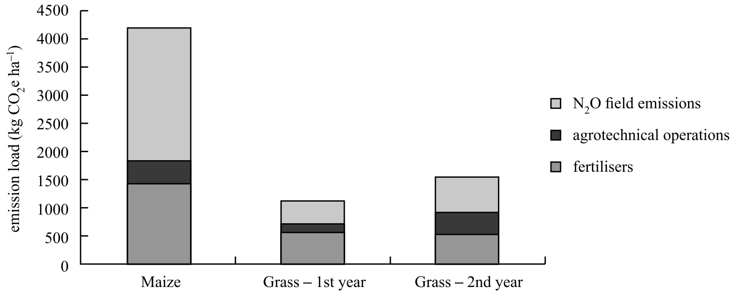

Fig. 3. Emission production per the area unit (kg CO_2e ha^{-1})
Note: All energy inputs in the first three years of cultivation are included in system processes. When assessing emission load per the area unit, the phytomass yields are not included in the calculations

Therefore, the production of greenhouse gases (CO_2e) could be decreased by growing less energy-intensive perennial plants[32,38], even with a satisfactory yield potential which can be compared with maize in the long term. Other benefits of perennial plants are carbon sequestration[39] and support of biodiversity[12]. Within the cultivation of maize, questions regarding crop rotation[40] or efficient N fertilisation management[30] and fertilising by digestate[41] should be addressed. Overall, such aspects are implicates in many studies approaching the issues of sustainable agriculture. In the world, there is also known an option for reducing greenhouse gas emissions through GIS (Ref. 42), or by using biochar sequestration with energy plants[43].

CONCLUSIONS

In the long term, perennial energy plant species, such as Reed canary grass (*Phalaris arundinacea* L.) and *Elymus elongatus* subsp. ponticus cv. Szarvasi-1, can be grown with a satisfactory and stable yield and at the same time, it can be achieved a significant reduction of emission load per the production and area unit when compared with maize. In comparison to all monitored plants in the first three years of cultivation, the highest yield of dry matter and methane (roughly three times the amount) was achieved with maize. However, also the emission load (for the Climate change impact category) expressed in kg CO_2e kg^{-1} of DM was higher with maize (on average) by 20% and from the viewpoint of N_2O field emissions (converted to CO_2e) generating after the application of N fertilisers, by up to 50%. For emission load assessed per the area unit (kg CO_2e ha^{-1} per year), emission of both energy grass species are by 70–80% lower when compared with maize. The highest emission load is associated with the application of nitrogen fertilisers, the field N_2O emissions (generating after the application of N fertilisers) and partially agrotechnical operations as well. Any mitigation in the amount of CO_2e produced within growing maize or selected energy grass species for BGP can be initiated by better management of mineral N fertilisers, the use of other environmentally friendly energy plants and of appropriate cultivation technology.

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CULTIVATION OF TALL WHEATGRASS AND REED CANARY GRASS FOR ENERGY PURPOSES IN TERMS OF ENVIRONMENTAL IMPACTS

J. Bernas, M. Kopecký, J. Moudrý Jr., Z. Jelínková, J. Moudrý, K Suchý

Faculty of Agriculture, University of South Bohemia in České Budějovice, Czech Republic

Abstract

Cultivation of energy crops for the production of thermal energy through direct combustion has become one of the trends within the ecological energetics. A number of perennial plants is grown in the conditions of the Czech Republic, too, for this purposes. One of them is reed canary grass (RCG). This species might gradually be replaced by another grass, better-performing tall wheatgrass (*Elymus elongatus* subsp. *ponticus* cv. Szarvasi-1). Greenhouse gas emission savings may be achieved due to the higher yield potential and energy yield when growing it. This article presents the results of emission load monitoring resulting from the RCG and Szarvasi-1cultivation for energy purposes. The simplified LCA method, respectively its Climate change impact category is used as a tool for emission load measuring. The results show that the emission savings of up to 45% per 1 GJ can be achieved when growing Szarvasi-1 for energy purposes in comparison with RCG.

Key words: energy grasses, greenhouse gases emissions, Life Cycle Assessment.

INTRODUCTION

Global energy demand increases in the context of demographic transition (HO AND SHOW, 2015). Fossil fuels represent a major source (VOSTRACKÝ ET AL., 2009). However, their combustion contributes to environmental pollution (NICOLETTI ET AL., 2015) and is responsible for a significant share of greenhouse gas emissions (GHG) (MOUTINHO ET AL., 2015). Moreover, they are not renewable (MASTNÝ ET AL., 2011) and thus their use is not sustainable (LIBRA AND POULEK, 2007). The importance of renewable energy sources (RES) increases in relation to the finite nature of fossil fuels (GÜRDIL ET AL., 2009). RES are considered as "clean" sources of energy (PANWAR ET AL., 2011). The most important renewable energy source is BIOMASS (JASINSKAS AND ŠATEIKIS, 2009) and the combustion of biomass, in particular (MALAŤÁK ET AL., 2008). The production of biogas is also widespread (JASINSKAS ET AL., 2008). Switching to biomass offers a range of economic, social and environmental benefits (SAIDUR ET AL., 2011), including the reduction in carbon dioxide emissions within the energy sector (LIND ET AL., 2016). The importance of the emission reduction, as well as fight against the climate change has been widely acknowledged (HOEL, 2011).

Many agricultural products may be used, inter alia, for energy purposes (ROBBINS ET AL., 2012). However, some plants are grown specifically for this purpose (LEWANDOWSKI ET AL., 2003). Their suitability has been examined to the present day (MAST ET AL., 2014) and, in the context of a changing climate, the special emphasis has been placed on the drought tolerance (KONVALINA ET AL., 2010). Perennial plants appear to be more suitable from an environmental point of view (KOPECKÝ ET AL., 2015). Grasslands perform a range of non-productive functions (SKLÁDANKA, 2007) and may also be recommended for the areas with high erosion risk (DUMBROVSKÝ ET AL., 2014). In addition, fewer fertilisers are required (LEWANDOWSKI ET AL., 2003) and grasslands have lower requirements for the pest and disease management (LEWANDOWSKI ET AL., 2000) in comparison with annual plants. For instance, RCG (*Phalaris arundinacea* L.) (TAHIR ET AL., 2011) or *Elymus elongatus* subsp. ponticus cv. Szarvasi-1 (CSETE ET AL., 2011) may be included into energy crops.

Although energy plants offer many advantages compared to fossil fuels, it is necessary to determine the impacts on all components of the environment that may be affected by their production (SAIDUR ET AL., 2011) or operation of the facilities using biomass for energy production (MALAŤÁK AND VACULÍK, 2008). Combustion of biomass in the combustion chambers intended for fossil fuels is technically possible, but very inefficient and high emissions of carcinogenic substances and aromatic hydrocarbons are produced. This also applies under unfavorable combustion conditions, as may be the low temperature combustion (OCHODEK ET AL., 2006). Many authors (i.e. DAS ET AL., 2010; OCHODEK ET AL., 2006) point out that energy plants compete with food crops for arable land. Therefore, it is recommended to grow energy crops on

marginal lands (LEWANDOWSKI ET AL., 2003) or degraded lands (VASSILEV ET AL., 2012).
For the quantification of specific emission loads in different farming systems, the LCA (Life Cycle Assessment) study (KOČÍ, 2009) or the simplified LCA (HOCHSCHORNER AND FINNVEDEN, 2003), evaluating environmental impacts of a product based on the assessment of the impact of material and energy flows that the monitored system exchanges with the environment (BISWAS ET AL., 2010), may be used. LCA is a transparent scientific tool (WEINZETTEL, 2008) which evaluates the environmental impact on the basis of inputs and outputs within the production system (O'BRIEN ET AL., 2014).
The aim of this study was to draw up models of technological processes during the practical cultivation of RCG (the Chrastava variety) and Szarvasi-1 and determine their emission load impact on the environment.

MATERIALS AND METHODS

The simplified method of Life Cycle Assessment (LCA), defined by the international standards of ČSN EN ISO 14 040 (CNI, 2006A) and ČSN EN ISO 14 044 (CNI, 2006B) was used as a tool to calculate the emission load. The results of the study were related to *the Climate Change Impact Category* expressed as an indicator of carbon dioxide equivalent (CO_2e). The SIMA Pro software and the ReCiPe Midpoint (H) method was used for the calculations. The functional unit of the system was 1 kg of the final product - dry matter (hereinafter referred to as DM) and 1 GJ obtained through combustion of the final product. Technological processes of the cultivation of RCG and Szarvasi-1 intended for the direct combustion was compiled based on primary data (field experiments at ZF JU in České Budějovice), as well as secondary data (acquired from the *Ecoinvent 2010* database, literature search and normative data on agricultural production technologies). The database uses data geographically related to central Europe. The primary data were collected between 2013 - 2016 and the secondary data between 2000 - 2015. The data selected for modelling are based on the average of commonly applied intensive farming technologies (KAVKA, 2006; WROBEL, 2009; CSETE ET AL., 2011; STRAŠIL, 2012). Agrotechnical operations from seedbed preparation, the amount of seeds and seedlings, the use of plant protection products, production and application of fertilizers, etc., to harvesting the main product and transport were included into the model system. Infrastructure was not included into the system processes.
Besides the emissions arising from the inputs mentioned above, so called field emissions (N_2O emissions) are also produced after the application of nitrogen fertilizers. The IPCC methodology (*Intergovernmental Panel on Climate Change*) is used to quantify them (DE KLEIN ET AL., 2008).
Furthermore, the CHNS analysis (elemental composition of phytomass) was carried out using the Vario EL CUBE within the BBOT Standard. The heat of combustion was calculated using the Mendeleev's Formula $Q_s^r = [81\cdot C+300\cdot H–26\cdot(0–S)]\cdot 4.187$ ($kJ\cdot kg^{-1}$), as well as calorific value from the formula $Q_u = Q_v–5.85\cdot(W+8.94\cdot H)\cdot 4.186$ ($kJ\cdot kg^{-1}$), where Q_v is the heat of combustion in $kcal\cdot kg^{-1}$ (HUBÁČEK ET AL., 1962).

RESULTS AND DISCUSSION

This paper evaluates the results of the 3-year cultivation of RCG and *Elymus elongatus* subsp. ponticus cv. Szarvasi-1 for the direct combustion purposes using the intensive farming technologies under one cut treatment. Based on the methodology and acquired data (DM yields, inputs and outputs of the growing cycle, heat of combustion and calorific value calculated from the elemental composition), it was possible to compile the life cycle of chosen energy plants and quantify their impact on the environment. As already mentioned, the results of the study were related to the *Climate Change Impact Category* expressed in the carbon dioxide equivalent where CO_2e = 1x CO_2; 23x CH_4; 298x N_2O, based on the difference in the effectiveness of these greenhouse gases (FORSTER ET AL., 2007; SOLOMON, 2007).
Fig. 1 shows the amount of phytomass harvested during each season The grasslands always underwent a one-phase harvest in late winter or early spring. In this period, the plants contain the highest amount of DM (Ø>75%) (STRAŠIL ET AL., 2011) which is favourable for the direct combustion.process. In this case, the harvest took place from 17.3. - 1.4. , when RCG contained on average 80.6% of DM and Srazvasi-1 78% of DM. The CHNS analysis (elemental composition) was carried out and the heat of combustion (Q_s^r) and calorific value (Q_u) was calculated in DM samples. Values are reported in Fig. 2.

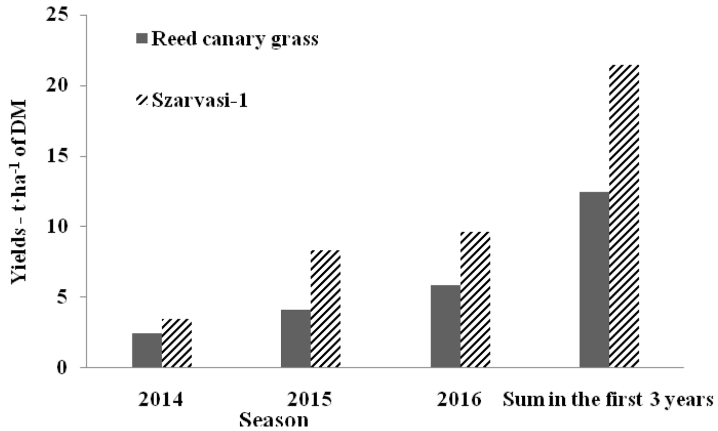

Fig. 1. – DM yields in particular years

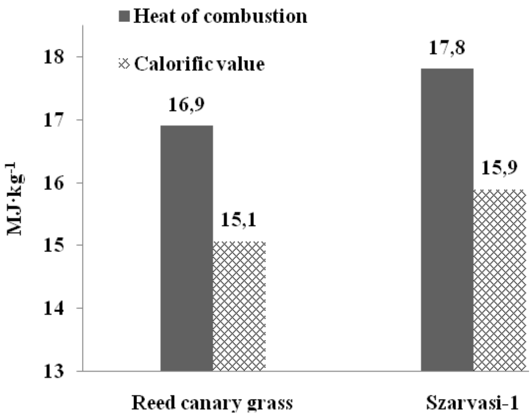

Fig. 2. – Heat of combustion and calorific value of chosen grasses calculated from the elemental analysis (MJ·kg^{-1})

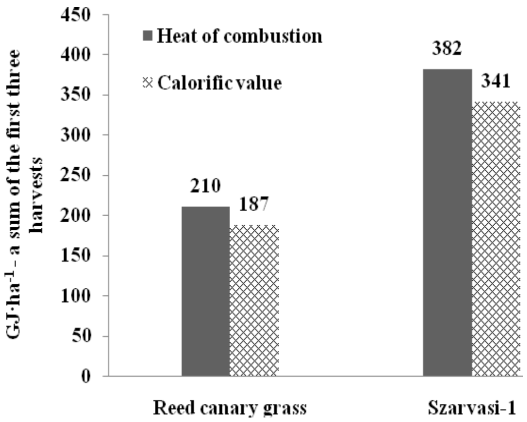

Fig. 3. – Net energy gain (a sum of the first three harvests) (GJ·kg^{-1})

The heat of combustion values of RCG (Q_s^r) are in accordance with ŠTINDL ET AL. (2006). He notes that the value is 16.6 ±0.20 (MJ·kg^{-1}) (calculated according to the Mendeleev's Formula). The heat of combustion of Szarvasi-1 is, according to the obtained data, on Ø 7% higher [Q_s^r = 17.8 (MJ·kg^{-1})], as well as the calorific value (Q_u Szarvasi-1 > Q_u RCG) in comparison with RCG (see Fig. 2). Q_u value is variable depending on the current moisture content of harvested phytomass. Fig. 3 presents the values of the total net energy gain (GJ·ha^{-1}) for the first three years. Szarvasi-1 can be regarded as more energy efficient due to the higher energy yield per production unit and higher production of phytomass per area unit. The total net energy gain of Szarvasi-1 (GJ·ha^{-1}) is almost $^1/_2$ higher in comparison with RCG on the basis of three-year monitoring. Based on these values, the emission load (in the form of CO_2e) per 1 kg DM and 1 GJ of the phytomass intended for direct combustion was then quantified (see Fig. 4).

Due to the identical farming technologies used for both species, the total net energy gain and yield is crucial in order to determine the difference between the emission loads at a profit of 1 GJ . As shown in Fig. 4, the difference in the total emission load in Szarvasi-1 cultivation (11.1 kg CO_2e·GJ^{-1}) and RCG cultivation (20.2 kg CO_2e·GJ^{-1}) is about 45%. A share of particular inputs and outputs of the growing cycle, making up the total emission load, is shown in Fig. 5.

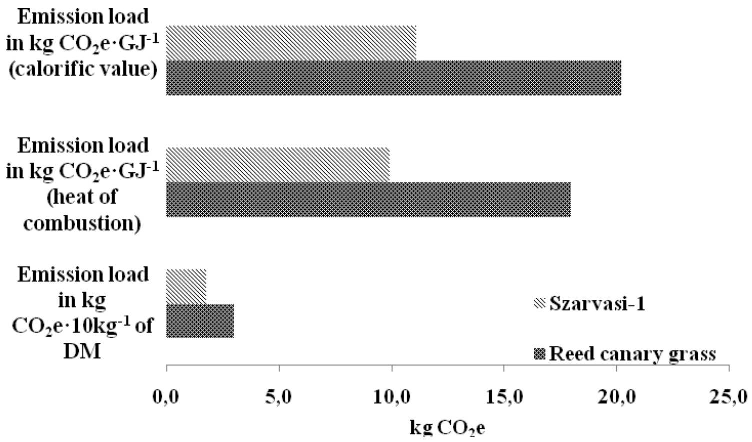

Fig. 4 - Emission load (kg CO_2e) per the production unit (1 GJ and 10 kg of DM)

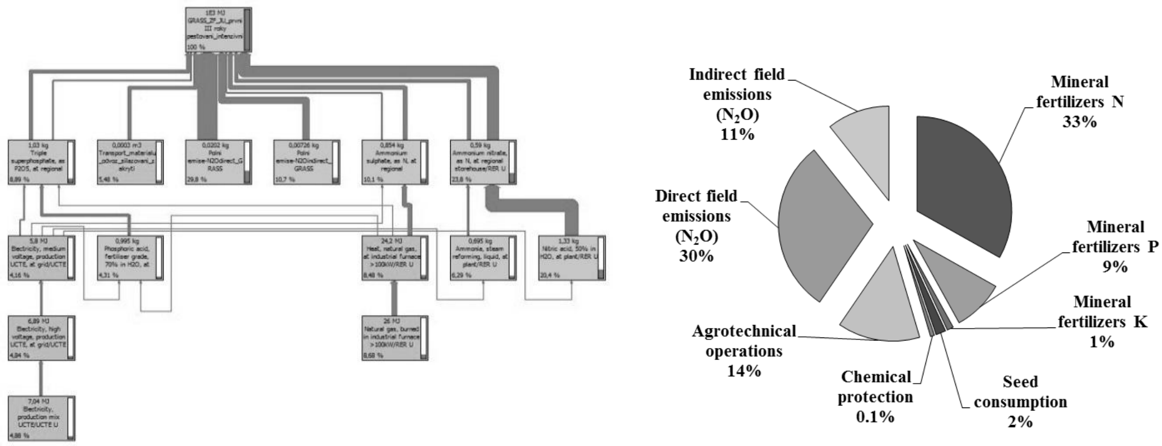

Fig. 5. – A share of particular inputs (in %) contributing to GHM emissions

Legend: Percentage of individual inputs is identical for both monitored grasses owing to the same farming technologies used.

The largest sources of GHG emissions from the crop production are fertilizers and their application (GATTINGER ET AL., 2012). In this case, the emissions arising from the use of mineral nitrogen fertilisers (33%) and the emissions resulting from their application represent the largest share of total emissions. These are known as field emission and can be divided into two categories: direct (30%) and indirect (11%). Agrotechnical operations (14%), particularly characterized by the consumption of fossil fuels, have a significant impact on the emission load. However, their consumption in the agricultural sector is, according to SAUERBECK (2002), considered less significant in comparison with the overall fuel consumption (in agriculturally advanced countries it is only about 3-4.5%).

Speaking of reductions in CO_2e production within the chosen cultivation process, it is necessary to focus especially on two of the strongest sources (application of nitrogen fertilizers and field emissions arising after the application of nitrogen fertilizers). For example, SMITH (2008) provides a variety of options of GHG mitigation within crop production In this regard, the issue of reduction in the dose of fertilizers or the total change of the agricultural system is often discussed (PAUSTIAN ET AL., 1998; MOUDRÝ ET AL., 2013). Also, the amount of emissions from agriculture is influenced to a great extent by farming systems. Conventional farming systems use more inputs in the form of fertilizers (organic and mineral), which are key factors in the mitigation of N_2O a NO emissions from soil. N_2O may be considered as the main greenhouse gas and organic farming systems generally produce less N_2O, as well as CO_2emissions due to lower inputs (BOS ET AL., 2007) and more close production cycle (KONVALINA ET AL. 2014A,B).

This paper points out the possibility of GHG mitigation per production unit (GJ) when growing different, more efficient energy grasses (Szarvasi-1) for direct combustion with the identical farming technologies. As the results show, Szarvasi-1 appears to produce more DM (21.4:12.4 $t \cdot ha^{-1}$ - (a sum of three harvests). It also has a higher heat of combustion (Q_s^r) (17.8:16.9 $MJ \cdot kg^{-1}$ of DM), as well as calorific value (Q_u) (15.9:15.1 ($MJ \cdot kg^{-1}$ of harvested material) and, in connection with this, a lower emission load per energy unit (11.1:20.2 kg CO2e·GJ-1). Therefore, Szarvasi-1 has a potential to gradually replace RCG, which has been grown for energy purposes last few years and, for example, has covered almost 70 thousand hectares in Finland (GHICA AND SAMFIRA, 2011).

CONCLUSIONS

The emission load per energy unit was quantified based on a three-year monitoring of selected energy grasses (RCG and *Elymus elongatus* subsp. ponticus cv.Szarvasi-1) grown for direct combustion. Based on the measured values, Szarvasi-1 appears to be more environmentally friendly alternative in comparison with RCG (11.1: 20.2 kg $CO_2e \cdot GJ^{-1}$). According to the monitoring, the difference is 45% per kg $CO_2e \cdot GJ^{-1}$. The article shows that GHG mitigation (related to a production unit) may be achieved through the replacement of existing plants by a more energy and yield efficient plant while maintaining the identical farming technologies. Further, mitigation could be initiated through the better management of mineral nitrogen fertilisers, extensive farming methods or a change of farming technology. Besides, cultivation of these perennial energy grasses brings extra benefits, such as the soil erosion protection, promotion of biodiversity and, when achieving appropriate yields of dry matter (> 12 $t \cdot ha^{-1}$ DM), economic efficiency.

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Corresponding author:

Jaroslav Bernas, Faculty of Agriculture, University of South Bohemia in České Budějovice, Studentská 1668, České Budějovice, 370 05, Czech Republic, e-mail: bernas@zf.jcu.cz

agriculture

Article

The Energy and Environmental Potential of Waste from the Processing of Hulled Wheat Species

Jaroslav Bernas [1,*], Petr Konvalina [1], Daniela Vasilica Burghila [2], Razvan Ionut Teodorescu [2] and Daniel Bucur [3]

[1] Faculty of Agriculture, University of South Bohemia, Studentska 1668, 37005 Ceske Budejovice, Czech Republic; konvalina@zf.jcu.cz
[2] Department of Environment and Land Improvements, Faculty of Land Improvements and Environmental Engineering, University of Agronomical Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd., 011464 Bucharest, Romania; burghila.daniela@edu.gov.ro (D.V.B.); razvan.teodorescu@usamv.ro (R.I.T.)
[3] Department of Pedotechnics, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine of Iasi, 3 Mihail Sadoveanu, 700490 Iasi, Romania; dbucur@uaiasi.ro
* Correspondence: bernas@zf.jcu.cz; Tel.: +420-389-032-401

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Abstract: Organic farmers farming on arable land have often had, in addition to the cultivation of common species of cultivated crops (such as wheat, rye, triticale or potatoes), interest in the cultivation of marginal crops such as hulled wheat species (Einkorn, Emmer and Spelt wheat). The production of marginal cereals has seen significant developments in the European Union related to the development of the organic farming sector. Just the average annual organic production of spelt in the Czech Republic reached more than 9000 tons in 2018. The cultivation of these cereals requires post-harvest treatment in the special method of dehulling. The waste emerging after dehulling of spikelet (i.e., chaff) accounts for about 30% of the total amount of harvest and can be used as an alternative fuel material. When considering the energy utilization of this waste, it is also necessary to obtain information on the energy quality of the material, as well as environmental aspects linked to their life cycle. For evaluating the energy parameters, the higher and lower heating value, based on the elemental (CHNS) analysis, was determined. The environmental aspects were determinate according to the Life Cycle Assessment (LCA) methodology where the system boundary includes all the processes from cradle to farm gate, and the mass unit was chosen. The SimaPro v9.1.0.11 software and ReCiPe Midpoint (H) within the characterization model was used for the data expression. The results predict the energy potential of chaff about 50–90 TJ per year. The results of this study show that in some selected impact categories, 1 kg of chaff, as a potential fuel, represents a higher load on the environment than 1 kg of lignite, respectively potential energy gain (1 GJ) from the materials.

Keywords: hulled wheat species; energy; life cycle assessment

1. Introduction

The production of marginal cereals has seen significant developments in the European Union related to the development of the organic farming sector. The typical marginal wheat species in the Czech Republic are Einkorn, Emmer, and especially Spelt wheat [1,2]. They can be defined as the cultural hulled wheat species, which replace, expand, and supplement the existing range of cereals and contribute to broadening the spectrum of crop production [3]. These marginal cereals have usually lower harvest index but have less input intensity requirements. Thanks to this aspect, these grains are particularly suitable for organic farming systems [3–5]. The benefits of introducing these marginal cereal species include extending the food spectrum, maintaining the production capacity of the soil, and the efficient use of marginal and less-favored areas [6,7]. However, the disadvantages are low yields (low harvest index) and uneven ripening, which causes large losses during harvesting [5,8]. The processing of these hulled wheat species generates a relatively large amount of waste-chaff [9], which can be used in various ways, for example, can be composted [10], used as litter [9] or as an additive to building materials [11], or could be directly put back to the agricultural land to help to maintain the soil fertility [2,5]. Due to the high content of mycotoxins, however, it is not recommended to use chaff from hulled wheat as litter and it is preferable to use it for energy production and to burn it [9], optimally in the form of pellets [12,13]. The energy use of such residual agricultural biomass has great potential not only across the EU [14]. The potential for energy utilization, the energy parameters of chaff and the removal rate, including pelleting issues, have been summarized for Spelt and Emmer in some studies [9,10,13,15]. However, the crop residue removal for biofuel production can have a significant impact on crop productivity, soil health, and greenhouse gas emissions [16].

In addition to Spelt and Emmer wheat, this manuscript also evaluates the energy parameters of Einkorn chaff. The energy use of chaff of these marginal cereal species is often perceived as an environmentally friendly source of energy, because it is energy from biomass. However, it has to be considered in terms of inputs into the cultivation process. This work aims to point out environmental aspects related to hulled wheat chaff and quantitative and qualitative parameters of individual wheat species using the Life Cycle Assessment (LCA) method.

2. Materials and Methods

2.1. Field Trails

Data for evaluation was based on field trials (the University of South Bohemia, Faculty of Agriculture, location: Zvíkov, GPS 48.9758531N, 14.6245594E; production region: cereal production region; altitude: 490 m; year temperature: 7.2 °C; year rainfall: 634 mm; type of soil: brown soil; sort of soil: loamy soil—medium) realized in the regime of organic farming. The field trails are used to assess yield potential, environmental, and economic aspects of cultivation. The fieldwork methodology was chosen based on commonly used organic farming technologies. Selected cultivation practices are typical for the conditions of the Czech Republic [2]. The design of randomized field trails in three replicates with an average area of an experimental plot of 10 m^2 was used. The growing period related to this study was from September 2017 to August 2018. Fodder pea—winter type was the preceding crop. Organic fertilizers were applied to the soil before sowing (6.6 ton ha^{-1} of manure/solid cattle; organic production) and the soil was loosened with a mid-deep ploughing to a 14–18 cm depth and levelled with a cultivator within the framework of pre-sowing preparatory works. Sowing of Spelt (winter type) was carried out in October 2017. Sowing of Emmer and Einkorn was carried out in April 2018 (spring types). The sowing depth was 3–4 cm. The amount of seed was 180 kg per ha. The harvest was performed during the July and August 2018. After harvest were taken samples from each replication and homogenized (hammer mill PSY MP 20/MP 40). Individual operations are shown in Table 1.

Table 1. Input data inventory.

Input	Unit	Investigated Crop		
		Spelt ^{W}	Emmer	Einkorn
Manure (solid cattle)	ton ha^{-1}	6.6	6.6	6.6
Solid manure loading and spreading	ton ha^{-1}	6.6	6.6	6.6
Tillage, ploughing	ha	1	1	1
Tillage, cultivating, chiselling	ha	1	1	1
Sowing	ha	1	1	1
Seeds, organic	kg ha^{-1}	180	180	180

Table 1. *Cont.*

Input	Unit	Investigated Crop		
Tillage, rolling	ha	1	-	-
Tillage, harrowing	ha	1	1	1
Combine harvesting	ha	1	1	1
Transport, tractor and trailer	tkm	50	50	50
Electricity for processing	kWh ton^{-1}	0.3	0.3	0.3

Transport included in the process as a flat rate 50 tkm. It is calculated with the same weight for all crops (max 8 tons per load); ^{W} = Winter Spelt wheat.

2.2. Analysis of Phytomass

For the purposes of this study, the elemental composition of chaff that remained after the dehulling of grains of Spelt, Emmer, and Einkorn was determined. The design of randomized field trails in three replicates for Spelt, Emmer, and Einkorn was used. After harvest, samples of chaff were taken from each replication and homogenized. For the elemental composition of chaff, two homogenized samples were used from each hulled wheat species. The CHNS analysis (the elemental composition of chaff) was carried out using the elemental analyzer (Vario EL CUBE). The method of direct jet injection of oxygen and combustion in the high furnace temperatures of up to 1200 °C with a complete conversion of the sample to measuring gas was used. The higher heating value (HHV) was calculated using the Mendeleev's equation (Equation (1)) [17], as well as lower heating value (LHV) from the equation (Equation (2)) [18], where Qv is the heat of combustion in kcal kg^{-1} [18]. Based on the observed elementary composition and empirical formulas, the HHV and LHV of the chaff were determined.

$$Q_s{}^r = [81 \times C + 300 \times H - 26 \times (O - S)] \times 4.186\ (kJ\ kg^{-1}), \quad (1)$$

where: * $Q_s{}^r$ = HHV [kJ kg^{-1}]; C = carbon in the sample (%); H = hydrogen in the sample (%); O = oxygen in the sample (%); S = sulphur in the sample (%); 4.186 = conversion factor from kcal kg^{-1} to kJ kg^{-1}

$$Q_u = Q_v - 5.85\ (W + 8.94 \times H) \times 4.186\ (kJ\ kg^{-1}), \quad (2)$$

where: * Q_v = HHV in kcal kg^{-1}; Q_u = LHV in kcal kg^{-1}; W = moisture (%) in the sample (average amount of moisture in the sample of chaff was determined according to Beloborodko et al. [19] and Žandeckis et al. [20]); H = hydrogen in the sample; 4.186 = conversion factor from kcal kg^{-1} to kJ kg^{-1}.

2.3. Environmental Aspects

A life cycle assessment method was used for environmental load quantification. This method is defined by the international standards of ČSN EN ISO 14 040 [21] and ČSN EN ISO 14 044 [22]. The system boundaries are set within the chaff from the cradle to the farm gate and within the lignite from the cradle to the gate (from mining to raw material ready for use). The results of this study are related to the 19 impact categories (characterization model). SimaPro v9.1.0.11 software and ReCiPe Midpoint (H) V1.13/Europe Recipe H., an integrated method, were used for environmental load quantification. One GJ of energy (from potential energy profit) was used as the defined unit/functional units (FU). The technological processes of growing the hulled wheat species were set up based on primary data (field trials carried out on plots at the University of South Bohemia) and secondary data (data gained from the Ecoinvent v3.6 database [23] and commonly used cultivation practices of organic farming [2]). Mass allocation approach was used (grain/straw/chaff). Data geographically related to central Europe was used. The primary data was collected between 2018 and 2019. The data selected for modelling is based on the average of commonly applied organic farming technologies [2,24]. Agrotechnical operations from seedbed preparation, the number of seeds, the use of agrotechnological operations for plant protection, treatment and application of organic fertilizers to harvesting, transporting of the harvested grain and processing the grain were included into the model system.

The usage of mineral and organic nitrogenous fertilizers and lime application results in the release of so-called direct and indirect emissions of N_2O, CO_2, NH_3, NO_3^- and NO_x. The following were taken into account in the monitoring of field and agricultural emissions: liming, NH_3 and NOx volatilization, and nitrogen loss from leaching and surface outflow. The emission load was determined following the IPCC (Intergovernmental Panel on Climate Change) methodology called Tier 1 [25,26], and with Nemecek and Kägi [27] and the national greenhouse gas inventory report of the Czech Republic (the agricultural section) [28]. Emissions of phosphorus due to leaching and run-off were estimated following recommendations from Nemecek and Kägi [27].

The individual steps determined by the methodology are shown in Figure 1.

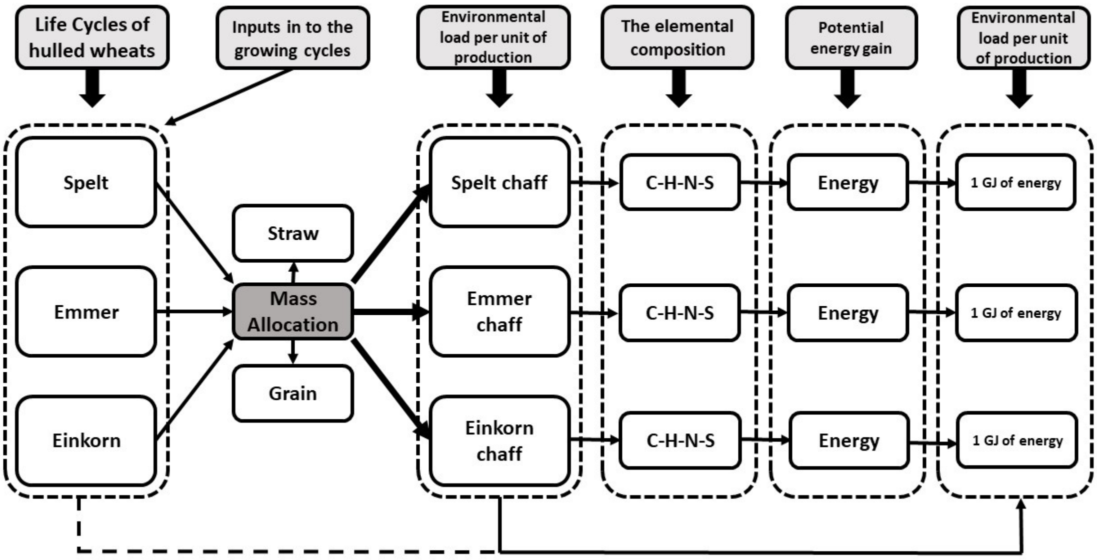

Figure 1. Workflow scheme.

3. Results and Discussion

3.1. Field Trial Results

The basic data source were field trials established according to the methodology plan. The data obtained from field trials are included in Table 2.

Table 2. Field trials results.

	Yield Range (t ha^{-1})	Grain Average Yield (t ha^{-1})	Straw Average Yield (t ha^{-1})	Chaff Rate (%)	Grain Net Yield (t ha^{-1})	Chaff Yield (t ha^{-1})
Spelt	2.80–3.27	2.96	4.75	33.23	1.98	0.99
Emmer	1.77–2.90	2.40	3.73	23.82	1.83	0.57
Einkorn	1.17–1.84	1.65	3.13	26.16	1.21	0.43

The results are based on one-year field trials under the organic farming system. The study aimed to obtain samples of waste material (chaff) and information about its quantity independence on yield level. The largest amount of chaff is produced during the peeling of Spelt wheat (average 1.45 t ha^{-1}), reps. the removal rate was 33.23%. This corresponds to the results reported in the study by Weiss and Glasner [13], which reported the removal rate of about 33%, and according to Wiwart et al. [9], of about 30%–35%. In the comparison of selected hulled wheat species, spelt wheat is also the most represented in the Czech Republic (3400 ha) [29]. This represents only 0.35% of the sowing areas of all winter cereals in the Czech Republic [29]. The lowest removal rate was recorded for Emmer wheat (23.82%), but the lowest chaff yield was for Einkorn (0.43 t ha^{-1} on average), given the lowest grain yield per hectare (1.65 t ha^{-1} on average).

3.2. Elemental Composition and Statistical Evaluation

For the study, elementary analysis of representative samples was carried out according to the methodology (Section 2.2). The results of elemental analysis are an essential source of information for the determination of HHV and LHV. The results of this analysis are included in Table 3.

Table 3. Elemental composition of chaff.

		N		C		H		S	
Sample	**Sample Weight (mg)**	**Ø%**	**S.D.**	**Ø%**	**S.D.**	**Ø%**	**S.D.**	**Ø%**	**S.D.**
Emmer	4.8545	0.6025	0.000707	41.5810	0.098995	6.1008	0.002121	0.0896	0.016971
Spelt	5.4315	1.1434	0.072832	42.3710	0.098995	6.4031	0.002121	0.0915	0.023335
Einkorn	5.1870	0.9230	0.028991	41.0150	0.007071	6.3185	0.002828	0.0697	0.054447

The average values of the homogenized samples; S.D. = standard deviation; Ø% = average percentage.

Based on the results of the elementary analysis, statistical evaluation was carried out. The ANOVA and Tukey HSD test were used. Individual samples within the percentage content of C, N, H, and S were shown to be statistically demonstrably different from each other at a significance level of $p = 0.05$ (Table 4).

Table 4. Statistical evaluation—variance analysis ANOVA.

C	$F_{2.3} = 141$; $p = 0.001075$
N	$F_{2.3} = 72.268$; $p = 0.002900$
H	$F_{2.3} = 38.5$; $p = 0.007272$
S	$F_{2.3} = 49.794$; $p = 0.005001$

p = level of significance ($p = 0.05$).

The following post-hoc Tukey HSD test (Table 5) showed that all crops differed within percentage content of C and N. However, within the percentage content of H, the samples of Einkorn and Spelt chaff did not differ from each other and within the percentage content of S, the samples of Einkorn and Emmer chaff did not differ from each other.

Table 5. Statistical evaluation—post-hoc Tukey HSD test.

Category	C	N	H	S
Emmer × Einkorn	$p = 0.004837$	$p = 0.002753$	$p = 0.007136$	no difference
Einkorn × Spelt	$p = 0.001136$	$p = 0.033646$	no difference	$p = 0.006019$
Emmer × Spelt	$p = 0.012420$	$p = 0.011883$	$p = 0.017988$	$p = 0.007922$

p = level of significance ($p = 0.05$).

The ash content of the sample was derived from the Sheng and Azevedo study [30] and the percentage content of oxygen was determined based on the difference. Moisture in the chaff sample was derived from the study by Beloborodko et al. [19] and Zandeckis et al. [20].

3.3. HHV, LHV and Potential Energy Profit Ha

Based on the data obtained from the elementary analysis, the HHV and LHV were determined. The resulting values are included in Table 6.

Table 6. Energy parameters of hulled wheat chaff.

	HHV ($MJ\ kg^{-1}$)	LHV ($MJ\ kg^{-1}$)	Energy Potential ($GJ\ ha^{-1}$) E	Energy Potential for CZ ($TJ\ rok^{-1}$)
Spelt	17.74	15.90	13.21–26.41	50–90
Emmer	16.92	15.14	6.49–10.46	-
Einkorn	16.99	15.16	4.76–7.53	-

E = The energy potential is related to the yield range obtained in the field trials; HHV = higher heating value; LHV = Lower heating value; CZ = Czech Republic.

In the frame of the study, the HHV and LHV of Spelt chaff (17.74 MJ kg^{-1} respectively 15.90 MJ kg^{-1}), Emmer chaff (16.92 MJ kg^{-1} resp. 15.14 MJ kg^{-1}), and Einkorn chaff (16.99 MJ kg^{-1}, resp. 15.16 MJ kg^{-1}) were determined. The HHV and LHV of Spelt and Emmer chaff did not differ significantly from those reported in some earlier studies [9,10,13,15]. For example, according to the study by Wiwart et al. [9] the energy values (HHV and LHV) of Spelt and Emmer chaff were also determined. The chaff of Spelt and Emmer are generally defined by the higher HHV (18.75 MJ kg^{-1} resp. 18.31 MJ kg^{-1}), higher LHV (16.74 MJ kg^{-1} resp. 16.35 MJ kg^{-1}), significantly lower ash content (3.79% resp. 6.16%), and also lower content of the volatile matter (70.3% resp. 74.9%) in comparison with wheat and barley straw. Despite the relatively high Sulphur content (0.148%), the Emmer chaff has significant energy potential. Considering the LHV of 15.1 MJ kg^{-1} and the removal rate of 0.33, winter wheat and Spelt chaff has a theoretical potential of 191 PJa^{-1} in the EU [13]. For the Czech Republic only, the energy potential of Spelt is about 50–90 TJ $year^{-1}$.

3.4. Environmental Impact Assessment and Economy Aspects

For the study, an evaluation of the environmental load related to individual hulled wheat species and waste (chaff) resulting from their processing was compared with the traditional non-renewable fuel type lignite. The inputs to the growing cycle are part of the Field Trails methodology. The results are generated within the characterization model (Table 7).

Table 7. Environmental load per 1 GJ of potential energy profit.

Impact Category	Unit	Spelt	Emmer	Einkorn	Lignite [EI]
Climate change	kg CO_2 eq	1.35×10^{1}	1.75×10^{1}	2.25×10^{1}	1.60
Ozone depletion	kg CFC-11 eq	6.25×10^{-7}	7.95×10^{-7}	1.02×10^{-6}	1.23×10^{-7}
Terrestrial acidification	kg SO_2 eq	1.21×10^{-1}	1.58×10^{-1}	2.03×10^{-1}	5.22×10^{-3}
Freshwater eutrophication	kg P eq	1.69×10^{-3}	2.15×10^{-3}	2.76×10^{-3}	2.35×10^{-1}
Marine eutrophication	kg N eq	3.57×10^{-2}	4.72×10^{-2}	6.06×10^{-2}	4.92×10^{-2}
Human toxicity	kg 1,4-DB eq	1.30	1.61	2.07	1.32
Photochemical oxidant formation	kg NMVOC	5.04×10^{-2}	6.40×10^{-2}	8.22×10^{-2}	4.48×10^{-2}
Particulate matter formation	kg PM10 eq	2.92×10^{-2}	3.76×10^{-2}	4.82×10^{-2}	2.16×10^{-3}
Terrestrial ecotoxicity	kg 1,4-DB eq	1.17×10^{-3}	1.52×10^{-3}	1.95×10^{-3}	7.64×10^{-5}
Freshwater ecotoxicity	kg 1,4-DB eq	1.61×10^{-1}	2.00×10^{-1}	2.56×10^{-1}	3.28
Marine ecotoxicity	kg 1,4-DB eq	1.44×10^{-1}	1.79×10^{-1}	2.29×10^{-1}	3.13×10^{-1}
Ionising radiation	kBq U235 eq	2.85×10^{-1}	3.59×10^{-1}	4.60×10^{-1}	4.80×10^{-1}
Agricultural land occupation	m^2a	8.46×10^{1}	1.12×10^{2}	1.44×10^{2}	1.17×10^{-1}
Urban land occupation	m^2a	1.06×10^{-1}	1.30×10^{-1}	1.67×10^{-1}	1.19×10^{-1}
Natural land transformation	m^2	1.36×10^{-3}	1.73×10^{-3}	2.22×10^{-3}	1.64×10^{-3}
Water depletion	m^3	7.52×10^{-2}	9.85×10^{-2}	1.26×10^{-1}	6.82×10^{-2}
Metal depletion	kg Fe eq	8.77×10^{-1}	1.06	1.36	8.21×10^{-2}
Fossil depletion	kg oil eq	1.38	1.75	2.24	2.30×10^{1}

[EI] = source from Ecoinvent library (3.6 v); ReCiPe Midpoint (H) method, Characterization model, Results are expressed per GJ of potential energy profit; eq = equivalent; CFC-11 = Trichlorofluoromethane; 1,4-DB = 1,4-dichlorobenzene; NMVOC = Non-methane volatile organic compound; PM10 = Particulate matter <10 µm; U235 = Uranium235; m^2a = Potentially disappeared fraction (PDF)*m^2*year/m^2.

Due to the different material properties (such as combustion rate in the incineration unit), the resulting values are recalculated to potential energy gain (1GJ) compared to 1 kg of lignite with LHV of 9.9 MJ kg^{-1} (resp. 1GJ of potential energy gain). The most significant environmental savings compared to lignite can be found in the impact categories of freshwater eutrophication (k P eq), human toxicity (kg 1,4-DB eq), freshwater ecotoxicity (kg 1,4-DB eq), marine ecotoxicity (kg 1,4-DB eq) and fossil depletion (kg oil eq). On the other hand, the potential gain of 1 GJ from lignite was associated with lower environmental impacts for the other selected impact categories. The most important difference was determined among the impact categories of climate change (kg CO_2 eq), terrestrial acidification (kg SO_2 eq), photochemical oxidant formation (kg NMVOC), particulate matter formation (kg PM10 eq), terrestrial ecotoxicity (kg 1,4-DB eq), and metal depletion (kg Fe eq). In general terms, the highest environmental load was associated with the Einkorn chaff (within all impact categories). It is caused by the grain yield per hectare and lower LHV compared to Spelt chaff.

The evaluation results are influenced by the selected allocation approach—in this case, mass allocation (Chart 1). In terms of mass allocation, the environmental load associated with Spelt, Emmer, and Einkorn chaff was 12.8%, 9.3%, resp. 9.0% of the total environmental load connected with the growing cycle. On the other hand, the environmental load associated with the production of Spelt, Emmer, and Einkorn chaff would be, according to the economy allocation, 5.8%, 4.6% and 3.8%, respectively, of the total environmental load linked to the growing cycle (Table 8). However, price relations are highly volatile, and the economy has no direct impact on yield relations and therefore the economy allocation is not considered appropriate in this assessment. A comparison of allocation approaches and market price data is also included in Table 8.

Table 8. Allocation approach and market price.

	Product	Field Production (t ha^{-1})	Mass Allocation (%)	Market Price (Eur ton^{-1}) without VAT	Economy Allocation (%)
Spelt	Grain	1.98	25.6	400	78.5
	Straw	4.75	61.5	80	15.7
	Chaff	0.99	12.8	30	5.8
Emmer	Grain	1.83	29.9	560	83.5
	Straw	3.73	60.8	80	11.9
	Chaff	0.57	9.3	30	4.6
Einkorn	Grain	1.21	25.4	680	86.1
	Straw	3.13	65.6	80	10.1
	Chaff	0.43	9.0	30	3.8

VAT = value-added tax.

From the values given in Table 8, the price for 1GJ of potential energy gain and the amount of material needed to obtain the same amount of energy can be predicted (Table 9).

Table 9. Price relations.

	LHV (MJ kg^{-1})	Market Price (Eur ton^{-1}) without VAT	Price (Eur per GJ) (Potential)	Amount of Material to Obtain the Same Amount of Energy (kg)
Spelt chaff	15.90	30	1.88	1
Emmer chaff	15.14	30	1.98	1.05
Einkorn chaff	15.16	30	1.98	1.05
Lignite	9.9	140	14.14	1.61

VAT = value-added tax; HHV = Higher heating value; LHV = Lower heating value.

The results of the environmental impact assessment show that the use of waste material (chaff) arising after processing hulled wheat species for energy purposes does not necessarily mean lower environmental load. This is due to inputs into the growing cycles, yield level, chosen technological processes, and selected allocation approach. The advantages of the lignite are the relatively high yield per area unit, easier logistics and generally better fuel properties, and currently also the price and availability. However, it is a non-renewable energy source that is generally considered to be very problematic, especially concerning climate change, air quality impacts, landscape, water quality and other environmental categories. Biomass is generally considered to be a renewable source of energy [31], but from the LCA methodology point of view, this is not the case even when organic farming production is involved. The results of this study show that in some selected impact categories (e.g., climate change, terrestrial acidification, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, and metal depletion), 1 kg of chaff, as a potential fuel, represents a higher load on the environment than 1 kg of lignite, resp. potential energy gain (1 GJ) from the materials.

4. Conclusions

In a comparison of the monitored wheat species, the largest amount of the chaff is generated after processing of Spelt wheat (33.23% removal rate) with an average HHV value of 17.74 MJ kg^{-1} and LHV 15.9 MJ kg^{-1}. Compared to that, in the case of Einkorn and Emmer 26.16% resp. 23.82% of chaff with HHV 16.99 MJ kg^{-1} resp. 16.92 MJ kg^{-1} and LHV 15.16 MJ kg^{-1} resp. 15.14 MJ kg^{-1} can be expected. Based on the yields obtained in field trials, a potential energy gain of 26.41 GJ ha^{-1} for spelt wheat, 19.84 GJ ha^{-1} for Einkorn, and 18.03 GJ ha^{-1} for Emmer wheat can be predicted. Only Spelt wheat is grown in the Czech Republic at around 3400 ha per year, and the energy potential of chaff at 50–90 TJ $year^{-1}$ concerning the yield can be estimated. This can be expressed by the lignite equivalent (with LHV of 9.9 MJ kg^{-1}) corresponding to a very rough estimate of 103.3–206.5 boxcars/wagons of lignite. Concerning the environmental aspects, hulled wheat chaff is an interesting alternative energy source, ideally in the region of cultivation and processing. Regarding the assessment of the environmental aspects, it is also necessary to choose an appropriate allocation approach. According to study results, when using the mass allocation principle, the share of the total environmental load associated with the production of chaff is 9.0%–12.8%, but when using the economy allocation principle, it is only 3.8%–5.8%. An appropriate allocation approach can improve the quality of data and their interpretation. The results also show that hulled wheat chaff can be a cheaper source of energy compared to lignite.

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Cup plant, an alternative to conventional silage from a LCA perspective

Jaroslav Bernas[1] · Tereza Bernasová[1] · Pedro Gerstberger[2] · Jan Moudrý[1] · Petr Konvalina[1] · Jan Moudrý Jr.[1]

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Abstract

Purpose The growing awareness of the importance of biodiversity in agroecosystems in increasing and ensuring the supply of biomass has led to heightened interest from governments and farmers in alternative crops. This article assesses one such alternative crop, cup plant (*Silphium perfoliatum* L.), in terms of the environmental aspects of cultivation for forage production. Many studies have previously focused on cup plant, but so far, this plant has not been assessed using the life cycle assessment (LCA) method.

Materials and methods This study compares the environmental load of cup plant with the most commonly grown silage crops in Central European conditions—maize—and with another common forage crop—lucerne using LCA. The system boundaries include all the processes from cradle to farm gate and both mass-based (1 ton of dry matter) and area-based (1 ha of monoculture) functional units were chosen for the purposes of this study. The results cover the impact categories related to the agricultural LCAs, and the ReCiPe Midpoint (H) characterization model was used for the data expression, by using SimaPro 9.0.0.40 software.

Results This study compares the cultivation of cup plant with the most commonly grown silage crop in Central European conditions—maize—and with another common forage crop—lucerne. The paper shows the potential of cup plant to replace conventional silage (maize and lucerne silage mix) with certain environmental savings in selected impact categories, and importantly, while still maintaining the same performance levels in dairy farming as with conventional silage, as already reported in previous publications. For the Czech Republic alone, this would, in practice, mean replacing up to 50,000 ha of silage maize and reducing the environmental load by about tens of percent or more within the various impact categories and years of cultivation.

Conclusion Cup plant can replace the yield and quality of silage maize, represents a lower environmental load per unit of production and unit of area and generally carries many other benefits. Thus, cup plant is a recommendable option for dairy farming. Given the recent experience and knowledge of the issue, the cup plant can be considered an effective alternative to conventional silage.

Keywords Agricultural LCA · Environmental aspects · Cup plant · Silage maize · Lucerne · Perennial cropping system

1 Introduction

The growing of silage maize for silage production has increased in the Czech Republic in recent decades. The amount of land used for maize silage in the Czech Republic in 2018 was almost 231,000 ha (9.1%) (CZSO 2020). However, there are problems associated with such an increase in the cultivation of high-yield annual crops, among which maize belongs. The tendency has led to changes in crop rotation, natural scenery, biodiversity and animal populations and increased the susceptibility of the crop to disease and pests (Sithole et al. 2018). In addition, maize cultivation is associated with an increased risk of soil

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✉ Jaroslav Bernas
bernas@zf.jcu.cz

[1] Faculty of Agriculture, University of South Bohemia, Ceske Budejovice, Czech Republic

[2] Department of Plant Ecology, University of Bayreuth, Bayreuth, Bavaria, Germany

erosion (Vogel et al. 2016; Ghabbour et al. 2017), particularly when cultivated on sloping land (Poláková et al. 2018), which leads in turn to the eutrophication of waterways, poor soil quality and even flooding (Gansberger et al. 2015). For the reasons mentioned above, some agricultural operators have started to use alternative crops (Lewandowski et al. 2003; Ericsson et al. 2009; De Wit and Faaij 2010). Some alternative crops are available, but their yield level, forage quality, ensilage, habitat suitability or environmental impact can prove problematic (Bernas et al. 2019b). An exception to this is cup plant (*Silphium perfoliatum* L.), which has a high biomass yield, a low care requirement compared with annual crops and ecological advantages over traditional forage crops such as maize (Gansberger et al. 2015). Cup plant is also a crop that can be stored (as silage) for a long time with minimal losses, is also favourable for biogas production and easily ensilable (Aurbacher et al. 2012; Haag et al. 2015). In recent decades, many experiments have been carried out regarding the cultivation of cup plant, but the most information and practical experience of growing cup plant are currently to be found in Germany, Austria and the USA (Van Tassel et al. 2017; Gansberger et al. 2015). This promising and efficient fodder plant was also grown experimentally on an extreme, dry stand in the Czech Republic (Troubsko) from 1984 to 1990. The plant has also been tested in some European countries with good results, especially on the territory of the former USSR and other countries around the world (Gansberger et al. 2015). Green mass yields reached from 60 to 95 tons per ha. Under the conditions found in the Czech Republic, cup plant appears to be good quality, high-yielding and vital fodder plant, sufficiently adaptable to the stand (Vacek and Řepka 1992; Usťak and Munoz 2018). However, in most cases, the cultivation of cup plant has not been implemented in agricultural practice. This was often caused due to a lack of knowledge and experience and distrust. The proper temperature stratification of seeds and the effective preparation of cup plant seedlings are also problematic (Gansberger et al. 2017). At this time, cup plant is much more well-known than before, and the cultivation of this plant is gaining in importance, among other things due to the good practical experience of it gradually gained by growers (Gansberger et al. 2015). Cup plant also provided an adequate yield that is comparable with maize (seen on the long-time horizon), has an exceptional ecological value (Majtkowski et al. 2009; Gansberger et al. 2015; Bufe and Korevaar 2018), high phytomass yields of very good quality over the other alternative forage crops (Stanford 1990; Albrecht and Goldstein 1997; Kowalski and Wolski 2005; Piłat et al. 2007; Ţîţei et al. 2013; Ţîţei 2014), is an excellent alternative for biogas production (Gansberger et al. 2015) and can be grown for 20–25 years with constant yields of phytomass (Matthews et al. 2015). Thanks to the perennial character and density of growth, cup plant also provides protection against water and wind erosion (Usťak and Munoz 2018), has low water requirements compared with maize (Pan et al. 2011), which corresponds to the water protection concept (Bernas et al. 2019a). Further, cup plant can be used in the pharmaceutical industry (Kowalski and Kędzia 2007; Wrobel et al. 2013), or in construction (Klímek et al. 2016), and is also presented as a crop with a high yield of honey (Stanford 1990). There is still a great need for research on this crop, particularly in developing a seed technology, investigating its susceptibility to potential plant pathogens and finding a suitable herbicide for weed management in the establishment year. Overall, this crop is a very promising alternative crop for biogas (Gansberger et al. 2015) and, finally, forage production (Piłat et al. 2007; Albrecht et al. 2017). A number of publications have focused on the quality of forage for feed purposes or biogas production (Gansberger et al. 2015).

This article builds on the results of a study by Albrecht et al. (2017) and arises from a comparison of environmental aspects of maize silage, lucerne silage and cup plant silage. Commonly, ration intake and milk yield decrease linearly with increasing substitution rate. However, we can conclude from the results that cup plant silage can replace at least 30% of the conventional silage in the ration without sacrificing dairy cow performance (Albrecht et al. 2017). This work evaluates the environmental aspects that arise while replacing maize and lucerne silage mix with cup plant from 33% upwards at different intensities of cultivation. The intensity of fertilization and agrotechnological methods were established according to standard intensive agricultural technologies for the production of maize (Kavka et al. 2006), lucerne (Hakl et al. 2014) and cup plant (Usťak 2012) for the conditions prevalent in the Czech Republic. This study is also based on a 4-year small-plot field trial involving a cup plant. The results of this article indicate a potential reduction in environmental impacts when replacing 33% of maize and lucerne silage mix with the same proportion of cup plant silage while maintaining the same milk production (according to study Albrecht et al. (2017)). Many studies have previously focused on cup plant, but so far, this plant has not been assessed using the life cycle assessment (LCA) method. This work also contains integrating the perennial cropping cycle in the LCA, which very little attention was paid to in the thematically focused works (Bessou et al. 2013). The frequency and intensity of the input application in perennial short cycles can vary considerably from year to year, as well as the yields. This is why applying a multiyear perspective, in accordance with the putative lifetime of these crops, is strongly recommended to provide more accurate environmental results for the optimization of perennial systems (Escobar et al. 2017). The multiyear approach supports highlighting the importance of the multiyear approach in order to reduce variability and underestimated environmental impacts and should be considered also in crops with an average lifetime of 20 years or higher (Vinyes et al. 2015).

2 Materials and methods

2.1 Goal and scope definition

The goals of this study are to quantify the environmental impacts of the life cycle of cup plant (hereinafter referred to as CP), silage maize and lucerne and compare them with each other and within the selected silage ratio (33:33.5:33.5%). The results of this research may be used to motivate environmentally-friendly farming systems and as a source of information for agricultural subjects that focus on phytomass and its forage use. The three crops were analysed and evaluated, in accordance with LCA standards (ISO 14040 2006a; ISO 14044 2006b), to quantify their environmental impacts and to identify the environmental hot spots.

The results of a 4-year cycle of growing cup plant, a 4-year cycle of growing lucerne and three growing technologies of maize for the purpose of silage production are assessed in this study. The obtained results were used for quantification of the environmental load associated with the production unit (1 ton of dry matter) and the area unit (1 ha of the investigated crop). In the case of the area unit, the yield level of phytomass is not taken into account. The system boundaries include all the processes from cradle to farm gate. Agrotechnological operations were also incorporated into the model system: from pre-seeding preparation, through harvesting of the main product, to the transport of farming machinery, the production and use of crop-protecting agents, the production and use of fertilizers and the harvest and transport of the main product from the harvest site. Land use change for annual (silage maize) and perennial crops (cup plant and lucerne) were taken into account. Infrastructure processes are part of database inputs. Manure production (management) has been not included. Cow manure is considered to be a residual product of the animal production systems, so it does not include any of the emissions of the animal production system. Emissions that occur from manure application are included in the processes where this occurs (e.g., the crop cultivation processes). Waste management was excluded from this research because waste production is not expected within the monitored cropping systems. In the frame of this research, the transport distance from the farm to the field did not exceed 10 km.

A functional unit related to a production and area unit was chosen for the purposes of this study. The production unit is expressed as 1 ton of harvested dry matter; the area unit is expressed as 1 ha of a monoculture of the selected crop. The environmental impacts of the processes being investigated were not divided into two or more processes (all of the upper plant material was considered the final product in this study), and no allocation methods were employed.

Table 1 Temperature and precipitation characteristics—České Budějovice (modified from CHI (2020))

Year	Average temperature (°C)		Precipitation (mm)	
	Year	Season	Year	Season
2016	10.5	15.7	680.9	447.7
2017	9.7	16.4	630.3	438.8
2018	10.7	18.3	566.7	293.9
2019	10.6	16.8	586.0	351.1
Average (2016–2019)	10.4	16.8	616.0	382.9
Long-term average (1961–1990)	8.2	14.2	582.8	366.2

Season (i.e. growing season) from April to August

2.2 Data source and LCI

A field trial with cup plant was established for this research from 2016 to 2019, which was the source of the primary data for the life cycle inventory. The trial site characteristics are described in Table 1 and Table 2. On the other hand, for maize and lucerne, data on the agricultural practices in the Czech Republic were obtained from reference books and the technical and technological norms for agricultural production. Secondary data for background processes were taken from Ecoinvent v3.5 database, which includes data from Central Europe (Wernet et al. 2016) and Agri-footprint v4.0 (Durlinger et al. 2017).

3 Investigated crops

3.1 (1) Cup plant

The reference stand of the investigated cup plant was established in accordance with intensive growing technologies (system boundaries). Buckwheat, spring barley and oat were the preceding crops. The potential influence of the foregoing

Table 2 Station characteristics (modified from CHI (2020))

Parameters	
Altitude (MAMSL)	380
Agricultural production region	Cereal production
Soil texture class	Sand-loam class
Soil type	Pseudogley Cambisol
Soil pH	6.4
Global Positioning System (GPS) coordinates	48° 57′ 07″ N; 14° 28′ 17″ E

crops was not taken into account in this study. The soil was loosened with a mid-deep ploughing to a 14–18 cm depth and levelled with a cultivator within the framework of pre-planting preparatory works. Mineral fertilizers were applied to the soil before planting. The initial dose of mineral fertilizer per plot (50.6 m^2) was 1.25 kg of triple superphosphate (TSF), 2.75 kg of calcium ammonium nitrate (CAN) and 1.25 kg of potassium chloride (PCH). However, the doses of fertilizers were different in the productive years (inventorization—Table 3). The mineral fertilizers CAN, PCH and TSF were applied in spring before the growing season started. Planting was carried out in October 2016. The density was 4 seedlings per 1 m^2. The dates of mowing were adjusted according to the purpose of use of the phytomass. Cup plant's stand grown for the purpose of feed production was mowed and harvested once per year when the dry matter content was 28–33%, which corresponds to the time when the seeds ripen in bloom (Usťak 2012; Gansberger et al. 2015; Usťak and Munoz 2018).

3.2 (2) Maize

For the purposes of this investigation, cultivation practices related to silage maize were modelled. Selected cultivation practices are typical for the conditions of the Czech Republic. The technical and technological norms for agricultural production were used as sources of information and examples (Kavka et al. 2006; Agronormativy 2015). Silage maize cultivation practices correspond to three standardized intensities of treatment: standard (M-S), intensive (M-I) and low input (M-L). M-S—the standard method of cultivation in the Czech Republic, applied to the vast majority of agricultural enterprises. M-I—technology suitable for the most suitable natural conditions, high inputs into individual operations, herbicides and fertilizers are limiting factors of high yield. M-L—an extensive variant suitable only for marginal growing conditions. Pre-emergence protection is taken into account for silage maize (M-I; M-S and M-L): herbicide (1.2 l ha^{-1}) with active substance metolachlor (96%) and post-emergence protection (for M-I and M-S): herbicide (50 g ha^{-1}) with active substance rimsulfuron (25%). A list of inputs and outputs is a part of the data inventorization. Information on fertilization intensity linked to individual cultivation practices for standard growing technologies prevailing in the Czech Republic is included in the inventory table (Table 3).

3.3 (3) Lucerne

For the purposes of this investigation, cultivation practices related to lucerne (L) were modelled. Selected cultivation practices are typical for the conditions found in the Czech Republic. The technical and technological norms for agricultural production were used as sources of information and examples (Kavka et al. 2006; Agronormativy 2015; Hakl et al. 2014). Lucerne cultivation practice corresponds to the standardized intensity of treatment. Post-emergence protection is taken into account for lucerne: herbicide (1.25 l ha^{-1}) with active substance bentazone (43.2%). A list of inputs and outputs is a part of the data inventorization. Information on fertilization intensity linked to individual cultivation practices are included in the inventory table (Table 3). The benefits of biological nitrogen fixation are not considered in the study.

4 Software data inventorization

The intensity of fertilization and agrotechnological methods were established according to ordinary intensive agricultural technologies of silage maize (Kavka et al. 2006; Agronormativy 2015), cup plant (Usťak 2012; Usťak and Munoz 2018), and lucerne (Kavka et al. 2006; Agronormativy 2015; Hakl et al. 2014).

5 Determination of field emissions

The usage of mineral and organic nitrogenous fertilizers and lime application results in the release of so-called direct and indirect emissions of N_2O, CO_2, NH_3, NO_3^- and NOx (expressed as CO_2, N_2O and ammonia in Table 3). The following were taken into account in the monitoring of field and agricultural emissions: liming, NH3 and NOx volatilization, NO_3^- leaching to ground water and nitrogen loss from leaching and surface outflow. The emission load was determined in accordance with the IPCC methodology called tier 1 (De Klein 2006; IPCC 2006), and with Nemecek and Kägi (2007) and the national greenhouse gas inventory report of the Czech Republic (the agricultural section) (Exnerová and Beranova 2017). N fertilizers (mineral or organic) are not included within lucerne cultivation; therefore, NH_3 and NO_3^- emissions to air and water were not taken into account. Emissions of phosphorus due to leaching and run-off were estimated following recommendations from Nemecek and Kägi (2007). The risk of erosion, resp. P emissions through erosion was not considered in this study. The quantification of soil erosion losses is a very complex problem (Novotný et al. 2016), and there are no accurate values corresponding to the scope of the study. Using the inaccurate data related to soil erosion losses could bring in a certain disadvantage, especially when comparing annual and permanent crops. The production

Table 3 Inventory table: inputs and outputs of life cycle (for 1 ha)

Outputs	Unit	M-S	M-L	M-I	L[b]	CP (YoE)	CP (PY)
Unit of production—dry matter/green mass	ton	12.8/40	8/25	17.6/55	8.25[c]/42[c]	-	11.7[b]/48[b]
Unit of the area—1 ha of the selected crop	ha	1	1	1	1	1	1
Area needed for generating the same phytomass yield	ha	1	1.60	0.73	1.55[c]	-	1.09
Inputs from technosphere	Unit						
Nitrogen fertilizer, as N, calcium ammonium nitrate (a sum)[a]	kg	85	70	120	-	150	70
Application of plant protection products by field sprayer[a]	ha	2×1	1	2×1	1	-	-
Chopping[a]	ha	1	1	1	2.5[c]	-	1
Fertilization by broadcaster[a]	ha	4×1	3×1	4×1	1	1	1
Herbicide at plant[a]	kg	1.25	1.2	1.25	1.25	-	-
Maize seed for sowing[a]	kg	30	30	30	-	-	-
Lucerne seed[a]	kg	-	-	-	4[c]	-	-
Manure, solid, cattle[a]	ton	40	-	40	-	-	-
Seedlings, at greenhouse[a]	p	-	-	-	-	40,000	-
Potassium chloride (as K_2O)[a]	kg	70	50	100	90[c]	150	50
Solid manure loading and spreading, by hydraulic loader and spreader[a]	ton	40	-	40	-	-	-
Tillage, harrowing, by spring tine harrow[s]	ha	1	-	1	-	-	-
Tillage, ploughing[a]	ha	1	1	1	1	1	-
Tillage, rolling[a]	ha	1	1	1	1	-	-
Tillage, cultivating, chiselling/by disk harrow[a]	ha	3×1	2×1	3×1	1	1	-
Sowing[a]	ha	1	1	1	1	-	-
Planting[a]	ha	-	-	-	-	1	-
Transport, tractor, and trailer, agricultural[a]	tkm	400	250	550	419[c]	-	410.3[b]
Triple superphosphate (as P_2O_5)[a]	kg	50	40	70	23[c]	120	50
Lime[a]	kg	500	500	500	500[c]	-	-
Mulching[a]	ha	-	1	-	-	-	-
Tillage, currying, by weeder[a]	ha	-	-	1	1	1	-
Green manure[a]	ha	-	1	-	-	-	-
Land use change (annual or perennial crop)	ha	1	1	1	1	1	1
Inputs from nature							
Land occupation[a]	ha	1	1	1	1	1	1
Water (as a medium for plant protection products)	l	600	300	600	75[c]	-	-
Emissions to air							
Carbon dioxide (from fertilizers and limestone)[IPCC]	kg	220	220	220	220[c]	-	-
Dinitrogen monoxide (from fertilizers)[IPPC]	kg	6.80	3.05	7.64	0.78[c]	3.59	1.68
Ammonia (from fertilizers)	kg	2.82	1.4	3.52	-	3.00	1.4
Emissions to water							
Phosphorus (leaching and run-off)	kg	0.34	0.26	0.35	0.12[c]	0.30	0.27
Ammonia (from fertilizers)	kg	0.64	0.16	0.72	-	0.34	0.16

IPCC calculated in accordance with the IPCC (Intergovernmental Panel on Climate Change) methodology (determination of field emissions), M = silage maize cultivation practices: standard (M-S), intensive (M-I), and low input (M-L), *L* lucerne, *CP* cup plant, *PY* productive year, *YoE* year of establishment

[a]Input/s from Ecoinvent database or Agri-footprint

[b]3-year average

[c]4-year average

of pesticides, respectively, their active substances and their distribution has been taken into account by using data from Ecoinvent database (Wernet et al. 2016), but the fate of the pesticides in the environment was not taken into account. Therefore, the toxicity impact is not fully reflected.

Table 4 Field trials—phytomass yields of cup plant (t ha^{-1})

	YoE	1st PY	2nd PY	3rd PY
Dry matter	-	2.89	16.54	15.59
Green mass	-	13.77	55.14	54.24
% of dry matter	-	20.98	29.99	28.76

PY productive year, *YoE* year of establishment

5.1 Impact categories and impact assessment method

A life cycle assessment method is an instrument for environmental aspect assessment and is defined by specific norms (ISO 14040 2006a; ISO 14044 2006b). The results of this research are related to the impact categories of *climate change* (100 years IPCC 2007; kg CO_2 eq), *terrestrial acidification* (kg SO_2 eq), *freshwater eutrophication* (kg P eq), *marine eutrophication* (g N-eq), *terrestrial ecotoxicity* (g 1,4-DB-eq), *freshwater ecotoxicity* (g 1,4-DB-eq), *water depletion* (m^3-eq), *human toxicity* (kg 1,4-DBeq) and *fossil depletion* (kg oil eq). Selected impact categories are suitable for agricultural LCAs (Dijkman et al. 2018). SimaPro 9.0.0.40 software, ReCiPe Midpoint (H) V1.13/Europe Recipe H., an integrated method (Goedkoop et al. 2009) and Cut-off System Model approach were used for the assessment of the environmental aspects. One ton of final product (dry matter) and an area unit (1 ha) were used as functional units. For the purposes of the study, prediction of the environmental load associated with the long-term cup plant cultivation (for a 5-year, 10-year, 15-year and 20-year cycle) was also performed. Furthermore, a model corresponding to the concept of the study of Albrecht et al. (2017) and the results of this study were created. These sections were used as a sensitivity analysis.

6 Results

Field trials with cup plant cultivation were established for the purpose of this study. Based on this monitoring, data for inventory (inputs and outputs of the growing cycle) and yield parameters (Table 4) in the first 4 years of cup plant cultivation were obtained.

The cup plant stand was not harvested in the first year after establishment. The year of establishment is important for the strengthening of the root system. Since the crop stand of cup plant was established in autumn, the root system was still not optimally integrated in the first production year, resulting in low phytomass yields (2.89 t ha^{-1} of dry matter) in that year. In the second production year, the yield of phytomass had already reached 16.54 t ha^{-1} of dry matter, and in the third production year, 15.59 t ha^{-1} of dry matter. Data on yield parameters are essential for the evaluation of functional units of production (1 ton of dry matter).

6.1 Unit of production

A life cycle of three forage crops was created according to the selected methodology and the data available; the environmental load per 1 ton of dry matter was quantified. Table 5 shows the results of a 4-year cycle of growing cup plant and lucerne and three growing technologies of maize for the purpose of silage production and monitoring the environmental load according to a production unit (1 ton of dry matter). The characterization model was used for the data expression (Dijkman et al. 2018). The results of this research show that M-I imposes the lowest environmental load per production unit in the impact category of *terrestrial acidification and freshwater ecotoxicity*. In the impact category of *climate change*, the lowest environmental load per production unit is connected with L* growing and the highest with M-L. The highest environmental load

Table 5 Environmental load per production unit (1 ton of dry matter of silage of investigated crop)

	CP[a]	L[a]	M-S	M-L	M-I
Climate change (kg CO_2 eq)	3.66E+02	3.09E+02	5.82E+02	7.34E+02	4.61E+02
Terrestrial acidification (kg SO_2 eq)	1.84E+00	1.02E+00	1.77E+00	2.05E+00	1.52E+00
Freshwater eutrophication (kg P eq)	7.98E−02	6.04E−02	6.92E−02	9.07E−02	5.69E−02
Marine eutrophication (kg N eq)	1.03E−01	5.69E−02	1.71E−01	3.96E−01	1.39E−01
Human toxicity (kg 1,4-DB eq)	6.79E+01	5.50E+01	5.65E+01	7.42E+01	4.87E+01
Terrestrial ecotoxicity (kg 1,4-DB eq)	3.42E−02	7.72E−02	7.08E−02	9.15E−01	5.42E−02
Freshwater ecotoxicity (kg 1,4-DB eq)	1.92E+00	2.54E+00	1.92E+00	2.68E+00	1.61E+00
Water depletion (m^3)	7.77E+00	1.03E+00	1.48E+00	2.93E+00	1.39E+00
Fossil depletion (kg oil eq)	4.71E+01	4.68E+01	4.64E+01	5.64E+01	3.83E+01

ReCiPe midpoint (H) method, characterisation model, results are expressed per kilogram of dry matter of silage, M = silage maize cultivation practices: standard (M-S), intensive (M-I), and low input (M-L), *L* lucerne, *CP* cup plant

[a]4-year average

within the impact categories of *terrestrial acidification*, *freshwater eutrophication*, *marine eutrophication*, *human toxicity*, *terrestrial ecotoxicity*, *freshwater ecotoxicity* and *fossil depletion* is then associated also with M-L. Only within the impact category of *water depletion*, the highest environmental load is connected with CP* due to high water consumption connected with the seedling preparation. Considering this result, phytomass yield has the highest impact according to this quantification. However, values themselves need to be seen as a trend or indicator, not a constant numerical expression. A more detailed expression of the individual energy flows of the environmental load is included in Fig. 1.

The shares of individual inputs in the total environmental load are expressed in % within selected impact categories. Data are based on the characterization model. Individual cultivation technologies differ from each other, mainly in the intensity of inputs and the final phytomass yield per hectare (t ha^{-1} of dry matter). In general terms, the production and use of mineral fertilizers (most of which are nitrogen fertilizers) have the greatest impact on the overall environmental load. This represents a 0.34–48.09% share depending on the impact category. Another significant source of the environmental load is represented by agrotechnological processes, which, depending on the impact category, accounts for 0.5–70.9% of the total environmental load. Within the *climate change*

Fig. 1 Contribution analysis from the cradle-to-farm gate for environmental impacts; ReCiPe midpoint (H) method, characterisation model, results are expressed per kg of dry matter of silage (resp. in % share), M = silage maize cultivation practices: standard (M-S), intensive (M-I) and low input (M-L), L = lucerne, CP = cup plant, * = 4-year average

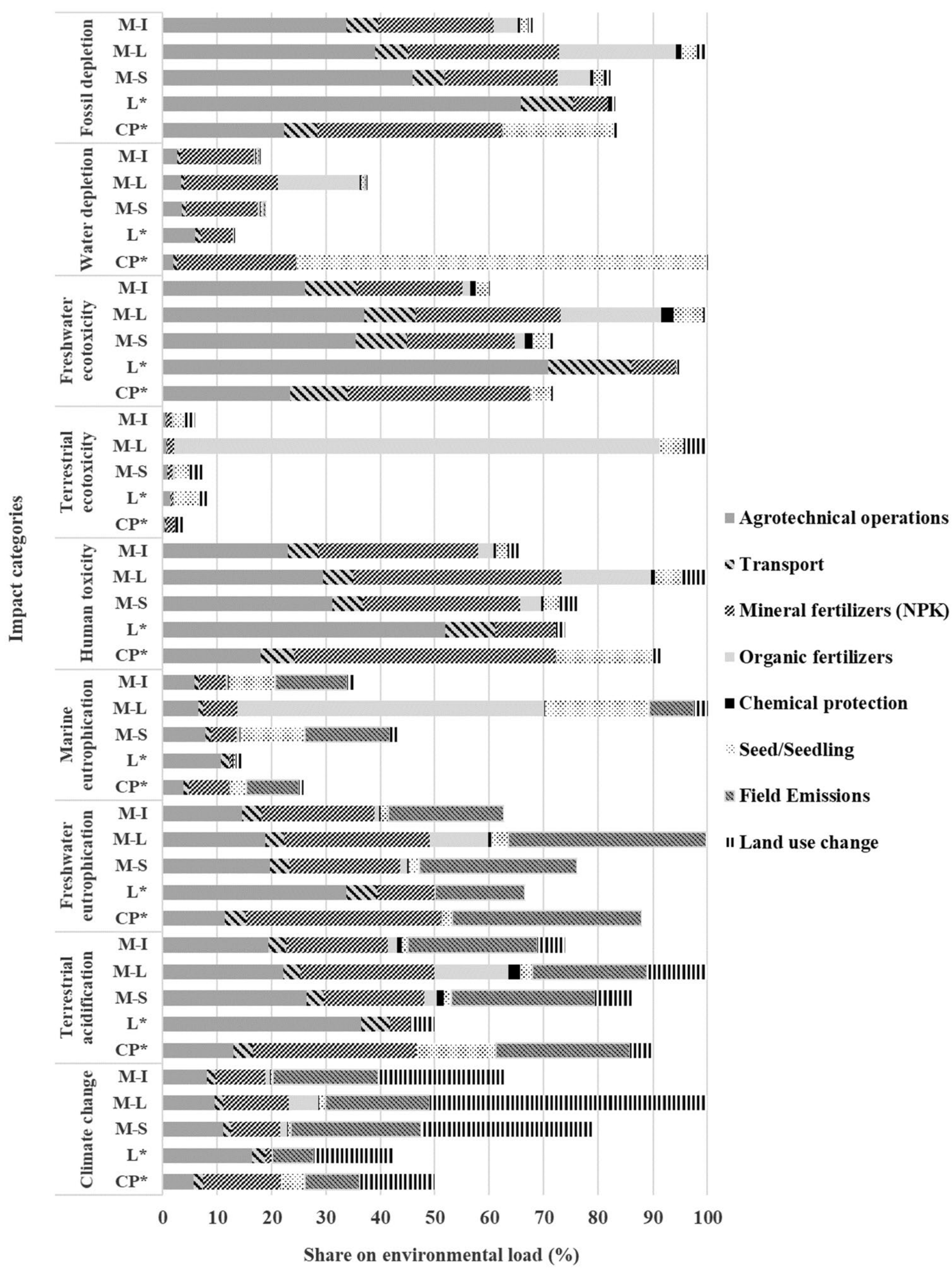
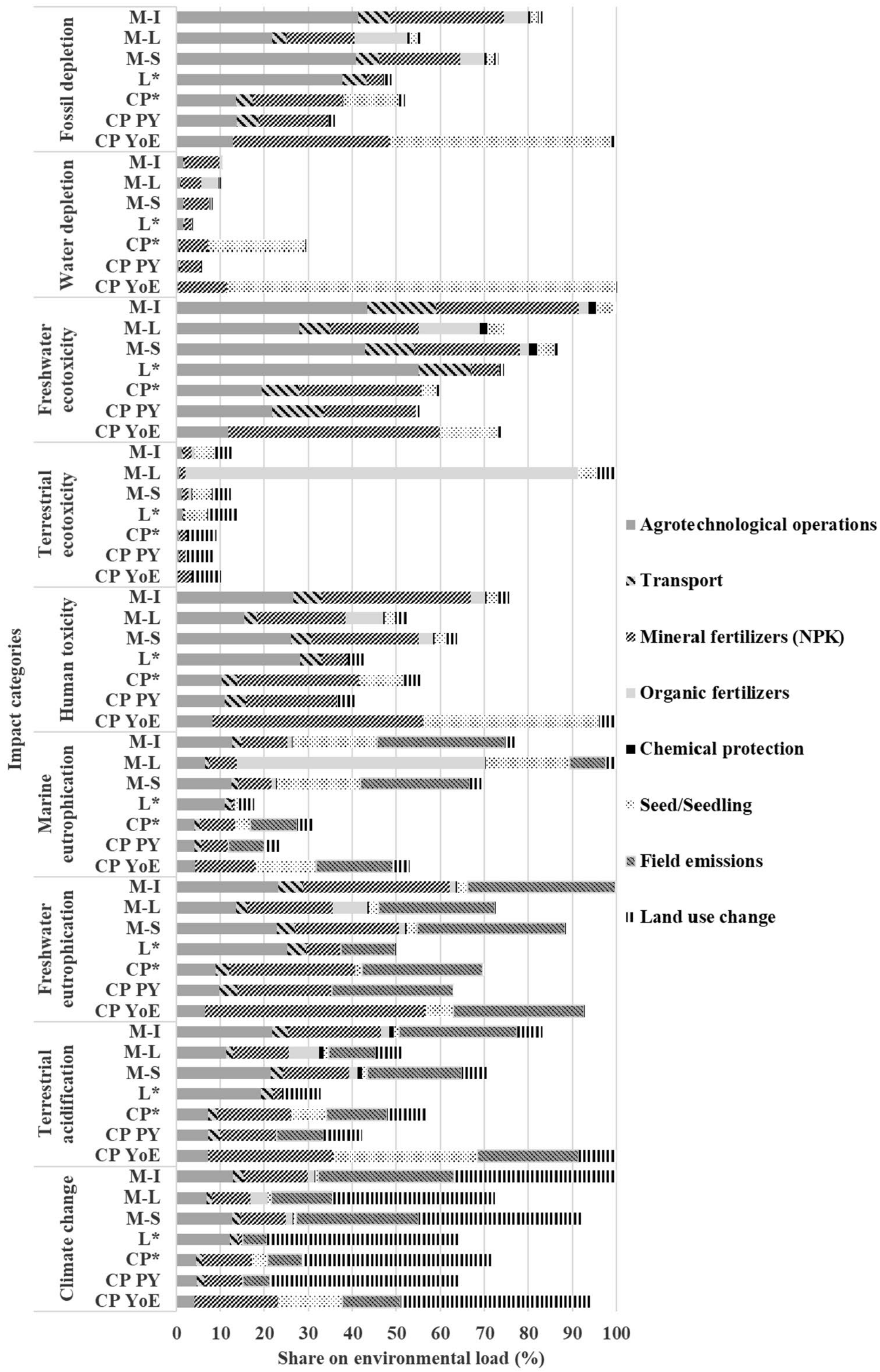


Fig. 2 Contribution analysis from cradle-to-farm gate for environmental impacts; ReCiPe Midpoint (H) method, characterisation model and results are expressed per ha of monoculture of investigated crop (in % share respectively), M = silage maize cultivation practices: standard (M-S), intensive (M-I) and low input (M-L); L = lucerne; CP = cup plant; * = 4-year average; PY = productive year (3-year average), YoE = year of establishment



impact category, direct and indirect emissions related to the use and application of fertilizers (mineral and organic) also represent a strong emission source. In this case, their share is up to 23.9% (standard maize cultivation technology). Within the impact categories of *terrestrial ecotoxicity* and *marine eutrophication*, the input of organic fertilizer (farmyard manure or green manure in case of M-L) in the M-L cultivation technology presents a major contribution to environmental load (89.1% of total environmental load and 56.4%, respectively) due to input of seed production for green manure. Although fewer inputs are bound to the growing process of cup plant (compared with the other silage crops), the final environmental load is influenced by a lower average phytomass yield. To establish a cup plant stand, it is necessary to grow seedlings under greenhouse conditions. This step is then most reflected in the impact category of *fossil depletion*, *terrestrial acidification*, *human toxicity* and mainly *water depletion*, where it contributes to 20.5%, 14.6%, 17.4% and 75.4%, respectively of the total environmental load. Savings in the life cycle should be calculated not only per production unit, which is how most LCA outputs are determined, but also per area unit and time unit (t ha^{-1} per year). However, many LCA inputs are usually calculated per production unit.

6.2 Unit of area

Unlike unit of production, unit of area does not take into account the phytomass yield. The environmental load is therefore dependent purely on inputs to the growing cycle. Considerably, different results are obtained in comparison with unit of production. A summary of results is shown in Table 6.

The lowest environmental load is tied to the cultivation of cup plant in the year of production and the cultivation of lucerne. Due to the permanent growing character of cup-plant, only fertilization and mowing with the subsequent transport and storage of green mass are considered within the inputs. This is one of the significant benefits of this promising forage crop (Fig. 2).

Environmental loads per area unit (1 ha) are another monitored aspect and evaluated category. Savings in the life cycle should be calculated not only per production unit, which is how most LCA outputs are determined, but also per area unit and time unit. However, many agricultural LCA inputs are usually calculated only per production unit. As in the previous figure (Fig. 1), the shares of individual inputs in the total environmental load are expressed in % within selected impact categories. Data are based on the characterization model, which includes all the material and energy flows for every year, but hectare yield is not included in the evaluation in this case. Generally, the overall environmental load is most affected by the production and use of mineral fertilizers (nitrogen fertilizers dominate). This input represents a 0.4–50.0% (CP YoE within the *freshwater eutrophication* category) share depending on the impact category and strategy of cultivation. Another important part of the environmental load is, again, agrotechnological procedures, which, depending on the impact category, account for 0.4–50.0% of the total load. The smallest need for agrotechnological operations is required for the cup plant, both in the year of production and also in the year of establishment. Within the *climate change*, *terrestrial acidification*, *freshwater eutrophication* and *marine eutrophication* impact categories, so called emissions related to the use and application of N and P fertilizers (mineral and organic) also represent a strong emission source. In this case, their share is up to 33.6% and 33.7%, respectively, within the standard and intensive maize cultivation technology. Within the impact categories of *terrestrial ecotoxicity* and *marine eutrophication*, organic fertilizer (farmyard manure or green manure in case of M-L) in M-L cultivation technology was a significant factor (89.1% and 56.4%, respectively). Within the impact categories of *fossil depletion*, *human toxicity*, *terrestrial acidification* and *mainly water depletion*, the preparation of the seedlings of the cup plant for the year of establishment contributed to 50.0%, 40%, 32.7 and 88.4%, respectively, on total environmental load (in CP YoE). In the year of establishment of the cup plant crop, the land is fertilized with higher doses of fertilizers than in the production years, and a number of agrotechnological operations are also carried out. Higher fertilizer inputs have a significant impact on the *freshwater eutrophication*, *human toxicity* and *fossil depletion* impact categories (50%, 47.7% and 35.5%, respectively, of total load). In general, the lowest environmental load is linked to CP PY and lucerne cultivation in all selected impact categories. In production years (i.e. harvest years), only the fertilization, harvesting and transport of harvested material are practiced in the cup plant cultivation. The mowing of cup plant can be done 2–3 times a year (depending on the season and area of cultivation), and fertilization can be adapted to soil-climatic conditions. Compared with selected maize cultivation technologies, cup plant appears to be a little more environmentally-friendly source of silage.

6.3 Prediction for the following years

An interesting comparison can be found in the modelling of the cup plant cultivation in 5-year, 10-year, 15-year and 20-year cycles, respectively (Table 7). This section was used as a sensitivity analysis. In this modelling, the environmental load is quantified for the unit of production, because the environmental load per unit of area is constant while maintaining uniform cultivation practices. Taking cup plant stands grown for 5, 10, 15 and 20 productive years into account, it was predicted that the production of the environmental load per production unit would change considerably (mainly in relation to the impact category of *climate change*). Table 7 shows some model values. The environmental load is quantified for 5-, 10-, 15- and 20-year cycles. The average yield of 15 t ha^{-1} of dry matter (related to the 5th to 20th years of cultivation) is considered in this modelling.

For example, with a 10-year cup plant cultivation and the average yield level of around 15 t ha^{-1} dry matter, an achievable yield level, the environmental load per unit of production would

Table 6 Environmental load per area unit (1 ha of monoculture of the investigated crop)

	CP YeE	CP PY	CP[a]	L[a]	M-S	M-L	M-I
Climate change (kg CO_2 eq)	7.64E+03	5.24E+03	5.84E+03	5.18E+03	7.46E+03	5.87E+03	8.11E+03
Terrestrial acidification (kg SO_2 eq)	3.21E+01	1.35E+01	1.82E+01	1.05E+01	2.27E+01	1.64E+01	2.67E+01
Freshwater eutrophication (kg P eq)	9.29E−01	6.32E−01	7.00E−01	5.00E−01	8.85E−01	7.25E−01	1.00E+00
Marine eutrophication (kg N eq)	1.68E+00	7.57E−01	9.88E−01	5.59E−01	2.19E+00	3.17E+00	2.44E+00
Human toxicity (kg 1,4-DB eq)	1.13E+03	4.60E+02	6.28E+02	4.87E+02	7.23E+02	5.94E+02	8.57E+02
Terrestrial ecotoxicity (kg 1,4-DB eq)	7.42E−01	6.38E−01	6.64E−01	1.00E+00	9.06E−01	7.32E+00	9.53E−01
Freshwater ecotoxicity (kg 1,4-DB eq)	2.10E+01	1.57E+01	1.70E+01	2.11E+01	2.46E+01	2.14E+01	2.84E+01
Water depletion (m^3)	2.32E+02	1.35E+01	6.82E+01	8.57E+00	1.90E+01	2.34E+01	2.44E+01
Fossil depletion (kg oil eq)	8.11E+02	2.92E+02	4.22E+02	3.96E+02	5.94E+02	4.51E+02	6,74E+02

ReCiPe midpoint (H) method, characterisation model, results are expressed per kilogram of dry matter of silage, M = silage maize cultivation practices: standard (M-S), intensive (M-I), and low input (M-L), *L* lucerne, *CP* cup plant, *PY* productive year (3-year average), *YoE* year of establishment

[a]4-year average

be 1.84E+02 kg CO_2 eq, 1.02E+00 kg SO_2 eq, 5.17E−02 kg P eq, 5.87E−02 kg N eq, 3.89E+01 kg 1,4-DB eq, 1.68E−02 kg 1,4-DB eq, 1.30E+00 kg 1,4-DB eq and 2.67E+01 kg oil eq ton^{-1} of dry matter, i.e. by 151%, 49%, 10%, 136%, 25%, 222%, 24% and 44%, respectively, less than in the case of intensive cultivation of maize (M-I) and by 217%, 73%, 34%, 192%, 45%, 321%, 48% and 74%, respectively, less than maize cultivation under standard technology (M-S). The differences increase with each further year of cultivation. Only within the impact category of *water depletion*, the emission load will be higher due to seedlings at greenhouse preparation, than within the M-I and M-S cultivation, about 50% and 46%, respectively.

6.4 Environmental load of silage mixes

Following the study by Albrecht et al. (2017), environmental load modelling and changes in environmental load were performed. By replacing up to 33% of lucerne and maize silage with cup plant silage, the same milk yield level from dairy cattle can be achieved while contributing to certain mitigation of environmental impacts (Table 8; Fig. 3). This section was used as a sensitivity analysis.

The modelling includes a 4-year average of cup plant cultivation (CP*). The environmental load linked to the selected impact categories is comparable within both silage mixes.

Table 7 Environmental load prediction (1 ton of dry matter)

	CP[a]	CP[b]	CP[c]	CP[d]	CP[e]	CP[f]	CP[g]
Climate change (kg CO_2 eq)	3.34E+03	5.68E+02	3.66E+02	2.90E+02	1.84E+02	1.58E+02	1.46E+02
Terrestrial acidification (kg SO_2 eq)	1.54E+01	2.75E+00	1.84E+00	1.50E+00	1.02E+00	9.04E−01	8.52E−01
Freshwater eutrophication (kg P eq)	5.61E−01	1.11E−01	7.98E−02	6.80E−02	5.17E−02	4.77E−02	1.33E+01
Marine eutrophication (kg N eq)	8.37E−01	1.51E−01	1.03E−01	8.42E−02	5.87E−02	5.24E−02	4.96E−02
Human toxicity (kg 1,4-DB eq)	5.66E+02	1.00E+02	6.79E+01	5.58E+01	3.89E+01	3.48E+01	3.29E+01
Terrestrial ecotoxicity (kg 1,4-DB eq)	3.18E−01	5.36E−02	3.42E−02	2.69E−02	1.68E−02	1.43E−02	1.32E−02
Freshwater ecotoxicity (kg 1,4-DB eq)	1.40E+01	2.61E+00	1.92E+00	1.66E+00	1.30E+00	1.21E+00	1.17E+00
Water depletion (m^3)	8.53E+01	1.33E+01	7.77E+00	5.67E+00	2.76E+00	2.05E+00	1.73E+00
Fossil depletion (kg oil eq)	4.07E+02	6.98E+01	4.71E+01	3.86E+01	2.67E+01	2.38E+01	2.24E+01

CP cup plant

[a]2-year average field trail

[b]3-year average field trail

[c]4-year average field trail

[d]5-year average model

[e]10-year average model

[f]15-year average model

[g]20-year average model

Table 8 Environmental load per unit of production (1 ton of dry matter)

	Unit of production		Unit of area	
	Silage mix 1	Silage mix 2	Silage mix 1	Silage mix 2
Climate change (kg CO_2 eq)	4.46E+02	4.20E+02	7.74E+03	7.29E+03
Terrestrial acidification (kg SO_2 eq)	1.40E+00	1.54E+00	1.95E+01	1.96E+01
Freshwater eutrophication (kg P eq)	6.48E−02	6.97E−02	8.30E−01	8.08E−01
Marine eutrophication (kg N eq)	1.14E−01	1.10E−01	1.53E+00	1.38E+00
Human toxicity (kg 1,4-DB eq)	5.57E+01	5.97E+01	7.39E+02	7.21E+02
Terrestrial ecotoxicity (kg 1,4-DB eq)	7.40E−02	6.09E−02	1.23E+00	1.06E+00
Freshwater ecotoxicity (kg 1,4-DB eq)	2.23E+00	2.13E+00	2.87E+01	2.53E+01
Water depletion (m^3)	1.25E+00	3.40E+00	1.61E+01	3.53E+01
Fossil depletion (kg oil eq)	4.66E+01	4.68E+01	6.04E+02	5.56E+02

Silage mix 1 = L* and M-S silage mix (50:50); silage mix 2 = CP*, L*, and M-S silage mix (33:33.5:33.5); M = silage maize cultivation practices: standard (M-S), intensive (M-I) and low input (M-L), *L* lucerne, *CP* cup plant, * = 4-year average

There may even be worsening environmental impacts within the impact categories of *terrestrial acidification*, *freshwater eutrophication*, *human toxicity* and *water depletion* mainly (Fig. 3). However, this is strongly influenced by the yield level in the first years of cup plant growing. A more significant decrease of the environmental load will be achieved during long-term cultivation. This prediction corresponds to modelling results (Table 7). It should also be taken into account that cup-plant stands can be maintained continuously for 20 years or more, while lucerne stands must be re-established at least 5 times (during this period) and maize stands annually. This will have a significant impact on the overall environmental load. Table 8 also evaluates the environmental load per unit of area. As with the production unit, the modelling includes a 4-year average of cup plant cultivation (CP*). A more significant decrease of the environmental load will be achieved during long-term cultivation. The results of the modelling have also been transferred into the figure (Fig. 3). This assessment also takes into account the area needed for generating the same phytomass yield (Table 3). This is a very important factor, which is often not taken into account in agricultural LCAs.

Processes entering the framework are included in the software data inventorization. The inputs in this figure were calculated for an average dry matter yield per ha of maize (M-S), lucerne cultivation (L^b) and 4-year cup plant cultivation. Multiyear cultivation and average dry matter

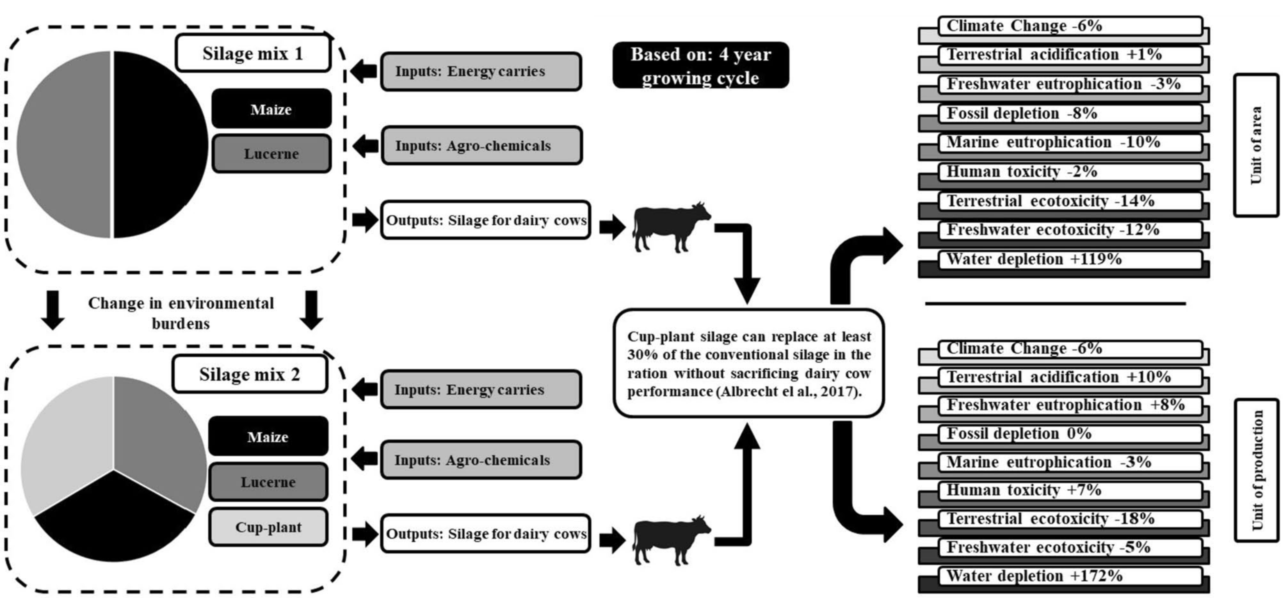


Fig. 3 The potential for environmental impact reduction when replacing 33% of maize and lucerne silage mix with the same proportion of cup plant silage while maintaining the same milk production

yield (in t ha^{-1} of dry matter) are considered in this model. Based on this modelling, it can be predicted that in practice, this farming strategy would bring a certain reduction in the environmental load, depending on the impact category and yield level of cup plant, lucerne and silage maize.

7 Discussion

Finding ways to mitigate greenhouse gas emissions, for sustainable water management in agriculture, and for environmentally-friendly farming practices is a key issue (Bellarby et al. 2008; Burke and Emerick 2016; Bernas et al. 2019a). Similarly, it is necessary to look for environmentally-friendly approaches in animal production while maintaining a sustainable level of food production (Herrero et al. 2016) with regard to the principles of sustainable agriculture and agroecology (Moudrý et al. 2018). There is also a need to seek mutually beneficial approaches—for agricultural and political goals. The results of the study show that cup plant is a suitable choice in terms of phytomass production (Gansberger et al. 2015), forage production (Albrecht el al. 2017) and also the environment. Environmental aspects were evaluated using the LCA method, which is a generally accepted and recommended method for assessing environmental impacts in agriculture (Bessou et al. 2016; Dijkman et al. 2018). In this work, unproductive years (as well the year of establishment) in perennial crops (lucerne and cup-plant) were also taken into account, which is often neglected in agricultural LCAs (Bessou et al. 2013) and may deliver misleading results (Escobar et al. 2017). In case of this study, the environmental load of cup plant and lucerne have been analysed throughout a 4-year cycle, also capturing phytomass yield variability by means of a unit of production. The phytomass yield variability is also taken into account within the environmental load prediction.

The results of this study show that this crop possesses valuable ecological properties, brings certain environmental savings (Fig. 3) and that an optimal growing process with high yields can occur if the requirements of the crop are taken into account. Cup plant has a long-term average yield of about 15 t ha^{-1} of dry matter (Aurbacher et al. 2012; Mast et al. 2014; Bauböck et al. 2014; Gansberger et al. 2015). According to the modelling performed in this study, if cup plant is grown intensively for 10 years and more, it will impose an environmental load of 183.6 kg of CO_2 eq ton^{-1} of dry matter (about 182.4 kg of CO_2 eq less than in the 4-year cycle). Compared with standard maize cultivation technology (M-S), it is 217% less in the *climate change* impact category. For instance, Dressler et al. (2012) or Bacenetti et al. (2013) showed very comparable results to this study (impact category *climate change*, kg CO_2 eq ton^{-1} of fresh silage) in the case of silage maize growing for silage production. Also within the impact categories of *terrestrial acidification* (kg SO_2 eq), *freshwater eutrophication (*kg P eq), *marine eutrophication* (kg N eq), *human toxicity* (kg 1,4-DB eq), *terrestrial ecotoxicity* (kg 1,4-DB eq), *freshwater ecotoxicity* (kg 1,4-DB eq) and *fossil depletion* (kg oil eq) environmental savings of 73%, 34%, 192%, 45%, 321%, 48% and 74%, respectively, can be achieved. By replacing 33% of the conventional silage with a cup plant, it is possible, on the basis of the available data, to predict significant environmental savings regarding selected impact categories, both per unit of area and unit of production. These significant environmental savings can be achieved while maintaining comparable phytomass production per area unit and the same milk production in dairy farming (Albrecht et al. 2017).

To address the potential mitigation of the environmental load within the framework of a standard farming process, we have to focus on all of the sources of emissions arising from the production process. As the results of this research show, the production and use of nitrogenous fertilizers and their field emissions are ranked among the top polluters in farming, and the farming process producing the most emissions (Smith et al. 2007; Hasler et al. 2015). These conclusions are already linked to a previous study focused on the cultivation of silage maize and other alternative crops (Bernas et al. 2019b). Agrotechnological interventions may also contribute heavily to emission load, depending on the intensity of farming; they may have an impact that falls into the *climate change* and *fossil depletion* category, which are expressed in terms of the consumption of fossil fuels. This approach, together with sustainable intensification, could bring significant environmental benefits for the entire agricultural sector (Campbell et al. 2014; Pretty and Bharucha 2014).

On the other hand, the chemical protection of crops and the fate of pesticides, which should be taken into account in agricultural LCAs (Bessou et al. 2013), has a relatively small effect in the case of this study. However, the fate of pesticides is very difficult to assess, and it is not possible to determine the effect of metabolites on environmental components without long-term field monitoring (Vašíčková et al. 2019). It is also important to know the character of pesticides and their active substances. Chemical protection in maize (active substance metolachlor and rimsulfuron) and lucerne (bentazone) crops were taken into account in this study. Bentazone is very mobile in soil and occurs in surface water, groundwater and drinking water. It can photodegrade in soil and water. It does not seem to accumulate in the environment. Metolachlor is fairly mobile and can contaminate groundwater or surface water under certain conditions. It can be lost from the soil through biodegradation, photodegradation and volatilization (WHO 2011). Rimsulfosulfuron is a short-residual herbicide, which breaks down rapidly in soil. There is minimal potential for movement into ground or surface waters, and the rapid breakdown in the soil allows for rotational crop flexibility (Koeppe et al. 2000). But without the complete assessing, the fate of pesticides (respectively, without the quantification of emissions arising after their application and impact on individual environmental compartments) cannot fully assess the toxicity impacts (e.g. human toxicity or ecotoxicity) (Gentil et al. 2020; Sinisterra-Solís et al. 2020).

There are yet more potential means of mitigating the environmental load, such as replacing existing cultivations and crops (e.g. maize) with other suitable crops, e.g. certain perennial grass species (e.g. Reed canary grass, Switchgrass or Sorghum) that have suitable properties (Lewandowski et al. 2003; Cattani et al. 2017). However, they are not an adequate substitute for maize from a production point of view (Bernas et al. 2019b). Nevertheless, energy grass species and perennial crops (such as cup plant) in general impose fewer critical requirements on fertilizer; therefore, they produce less carbon dioxide during their life cycle and they create fewer significant environmental impacts than all annual energy crops. The advantage of perennial crops is also the absence of the requirement of annual soil cultivation and the absence of tillage, which, e.g. entails the release of CO_2 (Neugschwandtner et al. 2014; Chimento et al. 2016). The advantage of cup plant cultivation is also in its low treatment requirements against diseases and pests (Gansberger et al. 2015). Compared with maize, cup plant cultivation generally requires a smaller amount of technological operations, and organic fertilizers in liquid and solid form can be used (von Cossel et al. 2020). However, the optimization of cup plant fertilization management, especially the choice of fertilizer, its amount and the method of its application in relation to N could significantly contribute to the mitigation of environmental impacts (Webb et al. 2013). This aspect would thus better correspond to the low-input agriculture concept and generally lower environmental impacts (Sarkar et al. 2020).

According to the results, maize imposes a higher environmental load than cup plant. An environmental load of maize per area unit is incomparable with that of cup plant. However, a significantly high environmental load (of cup plant) is associated with the *water depletion* impact category. This load can be effectively reduced by using sowing instead of seedlings (produced at the greenhouse). With proper treatment, a high percentage of seed germination can be achieved, and cup plant growth can be effectively established (Gansberger et al. 2017). Generally speaking, and from the point of view of environmental load per area unit and also production unit, growing cup plant can be more environmentally friendly than growing maize for silage production. But the outcomes of agricultural LCAs may radically change depending on the growth phase of the plant, local conditions and agricultural practices (Escobar et al. 2017).

8 Conclusion

The results of this study focused on the environmental impact assessment show certain savings in environmental load by replacing a significant part (33%) of maize and lucerne silage with cup-plant silage. This environmental load varies with respect to selected impact categories and functional units. After 4 years of cup plant cultivation, the differences in environmental load are not significant within the production unit (1 ton of dry matter of silage) and also within the area unit (1 ha of monoculture of the investigated crop). In some impact categories, the environmental load of cup plant is even higher compared with maize. But a significant reduction in environmental impact can be achieved with multiyear cultivation (10 years or more). For example, compared with maize grown in the standard method of cultivation in the Czech Republic, the environmental load of cup plant (per unit of production) would be significantly reduced in most of the impact categories (217% within *climate change*, 73% within *terrestrial acidification*, 34% within *freshwater eutrophication*, 192% within *marine eutrophication*, 45% within *human toxicity*, 321% within *terrestrial ecotoxicity*, 48% within *freshwater ecotoxicity* and 74% within *fossil depletion*).

The reduction of the environmental loads should be calculated not only per production unit, which is how most LCA outputs are determined, but also per area unit and time unit (t ha^{-1} per year). However, many LCA inputs are usually calculated per production unit. To quantify the environmental load associated with a unit of area, it is then essential to consider the area needed for generating the same phytomass yield when comparing two or more crops. It is also important to include the corresponding inputs and land use change and adjust the system boundaries accordingly. Without taking into account the area needed for generating the same phytomass yield (or plant product), there could be a significant disadvantage. This approach is then also suitable for predicting environmental loads using the LCA concept.

The reduction of livestock production-resp. milk production would currently be illogical given the need to maintain food production and the need for manure for soil regeneration and the supply of organic matter for the soil. For these reasons, it is necessary to look for steps that can be implemented quickly enough but rationally. The implementation of cup plant into farming strategies and the possibility of replacing conventional silage by as much as 33% can contribute to reducing environmental load and keep the same level of production. Cup plant is able to compensate for the yield and represents a lower environmental load per unit of production and also unit of area. Given the practical experience with cup plant cultivation in neighbouring Germany, for example, this is clearly a recommendable option for dairy farmers. Given the current experience and knowledge of the issue, the cup plant can be considered a fast and effective alternative to conventional silage.

It seems to be recommendable to observe the effect of cup plant cultivation on biodiversity, to monitor the microclimate of the crop stand, and the ability to retain water by interception. There is also space for the optimization of cup plant cultivation in relation to liquid organic fertilizers or low-input farming technologies that generally bring fewer inputs to the growing cycle. Because of the quality of silage and potential environmental benefits, cup plant cultivation could be an alternative for dairy farming in the organic sector or the precision agriculture sector.

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Authors' contributions Jaroslav Bernas: conceptualization, data collection, methodology, software, validation, formal analysis, investigation, resources, writing—original draft preparation, writing—review and editing, visualization, supervision; Tereza Bernasová: writing—original draft preparation, writing—review and editing, visualization, investigation; Pedro Gerstberger: material support; Jan Moudrý: material support; Petr Konvalina: supervision; Jan. Moudrý Jr.: supervision.

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Article

Agricultural LCA for Food Oil of Winter Rapeseed, Sunflower, and Hemp, Based on Czech Standard Cultivation Practices

Jaroslav Bernas [1,*], Tereza Bernasová [2], Václav Nedbal [2] and Reinhard W. Neugschwandtner [3]

1 Department of Agroecosystems, Faculty of Agriculture, University of South Bohemia, Studentska 1668, 37005 Ceske Budejovice, Czech Republic
2 Department of Applied Ecology, Faculty of Agriculture, University of South Bohemia, Studentska 1668, 37005 Ceske Budejovice, Czech Republic; veselt04@zf.jcu.cz (T.B.); nedbav00@zf.jcu.cz (V.N.)
3 Department of Crop Sciences, Institute of Agronomy, University of Natural Resources and Life Sciences Vienna (BOKU), 3430 Tulln, Austria; reinhard.neugschwandtner@boku.ac.at
* Correspondence: bernas@zf.jcu.cz

Abstract: The demand for food vegetable oil is rising and this trend is reflected in the agricultural sector of the Czech Republic. The traditional oil crops of the Czech Republic are winter rapeseed and sunflower. These oil crops have high demands on energy inputs, for example, in the form of land preparation and chemical protection. At the same time, they are characterized by high food oil production and oiliness. Moreover, marginal oils crops, such as hemp, are also gaining prominence. This work aimed to evaluate the environmental impacts associated with the cultivation of winter rapeseed and sunflowers based on standard cultivation practices typical of the conditions of the Czech Republic. For comparison, an intensive cultivation strategy for hemp was modelled, also corresponding to the conditions of the Czech Republic. This study assessed the environmental impact of traditional oil crops from the agricultural Life Cycle Assessment (LCA) perspective. The system boundaries included all the processes from the cradle to the farm gate. Mass-based (volume of food oil) and area-based (land demand for generating the same volume of food oil) functional units were employed. The results cover nine impact categories related to the agricultural LCA. ReCiPe Midpoint (H) characterization and normalization models were used for the data expression. Hemp is a plant with generally low demands on the inputs of the growing cycle but generally has a low oil production, which affects the character of the results relating to the goal and scope definition of the study. Hemp food oil thus generated a higher environmental impact per unit of production and area compared to sunflower and rapeseed food oil.

Keywords: agricultural LCA; vegetable food oil; hemp; winter rapeseed; sunflower

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1. Introduction

The food sector is one of the major consumers of food oil, and the demand for food vegetable oil has been increasing for a long time [1]. The world's most cultivated oil crops have long been soybeans, rapeseed, cottonseed, peanuts, sunflowers, palm kernels, and coconuts. European vegetable oil consumption is based mainly on rapeseed, palm oil, soybeans, and sunflowers [2]. In the Czech Republic, winter rapeseed, poppy, sunflower, soybean, mustard, and linseed have traditionally had the highest share in the area under oil crops [3]. The Czech Republic has 2,958,603 ha of arable land; winter rapeseed was grown on approximately 380,000 ha (12.5%) and sunflowers on about 15,000 ha (0.5%) in recent years [2]. Nearly half of winter rapeseed oil production is for food purposes. Hemp, which has good potential in food oil production [4,5], is also beginning to appear increasingly (at about 600 ha) on arable land in the Czech Republic [3].

All agricultural activity is more or less linked to the impact on the environment [6]. The intensity of these impacts is also related to the intensity of agricultural production itself. In particular, oil crops, such as rapeseed, are among the crops that generally have high demands in terms of treatment and care [7]. These demands are then reflected in the impacts on the environment and its individual components [8,9]. Sustainable development, sustainable production, and consumption in the agri-food sector are key issues stimulating the creation of many international activities and strategies to reduce environmental impacts and seek sustainable production routes [10]. Due to the wide range of possible impacts on the environment and their diversity, it is not easy to evaluate the complex effects of the agricultural system with one method. There are various methods for assessing one or more indicators that determine the level of a particular impact. They can be quantified, for example, through the agricultural Life Cycle Assessment (LCA) method [11] and can thus point out possible options that could lead to the mitigation of these impacts [12].

Thanks to LCA, it is also possible to carry out a comparative study, which can help find a suitable alternative or point to new possibilities in general crop production and oil crops production. Agricultural LCA aims for a comprehensive assessment of the environmental profile of the product system and is one of the most holistically applicable methods. Agricultural LCA is the widely accepted methodology for assessing the potential environmental impacts of agri-food chains and agricultural production systems. It is an analytical method that assesses the environmental impacts of products, services, technologies and human products and organizations in general [13]. In recent years, the number of studies evaluating the impact of agricultural products using the LCA method has increased. Comparative studies are often used to compare the environmental sustainability of products from different agricultural production systems [12]. Before the implementation of a potential sustainable farming system, scientists and the decision-makers need sufficient information about the positives and negatives of the production system with regard to productivity and performance. The LCA method provides a suitable assessment tool that meets the requirement of a comprehensive assessment of the environmental impacts of different production systems [12]. These outputs can then help implement concepts that correspond to the strategies of the common agricultural policy (CAP) and the European Green Deal [14]. However, for the conditions of the Czech Republic, such a model based on an LCA of winter rapeseed oil (sunflower oil and hemp oil, also) has not yet been implemented, although winter rapeseed is one of the dominant crops on arable land. Whereas rapeseed cultivation can bring more biological diversity to the landscape, as reported for Sweden which has a share of rapeseed on arable land of about 4% [15], the Czech Republic has a share of 14%—the highest in the EU [16].

This comparative LCA study aims to quantify the environmental impact associated with conventional winter rapeseed and sunflower food oil production, as the most widely represented oil crops in the Czech Republic, and to compare them with conventional hemp cultivation, which has in recent years gained great popularity in many agricultural sectors [17]. The attribution approach, the mass allocation principle, the characterization model, and the normalization model for data interpretation were chosen for this study. The functional unit related to the yield (volume of food oil yield) and the functional unit related to the area equivalent to the area needed to gain the same yield (volume of food oil) are used for data interpretation. This study reviews the environmental impact of rapeseed, sunflower, and hemp food oil production from the perspective of Czech standard cultivation practices. The results point to the impacts of individual inputs on the growing cycles and farming strategies, respectively, and allow for comparison of the two dominant oil crops (winter rapeseed and sunflower) and one minor alternative oil crop with the promised environmental potential. This paper will expand knowledge concerning winter rapeseed, sunflower, and hemp production with respect to environmental issues, and bring a new perspective to agronomy policy design.

2. Materials and Methods

2.1. Goal and Scope Definition

This study aims to quantify the environmental impacts of winter rapeseed oil, sunflower oil, and hemp oil by using the agricultural LCA. A functional unit (FU) related to production (1 m^3 of food oil) and area unit (land demand for generating the same yield of food oil) was chosen for this study. The system boundaries include all the processes "from cradle to farm gate". Data geographically related to central Europe and the Czech Republic were used. As in a study based on agricultural LCA [18,19], agrotechnological operations were also incorporated into the model system: from pre-seeding preparation, through harvesting of the main product, to the transport of farming machinery, the production and use of crop-protecting agents, the production and use of fertilizers, the harvest, and transportation of the main product from the harvest site. Land-use changes were taken into account. Infrastructure processes were part of database inputs. Manure production and management have not been included. Cow manure was considered to be a residual product of the animal production systems, so emissions from the animal production system were not included. Emissions that occur from manure application were included in the processes where this occurs (e.g., the crop cultivation processes) [19]. Waste management was included in the form of compost. In the frame of this research, the transport distance from the farm to the field did not exceed 10 km. A mass allocation principle approach (allocation based on significant characteristics of co-products; food oil, cake, and straw yield) was employed in this study. The results of this research may be used to motivate environmentally friendly farming systems and as a source of information on agricultural subjects that relate to farming practices (Bernas et al., 2021). The data were analyzed and evaluated by LCA standards [20,21].

2.2. Data Source and Life Cycle Inventory (LCI)

This study was based on the standards of agricultural practices related to the conditions of the Czech Republic [22] as the primary data source. Information on seed yield and straw yield were updated according to the Situation and Outlook Report on oil crops prepared by the Ministry of Agriculture of the Czech Republic [2,22]. Individual monocrops of selected oil crops were evaluated. Secondary data for background processes were taken from the Ecoinvent v3.7 [23], Agri-footprint v4.0 [24], and WFLDB [25] databases.

2.3. Software Data Inventorization

The cultivation approaches and fertilization intensity were set up according to standard intensive agricultural practices [22]. Data were related to the average conditions of the Czech Republic. Based on seed yield information [2,22], food oil yield level and cake yield level were determined. These data were used to determine the area needed for generating the same food oil yield. Information (input data) related to individual oil crops, the number and frequency of agrotechnical inputs, inputs from the technosphere, inputs from nature, information about emissions to water and air are included in the following table (Table 1). The mass allocation principle was set up according to outputs from the growing cycles of individual oil crops.

Table 1. Inventory table: inputs and outputs of the life cycle.

	Unit	Rapeseed	Sunflower	Hemp
Outputs				
Seeds yield	kg ha^{-1}	3500	2800	500
Straw yield	kg ha^{-1}	4200	7000	9000
Cake yield	kg ha^{-1}	2206.4	1715.8	409.9
Food oil	L ha^{-1}	1293.6	1084.2	190.2
Seed oiliness	%	42	44	36
Cake oiliness	%	12	12	12
Land demand for generating the same yield #	ha	1	1.3	6.8
Mass allocation principle (based on outputs)				

Table 1. *Cont.*

	Unit	Rapeseed	Sunflower	Hemp
Food oil	$\%^{EL}$	16.8	11.06	1.98
Cake	$\%^{EL}$	28.65	17.51	4.27
Straw	$\%^{EL}$	54.55	71.75	93.75
Inputs from technosphere—Material/fuels				
Tillage, cultivating, chiselling	ha	0.8	0.2	2
Tillage, rolling	ha	0.3	–	2
Tillage, harrowing, by spring tine harrow	ha	0.3	1.6	–
Tillage, harrowing, by offset levelling disc harrow	ha	–	0.3	–
Tillage, harrowing, by offset disk harrow	ha	–	1	–
Fertilizing, by broadcaster	ha	1.45	1.1	0.87
Potassium chloride, as K_2O, at plant	kg ha^{-1}	15	9	9
Phosphoric acid, as P_2O_5, at plant	kg ha^{-1}	23.03	–	–
Ammonium nitrate phosphate (ANP), as P_2O_5, at plant	kg ha^{-1}	–	9	–
Triple superphosphate, as P_2O_5, at plant	kg ha^{-1}	–	–	19.75
Solid manure loading and spreading	kg ha^{-1}	12,000	10,000	4000
Manure, solid, cattle	kg ha^{-1}	12,000	10,000	4000
Tillage, ploughing	kg ha^{-1}	1	1	0.1
Application of plant protection product by field sprayer	kg ha^{-1}	5.9	4.9	1.4
Napropamide	g ha^{-1}	90	–	–
Herbicide, unspecified, mix for oil crops, at plant	kg ha^{-1}	2.29	3.65	2.45
Fungicide, unspecified, mix for oil crops, at plant	kg ha^{-1}	–	6.1	–
Sowing	ha	1	1	1
Seeds	kg ha^{-1}	4	5	60
Chloroacetanilide herbicides, at plant	g ha^{-1}	372	–	–
Metaldehyde	g ha^{-1}	40	–	–
Fluazifop-p-butyl, at plant	g ha^{-1}	75	–	–
Calcium ammonium nitrate (CAN), as N, at plant	kg ha^{-1}	266.3	–	40
Nitrogen fertiliser, as N	g ha^{-1}	126	–	–
Manure management, cattle, liquid-slurry, warm, per kg DM	kg	100	–	200
Slurry application, spreader with trailed hoses, per m^3	m^3 ha^{-1}	2	–	4
Dinitrophenol herbicides, at plant	g ha^{-1}	0.12	–	–
Ammonium nitrate (AN), as N, at plant	kg	60	70	–
Plant growth regulator, at plant	g	0.37	0.2	–
Urea ammonium nitrate (UAN) (with 30% N), at plant	kg ha^{-1}	0.09	0	–
Magnesium oxide	kg ha^{-1}	0.03	3.5	–
Sulfur	kg ha^{-1}	0.024	–	–
Boric oxide	kg ha^{-1}	0.018	–	–
Insecticide, unspecified, mix for oil seed crops, at plant	kg ha^{-1}	0.65	0.25	0.25
Combine harvesting	ha	1	1	1
Transport, tractor, and trailer, agricultural	tkm	35	28	5
Land-use change, annual crop, annualized on 20 years	ha	1	1	1
Inputs from nature				
Land occupation *	ha	1	1	1
Water (as a medium for plant protection products) *	L ha^{-1}	2040	1470	557.5
Emissions to air				
Nitrogen oxides, CZ	kg ha^{-1}	1.75	1.21	0.31
Dinitrogen monoxide	kg ha^{-1}	8.32	5.74	1.46
Ammonia, CZ	kg ha^{-1}	11.86	6.01	10.29
Emissions to groundwater				
Nitrate	kg ha^{-1}	0.276	0.265	0.169
Phosphorus	kg ha^{-1}	0.848	0.266	0.275

Basis is the treatment with the highest food oil yield (1 ha of winter rapeseed). * Input/s from the Ecoinvent, Agri-footprint, or WFLDB database. Transport was included in the process with a flat rate 10 km × yield achieved (max 8 tons per load). tkm = tonne-kilometre; $\%^{EL}$ = share on the total environmental impact level; DM = dry matter.

2.4. Determination of Field Emissions

The usage of mineral nitrogenous fertilizers results in the release of so-called direct and indirect emissions of N_2O, NH_3, NO_3^-, and NO_x (expressed as dinitrogen monoxide and ammonia in Table 1). The following were taken into account in the monitoring of field and agricultural emissions: NH_3 and NO_x volatilization, NO_3^- leaching to groundwater, and nitrogen loss from leaching and surface outflow [26]. The risk of erosion was not considered in this study. The production of pesticides and herbicides, their active substances, and their distribution has been taken into account using data from the Ecoinvent 3.7 database [23], but the fate of the pesticides in the environment was not taken into account. Therefore, the toxicity impact cannot be considered as fully reflected.

2.5. Impact Assessment

A life cycle assessment method was used for environmental load quantification. The system boundaries were set from the cradle to the farm gate. The results of this research are related to the selected midpoint impact categories of climate change (kg CO_2 eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), marine eutrophication (g N eq), terrestrial ecotoxicity (g 1,4-DB eq), freshwater ecotoxicity (g 1,4-DB eq), water depletion (m^3 eq), human toxicity (kg 1,4-DB eq), and fossil depletion (kg oil eq). The Attributional approach was used for this study. Selected impact categories are suitable for agricultural LCAs [11,13]. SimaPro 9.2.0.1 software, ReCiPe Midpoint, Hierarchical (H) perspective V1.13/Europe Recipe H., an integrated method [27], and a cut-off system model approach were used for the assessment of the environmental aspects. One cubic metre of food oil and an area unit (land demand for generating the same volume of food oil) were used as functional units. The characterization approach was primarily used for data expression.

2.6. Study Limitations and the Study Completeness Check

Life cycle modelling of agricultural crops and subsequent evaluation of environmental impacts by the LCA method is a complex task. As the authors of the study, we are aware that there are always a number of issues that make objective and accurate evaluation difficult. (1) The study did not include the fate of pesticides and their metabolites in the environment, so the categories of ecotoxicity should not be considered complete. (2) The effect of the pre-crop, the balance of nutrients from the point of view of inputs from atmospheric deposition, mineralization, or decomposition, was not taken into account. (3) The case study was based on a dataset of standard cultivation procedures corresponding to the conditions of the Czech Republic. The results of the study, therefore, should not be considered as flat-rate. (4) The study compares the environmental impact associated with the volume of food oil production from rape, sunflower, and hemp, and the qualitative aspects of these oils were not taken into account.

3. Results and Data Interpretation

Based on the inventoried data and modelled standardized cultivation practices corresponding to the conditions of the Czech Republic, the results of environmental impact levels for winter rapeseed, sunflower, and hemp were determined, which correspond to nine impact categories. Characterization (Sections 3.1 and 3.2) and normalization (Section 3.3) approaches were used for data interpretation purposes.

3.1. Interpretation Based on the Unit of Production

Contribution analysis was performed for oil crop monocultures according to the characterization model (Figure 1). The results are related to nine impact categories and transferred to the environmental impact level in percentages. According to the data interpretation, it was also possible to define different environmental impacts between individual oil crops. The functional unit for this expression was one cubic metre of food oil.

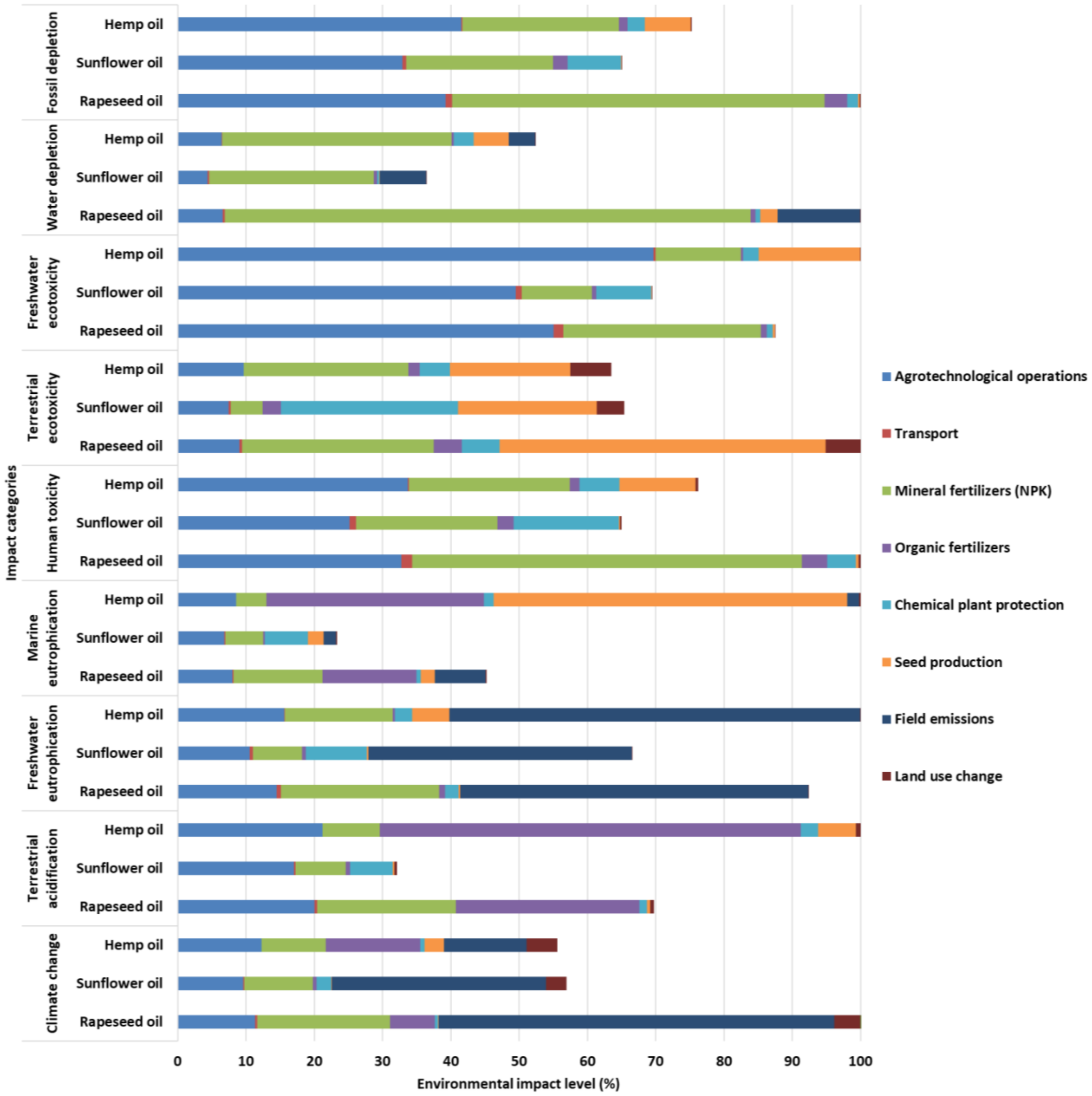

Figure 1. Environmental impact level for the unit of production (FU = 1 m^3 of food oil). Contribution analysis from the cradle-to-farm gate approach for environmental impacts; ReCiPe midpoint (H) method, characterization model, results were expressed per 1 m^3 of food oil.

According to the trend of interpreted data corresponding to the characterization model (Figure 1), the most significant environmental impact related to 1 m^3 of food oil was connected with rapeseed food oil production in the impact category of climate change, human toxicity, terrestrial ecotoxicity, water depletion, and fossil depletion. Within the impact categories of terrestrial acidification, freshwater eutrophication, marine eutrophication, and freshwater ecotoxicity, the highest environmental impact related to 1 m^3 of food oil was connected with hemp oil. The differences in environmental impact levels between individual oil crops and impact categories were important. According to models of life cycles, sunflower oil can be considered a product with the lowest environmental impact compared to hemp and rapeseed oil. According to results based on the FU of production, the environmental impact of 1 m^3 of food oil production of sunflower seems to be more environmentally friendly in comparison to hemp oil or rapeseed oil.

From the point of view of a contribution analysis, the impact on the environment was mainly reflected in the input of agrotechnologies and fertilizer production and utilization, and related to field emissions production. It was predominantly reflected in all the assessed impact categories. The inputs of agrotechnology—agrotechnical operations performed during pre-sowing tillage, fertilization and incorporation of fertilizers into the soil, application of plant protection products, and harvesting—had a substantial effect on the total environmental impact. These inputs were reflected mainly in the impact category of human toxicity, freshwater ecotoxicity, and fossil depletion, i.e., the category mostly related to the consumption of fossil fuels. A large share of the total impact on the environment belongs to the inputs of mineral fertilizers or their production and use. This input most affects the category of fossil depletion, water depletion, or human toxicity. In all cases, it was modelled with inputs of organic fertilizers (slurry or manure) and with the related field emissions. Their input does not manifest itself significantly. Apart from marine eutrophication, climate change, and terrestrial acidification (representing more than a 60% share of the environmental impact of hemp oil production), this input was low due to the nature and volume. Field emissions impact level then depended on the inputs of fertilizers (mineral and organic). In this study, the environmental impact associated with emissions to air (nitrogen oxides, dinitrogen monoxide, and ammonia) and emissions to groundwater (nitrate and phosphorus) from fertilizers were modelled. These emissions form a significant part of the environmental impact in the impact category of climate change (up to 55% in the case of winter rapeseed oil) and freshwater eutrophication (up to 60% in the case of hemp oil). Another input of growing cycles, with a relatively small impact (up to 6% on a total environmental load of impact categories), was land use. Land use was mainly reflected in the impact category of climate change and terrestrial ecotoxicity. The relatively high environmental impact was associated with the production and use of seeds (up to 50% in the case of hemp oil production, in terms of terrestrial ecotoxicity or marine eutrophication). The most affected impact category due to seed input and seed production was terrestrial ecotoxicity, and in comparison with the monitored oil crops, seed input was most pronounced for hemp. This affects the nature of the entry itself and the amount of seed needed to establish the stand (winter rapeseed 4, sunflower 5, and hemp 60 kg ha^{-1} of seed). Due to the higher demand for hemp seeds for sowing, this input was also reflected in the impact category of marine eutrophication or freshwater ecotoxicity. The last input considered was the production and usage of chemical plant protection products (pesticides, herbicides, and growth regulators). In sum, these inputs did not exceed (within the individual impact categories) 10% of the total environmental impact, except in the case of sunflower oil production under the impact category of terrestrial ecotoxicity (about 25% of the total environmental impact) and human toxicity (about 15% of the total environmental impact). However, it should be noted that their following distribution in the environment and the potential impacts of their residues were not taken into account.

Results were highly dependent on the inputs of the cultivation strategy (inputs and outputs) and on the final yield of seeds and the gain of food oil. Another critical aspect was the allocation approach (mass allocation principle), which determines the final share of the environmental impact.

3.2. Interpretation Based on Unit of Land Demand

The results of the environmental impact assessment from the point of view of the functional unit of area (the area of land needed for the generation of the same volume of food oil) differ widely from the assessment associated with the functional unit of production. The functional unit of equivalent area (land demand for generating the same volume of food oil) brought a significant change in the trend of environmental impacts. In the case of hemp, 6.8 ha were needed for the same volume of food oil which can be produced with 1.0 ha of land for winter rapeseed and 1.3 ha for sunflowers. From this perspective, hemp oil production was connected with the highest environmental impact in comparison to sunflower and rapeseed food oil production (Figure 2) within all assessed impact categories.

The environmental impact level of hemp was affected by the high land demand and the related more substantial inputs to the life cycle and cultivation strategy.

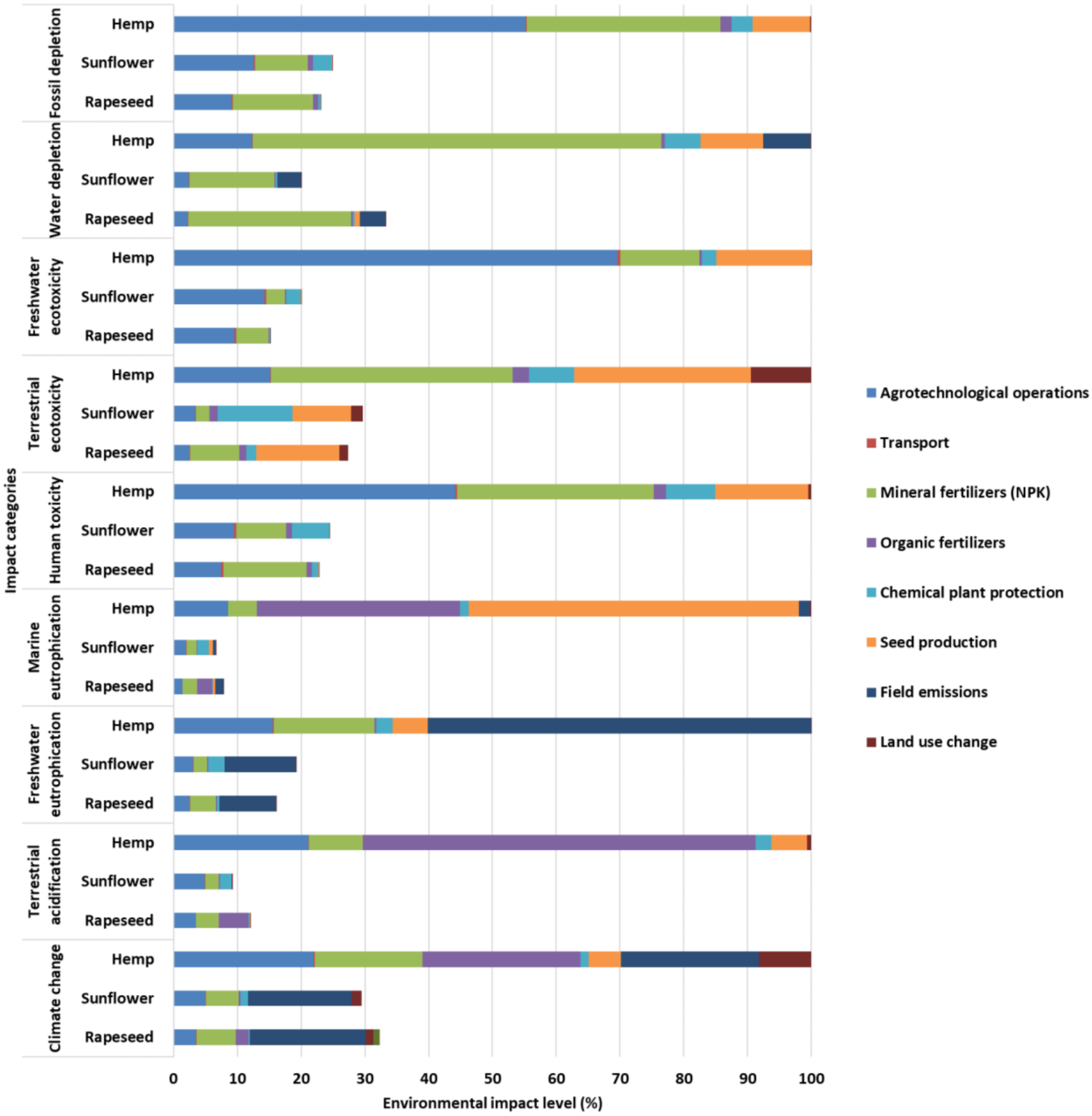

Figure 2. Environmental impact level for the unit of area (FU = land demand for generating the same volume of food oil). Contribution analysis from the cradle-to-farm gate approach for environmental impacts; ReCiPe midpoint (H) method, characterization model, results were expressed per land demand for generating the same volume of food oil.

Compared to the evaluation related to the functional unit of production, significant changes were found in hemp. The influence of field emissions and fertilizer inputs (mineral and organic) are most pronounced, though all inputs related to the growing cycle are represented. This was a proportional increase in the environmental impact, reflecting the higher demand for land to produce the same amount of food oil as rape and sunflower. The total environmental impact would increase two to nine times compared to sunflower or winter rapeseed, which showed a completely different trend. Thus, it turned out that assessing environmental impacts from the point of view of a unit of area is essential for a fair comparative study.

3.3. Normalization and the Data Weighing

Normalization of data sets was applied to take into account the most affected impact categories. No contribution analysis was employed for normalizations because percentage terms for individual impact categories would give identical characteristics to the characterization model. However, normalization is important for detecting the most affected categories, and therefore the components of the environment. Data normalization was done for both specified functional units (Figures 3 and 4).

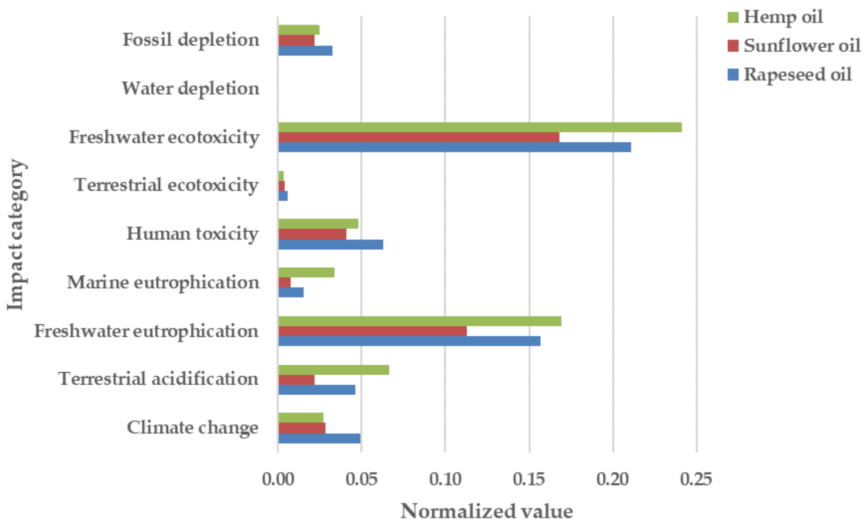

Figure 3. Normalization model for the unit of production (FU = 1 m^3 of food oil). From the cradle-to-farm gate approach for environmental impacts; ReCiPe midpoint (H) method, normalization model, results were expressed per 1 m^3 of food oil.

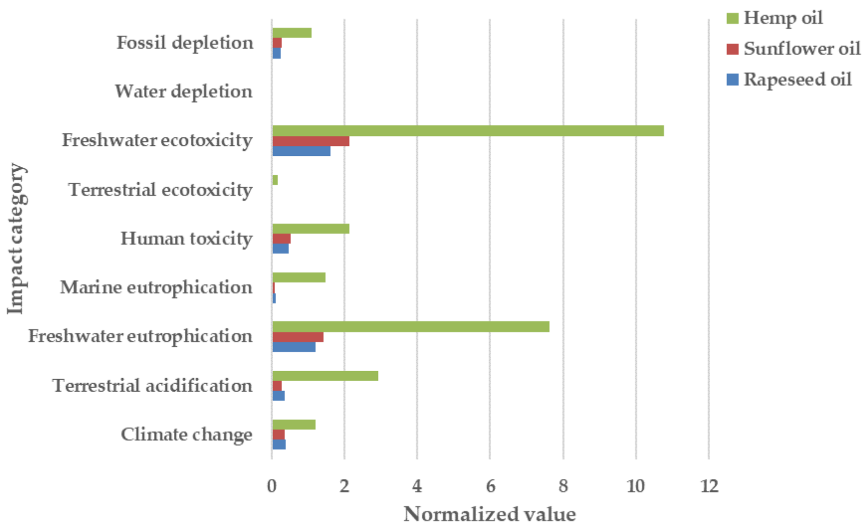

Figure 4. Normalization model for the unit of area (FU = land demand for generating the same volume of food oil). From the cradle-to-farm gate approach for environmental impacts; ReCiPe midpoint (H) method, normalization model, results were expressed per land demand for generating the same volume of food oil.

Following the normalization model (Figure 3), most affected were the categories of eutrophication and ecotoxicity. Fertilizer treatment, related field emissions, and agrotechnology creation were the most significant sources of environmental impact. In the impact category of fossil depletion, terrestrial ecotoxicity, human toxicity, and climate change, rapeseed oil production was related to the highest environmental impact. In the impact category of freshwater ecotoxicity, marine eutrophication, freshwater eutrophication, and terrestrial acidification, hemp oil was characterized by the highest environmental impact. The trend of environmental impact level points to the lower impact related to sunflower oil production (FU = 1 m^3 of food oil).

A comparison of selected oil crops based on the normalization model was also made within the land demand for generating the same volume of food oil (Figure 4). According to the results, the impact categories with the highest environmental impact were the categories of eutrophication and ecotoxicity, which was similar to FU production (m^3 of food oil). However, due to the higher demand for land in the case of hemp, the highest environmental impact was associated with the production of hemp oil in all assessed impact categories. The most striking increase was found in the category of freshwater ecotoxicity, freshwater eutrophication, terrestrial acidification, and human toxicity.

Although weighing provides only a general view of the overall environmental impact assessment, it is a suitable tool for data trend interpretation. A combination of both specified functional units within the weighing is suitable for data interpretation. Such a data expression can provide a comprehensive view of the assessed issues and thus determine the cultivation strategy, in this case, the oil crop with the lowest overall impact on the environment, and vice versa. This overall comparison is part of Figure 5.

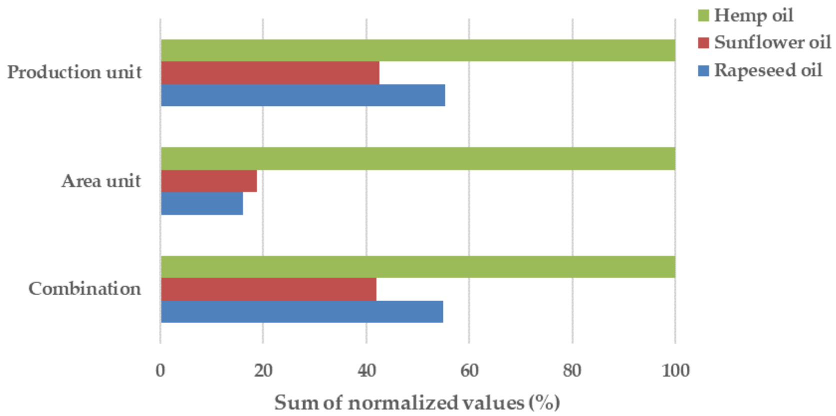

Figure 5. Weighing based on normalization mode. Production unit = 1 m^3 of food oil; Area unit = land demand for generating the same volume of food oil; Combination = interpretation based on the merger of both functional units.

According to the established study framework and models presenting winter rapeseed, sunflower, and hemp cultivation technologies, the environmental impacts were quantified according to the functional unit of production (1 m^3 of food oil) and the unit of land (land demand for generating the same volume of food oil) within nine impact categories corresponding to agricultural LCA. Thus, two perspectives with different trends of environmental impacts were obtained. Within the evaluation of FU production (m^3 of food oil), the highest impacts on the environment were associated with the production of hemp oil (Figure 5). Within the evaluation of the FU area (land demand for generating the same volume of food oil), the highest impacts on the environment were also associated with the production of hemp oil. The principle of data weighing, combining both functional units (Figure 5), was used to summarise the obtained data. Thus, a general trend for individual oil crops was obtained. From this point of view, sunflower oil production appeared to be the variant with the lowest overall impact on the environment, which was about 60% lower compared to the production of hemp oil, and about 20% lower compared to the production of rapeseed oil.

Within agricultural LCAs, the scope for detailed and deep discussion is often limited to methodological issues, as studies differ in their frameworks, data quality, and character, as well as their interpretations. Presenting the results as trends is thus a logical step, one that gives the discussion greater generality and makes it more readily understandable for readers.

4. Discussion and Perspective

A life cycle assessment method was chosen to model the life cycle of winter oil crops (rapeseed, sunflower, and hemp as an alternative). Due to its complexity, LCA is a very popular environmental management tool [13]. The results were related to impact categories corresponding to the requirements for the agricultural LCAs [11]. The approach to the elaboration of this study, the approach to modelling, the allocation approach, the functional unit (volume of food oil), the software used, and the source databases were similar to, for example, the study of Fridrihsone et al. [28,29], which also focused on oil crops.

Agriculture is widely perceived as a multifunctional production process. In addition to food, animal feed, and energy sources, non-commodity outputs, such as landscape management and ecosystem services, are also generated. However, LCA studies often focus only on the ecological/environmental sustainability of agricultural products, expressed in terms of impacts per unit of production, without any allocation between commodity and non-commodity outputs. This narrow view, which focuses only on production efficiency, can often favour conventional agricultural products, although when evaluated by other methods, these systems prove to be less environmentally friendly and less sustainable [30–32]. The solution to the issue of multifunctionality lies in choosing another functional unit that allows multifunctional outputs or allocating environmental impacts to the whole complex of products and services provided within the agricultural system [33]. The choice of the functional unit determines the nature of the study outputs and their interpretation and is one of the key moments in implementing the LCA study [34]. If the product has more functions, it is always necessary to select those relevant for the assessed system [35]. The functional unit provides the basis on which the input and output data are related. It must be clearly definable and measurable [21]. The functional unit thus expresses the measurable size of the function that we expect from the product system [35]. The universal solution seems to be to use both methods of calculating the environmental impact, both per unit area and per production unit [19,36]. Recent criticism points to the fact that these two functional units do not affect product quality, which can play a key role in defining product function. An example can be the types of quality wine [10]. In the LCA study of an agricultural commodity, more functional units should ideally be chosen for the examined system, contributing to a complete evaluation from several perspectives [37]. In addition, this step would clearly improve the comparability of the results with other studies of the same product [10].

The environmental aspects of rapeseed cultivation, from the LCA perspective, have recently received a relatively large amount of attention (e.g., [8,9,28,29]). This is because rapeseed oil was long thought to cause a lower environmental impact compared to mineral oils, for example. However, it has been shown that the systems running on rapeseed oil are not necessarily better for the environment. Many of the environmental issues examined in one study were affected more negatively by the use of rapeseed oil than mineral oil. The main exception to this was greenhouse gas emissions, which are consistently higher for systems using mineral oil because of the use of fossil resources for rapeseed oil production [38]. As Stow et al. [39] stated, biodiesel based on rapeseed is often considered to improve energy security and reduce the impact of fuel on climate change. However, there are concerns about the impact of biodiesel when its life cycle is considered. The potential impact of using biodiesel rather than conventional diesel was investigated using a life cycle assessment (LCA) of rapeseed biodiesel. Biodiesel leads to reduced fossil fuel use and is likely to reduce the impact of transport on climate change. However, it was found that the impact of biodiesel towards other categories, i.e., land use and respiratory inorganics (Particulate matter; PM2.5), was greater than petroleum diesel. Therefore, biodiesel production should be carefully managed to mitigate its impact on the environment.

Our study shows how the cultivation practices and the type/quantity of input influence the total environmental impact. Using the Life Cycle Assessment (LCA) method to assess the environmental impact of rapeseed and sunflower was also performed in the study of Palmieri et al. [8]. The study presents similar findings to ours. The practice of intensive farming with high fertilization and mechanization (machinery and fertilizer production and application) is responsible for the high environmental impact. However, when the level of productivity is low, the impact is still higher [8]. The results of our study also show that the highest environmental impacts would be associated with the production of hemp oil in comparison with rapeseed oil and sunflower oil. The results of Iriate et al. [40] also indicated that, compared to sunflower, rapeseed production has a better environmental performance (in nine out of the eleven impact categories evaluated) and lower water consumption. Although this study did not use the same methodological approach and framework to the present study, the trend of environmental aspects is similar. Iriate et al. [40] added that the energy demand of rapeseed is 4.9 GJ t^{-1} seed, 30% less than that of sunflower. Mineral fertilizers cause the highest environmental impact. According to Queiros et al. [41], the choice of fertilizer has strong implications for environmental impacts. The production of nitrogen fertilizers makes significant contributions to abiotic depletion, global warming, ozone layer depletion, and photochemical oxidation. The analysis of the life cycle of fertilizers indicates that extraction of raw materials and their production are key stages. Attempts to reduce the environmental impact and energy requirement of both crops should be mainly associated with the evaluation of other types of fertilization. In addition, particularly for sunflowers, low-impact herbicides should be evaluated, seed yield improved, and cultivation practices optimized [40].

Based on the study results and the assessed framework, a number of inputs contribute to the total environmental impact, and one of the most important is agrotechnical operations in general. The impact of agricultural technology was significantly reflected in the category of freshwater ecotoxicity (about 50–70% of the total impact when the FU of production was considered), where the main role was played by fuel and energy consumption. Other significantly affected categories are fossil depletion (about 33–42%) and human toxicity (about 25–33%). From a general point of view, agrotechnical operations can be divided into those that need fuel for their operation (chief amongst which is diesel-based agriculture) and those that need electricity or natural gas. The need for natural gas (e.g., for heating greenhouses) did not occur in the evaluated study. Post-harvest processing of agricultural raw materials (in our case, food oil processing was not reflected in the study framework) and irrigation systems both depend on electricity (though not in the case of this study). With respect to common field operations and fuel consumption, ploughing was a major factor (and thus a place to improve the product's environmental profile). Based on the study result, ploughing also had one of the dominant roles among agrotechnical inputs. One possibility for optimization is to shift to reduced or even no-tillage systems. Fuel consumption and energy input are much lower than in the conventional tillage system using a plough, but yields do not differ, as shown for maize, soybean, sugar beet, and winter wheat [42–44]. Minimization technologies or no-till systems are an alternative to energy-intensive operations. They use shallower tillage [45,46], e.g., by loosening or sowing surface-treated or untreated soil [47]. However, the impact on the final yield level has to be considered [46].

One of the most important inputs in the agricultural phase is that of fertilizers (organic and inorganic) [48,49]. For the reduction of greenhouse gas emissions from agricultural crop production, it is proposed to reduce the doses of nitrogen fertilizers used [50]. Reducing doses, especially of synthetic nitrogen, brings significant economic savings, in addition to the environmental benefits, which could provide an incentive for farmers to manage nitrogen properly, including the use of closed-cycle N-cycle recycling techniques [51]. It is also necessary to follow the principles of proper management of nitrogen fertilizers [52]. Furthemore, the nitrogen that is accessible through biological fixation is potentially high, as shown for faba beans and peas [53], not just in organic systems but also in conventional farming where nitrogen fertilizer is used [54,55]. The reduction of synthetic fertilizers can also be achieved through organic farming [56] or agroecological techniques [57]. Both of these concepts have a long tradition in the Czech Republic [58]. However, organic production is often associated with lower production per unit area, and with it often higher environmental pressures [59]. One way to support the reduction of the environmental impact of organic farming is to increase its yields while maintaining existing inputs [60]. This can be achieved, for example, by using a more balanced sowing procedure or by more efficient application and use of fertilizers [48]. The significant contribution of nitrogen fertilizers to the environmental impacts of rapeseed cultivation emphasizes the need for efficient nutrient management practices in order to minimize the application rates required [41]. Precise agricultural practices can be used for the purposes of minimizing fertilizer doses. For example, Nedbal et al. [61] showed how the most modern methods of spectral evaluation of plant nutrition can be used to calculate precise doses of nitrogen fertilizer. These techniques can help to decrease the leaching of nitrates into ground and surface water.

Transport is usually an important part of the life cycle assessment of agriculture and food production. Its importance and impact are growing mainly due to globalization tendencies [62]. It is often expressed in terms of "food miles", which summarize all the logistical routes of a product between farmers, producers, and consumers [63]. In the evaluated cycles, the transport was created using a tonne-kilometre (tkm), which expresses the transport of one ton of cargo over a distance of one kilometre. All modelled transport was realized with the help of road freight transport, and the transport distance was considered in the study to be 10 km. Only transport between the field and the farm was taken into account in the study. Overall, transport can be considered a minority input, as its share within the individual impact categories did not exceed 5%.

Based on the study results, the input of plant protection products did not exceed a 10% share of the total impact. However, it should be noted that the fate of pesticides in the environment was not considered, but only their impact arising from the production and application as represented in the databases (Ecoinvent v3.7 [23], Agri-footprint v4.0 [24], and WFLDB [25]). Within agricultural LCAs, field emissions of pesticides are quantified by modelling [64]. Despite the fact that from the point of view of the established framework and the nature of the inputs, sunflower and rape appear to be more environmentally friendly options compared to hemp, it is necessary to take into account aspects related to the use of pesticides. The fate of pesticides in the environment and their impact can be crucial when deciding on the application of plant cultivation strategies or their removal from the environment [65]. Based on the study related to the Czech Republic, the side effects of pesticides are one of the major factors often linked to bee colony losses. The most important pesticides related to the poisoning incidents were highly toxic chlorpyrifos, deltamethrin, cypermethrin, imidacloprid, and slightly toxic prochloraz and thiacloprid. Importantly, poisoning was associated with pesticide cocktail applications. Almost all poisoning incidents were investigated in relation to rapeseed [66]. Sunflower cultivation is also highly dependent on pesticides [67]. It is common practice in the Czech Republic to apply fungicides and pesticides together. This step also has an impact on biodiversity, including bee populations [68]. In contrast, hemp is grown without agrochemical inputs without any problems [17], thus eliminating the negative factors associated with them. It is still important to monitor the fate of pollutants and foreign substances in the environment. Due to the importance of the topic, this is an issue requiring appropriate attention. There are still many questions about the transport and behaviour of pollutants, their interactions with other substances, and the impact on human health. Effective ways for reducing their usage and achieving suitable management must be found [69].

Compared to sunflowers and rapeseed, hemp production has several other significant environmental benefits [70]. One of these is high sequestration. The soil carbon change associated with different agricultural management practices is an important factor contributing to the global warming impact [41]. In the case of hemp production, sequestration is up to 2500 kg CO_2 per ha per year [71]. In the case of rapeseed, carbon sequestration to soils varies between 112 kg CO_2 eq/1000 kg dry seeds (cool temperate dry climate) and 271 kg CO_2 eq/1000 kg dry seeds (warm temperate moist climate) [41]. According to Halvorson et al. [72], with no-till, an estimated 854 kg CO_2 ha^{-1} was sequestered each year in the annual crop system, which included sunflowers, compared with 92 kg CO_2 ha^{-1} with minimum till and a loss of 517 kg CO_2 ha^{-1} with conventional till. With respect to carbon sequestration, soils with high organic carbon content should not be converted to rapeseed cultivation to avoid excessive carbon emissions [41]. Another benefit of hemp that was not taken into account in the study is soil erosion. Whereas sunflowers belong to the category of plants with high erosion risk, and rapeseed belongs to the category of plants with mean erosion risk [73], hemp can enrich and stabilize unproductive lands by reducing weed pressure and soil erosion [70].

The demand for hemp products is growing. Hemp is considered an environmentally friendly crop with a lower environmental impact and higher yields, and can replace traditional materials used in the building, car, textile, paper, and biofuel industries. In addition to these benefits, hemp is also used in the food industry, as hemp seeds are rich in fat and proteins. Furthermore, demand for dietary supplements will grow as more consumers are looking for healthy or vegan food alternatives [5]. Hemp is an excellent plant for cultivation in organic farming systems [74] and is suitable for crop rotation [75].

5. Conclusions

The study presents the results of environmental impact assessments from the perspective of an agricultural LCA. The results concern the environmental issues associated with the production of vegetable food oil. According to the established study framework and data corresponding to standard cultivation practices for winter rape, sunflower, and hemp, hemp cultivation for food oil production may not meet the high sustainability predictions and low environmental impacts that are currently claimed for it. In this respect, the inputs to the growing cycle, and especially the low yields of food oil compared to traditional and efficient oils crops, including winter rape and sunflower, are significant. The applied methodological approach and interpretation of data in this study showed that the total environmental impact (based on the combination of production and area unit) associated with the production of hemp oil (volume of food oil) was about 40% higher than rapeseed oil and about 60% higher than sunflower oil.

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Sustainability Estimation of Oat:Pea Intercrops from the Agricultural Life Cycle Assessment Perspective

Jaroslav Bernas [1,*], Tereza Bernasová [2], Hans-Peter Kaul [3], Helmut Wagentristl [4], Gerhard Moitzi [4] and Reinhard W. Neugschwandtner [3]

[1] Department of Agroecosystems, Faculty of Agriculture, University of South Bohemia in Ceske Budejovice, Studentska 1668, 37005 Ceske Budejovice, Czech Republic
[2] Department of Applied Ecology, Faculty of Agriculture, University of South Bohemia in Ceske Budejovice, Studentska 1668, 37005 Ceske Budejovice, Czech Republic; veselt04@zf.jcu.cz
[3] Department of Crop Sciences, Institute of Agronomy, University of Natural Resources and Life Sciences Vienna (BOKU), 3430 Tulln, Austria; hans-peter.kaul@boku.ac.at (H.-P.K.); reinhard.neugschwandtner@boku.ac.at (R.W.N.)
[4] Experimental Farm Groß-Enzersdorf, Department of Crop Sciences, University of Natural Resources and Life Sciences Vienna (BOKU), 2301 Groß-Enzersdorf, Austria; helmut.wagentristl@boku.ac.at (H.W.); gerhard.moitzi@boku.ac.at (G.M.)
* Correspondence: Bernas@zf.jcu.cz

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Abstract: Winter cereal:legume intercropping is considered a sustainable arable farming system not only in temperate regions but also in Mediterranean environments. Previous studies have shown that with suitable crop stand composition, high grain yield can be achieved. In this study, a life cycle assessment (LCA) of the influence of sowing ratio and nitrogen (N) fertilization on grain nitrogen yield of oat (*Avena sativa* L.) and pea (*Pisum sativum* L.) in intercrops was performed to find the optimal design to achieve low environmental impact. This study compared the environmental impact of oat:pea intercrops using agricultural LCA. Monocrops of oat and pea and substitutive intercrops, which were fertilized with different levels of N, were compared. The system boundaries included all the processes from cradle to farm gate. Mass-based (grain N yield) and area-based (land demand for generating the same grain N yield) functional units were used. The results covered the impact categories related to the agricultural LCAs. The ReCiPe 2016 Midpoint and Endpoint characterization model was used for the data expression. According to the results, an unfertilized combination of oat and pea (50%:50%) had the lowest environmental impact in comparison with the other 14 assessed variants and selected impact categories. In the assessed framework, pea monocrops or intensively fertilized oat monocrops can also be considered as alternatives with relatively low impact on the environment. However, an appropriate grain N yield must be reached to balance the environmental impact resulting from the fertilizer inputs. The production and use of fertilizers had the greatest impact on the environment within the impact categories climate change, eutrophication, and ecotoxicity. The results indicated that high fertilizer inputs did not necessarily cause the highest environmental impact. In this respect, the achieved grain N yield level, the choice of allocation approach, the functional unit, and the data expression approach played dominant roles.

Keywords: LCA; intercrops; *Avena sativa* L.; *Pisum sativum* L.; attributional approach; land demand

1. Introduction

The common agricultural policy (CAP) combines social, economic, and environmental approaches for achieving a sustainable agricultural system in the European Union [1]. The aim of the "European Green Deal", and one of the targets of the "From Farm to Fork strategy", is to find ways to reduce the excess of nutrients in the environment, which are a major source of air, soil, and water pollution and thereby negatively impacts biodiversity and climate. The target of the agricultural policy is to reduce nutrient losses by at least 50%

and reduce fertilizer use by at least 20% by the year 2030 while ensuring no deterioration of soil fertility [2]. Different strategies can help meet these goals [3]; among those is the inclusion of legumes into the crop rotations or their use in intercrops to improve nutrient management [4].

Winter cereal:legume intercrops for grain production performed well in terms of productivity and environmental impacts, as well as energetic and economic performances [5]. In addition, the concept of intercropping corresponds to the principles of agroecology [6]. For example, wheat:pea intercropping was proved to be a cropping strategy for using N sources efficiently due to its self-regulating spatial dynamics, where pea improves its interspecific competitive ability in areas with lower soil N levels, and vice versa for wheat, paving the way for future option to reduce N inputs and negative environmental impacts of agricultural crop production [7]. Intercropping with legumes is particularly suitable for systems with low N availability, but a deeper mechanistic understanding is required to propose general crop management procedures. The advantages of intercropping fall into three basic categories, according to Mohler and Stoner [8]. Firstly, an intercrop may use the limited resources of light, water, and nutrients more efficiently than monocrops, and this can improve yields. Secondly, intercrops frequently have lower pest and disease incidence, especially insect pests, because the mixture confuses the insects, and a carefully chosen mixture attracts beneficial predators. Thirdly, intercropping may allow more effective management of cover crops. Intercrops are already largely adopted in organic farming, but additional research efforts are needed for their adoption in conventional farming, particularly for grain production. For instance, depending on the aim of the cereal:legume intercrop (food, feed, or bioenergy production), the choice and adaptation of species, cultivars, crop management, or agricultural machinery are crucial. This underlines the need for future investigation [5].

In substitutive intercrops of oat and pea, which were fertilized with different levels of N, the total grain yields were generally lower than in the respective monocrops. Still, grain N concentration of oat and pea increased (1) with N fertilization and (2) in intercrops for oat with lower oat share, whereas that of peas was not affected by the sowing ratio. Consequently, intercrops could attain a higher grain N yield in unfertilized treatments due to higher grain N concentrations of oat in intercrops. Thus, growing oat:pea intercrops can be reasonable for producing grain feed at a low N input level [4,9]. Further, concentrations of macro-and micronutrients in grain and residues of oat and pea can be affected by sowing ratio and N fertilization [10,11]. A low N fertilization rate did not impair N_2 fixation in oat: pea intercrops [12].

Each agricultural activity causes certain environmental impacts that can be expressed or quantified, for example, by the life cycle assessment (LCA) method [13]. With a suitable data source, equal system boundary settings, and a correctly chosen allocation principle, data can be generated that can adequately predict the environmental impacts of the selected system. LCA, coupled with other approaches, provides reliable and comprehensive information to environmentally conscious policymakers, producers, and consumers in selecting sustainable products and production processes [14]. Combinations of multiple functional units can contribute to more accurate and fair data expression [15].

In this study, intercrops of oat and pea were assessed for grain nitrogen (N) accumulation. The study focused on the agricultural life cycle assessment of 15 different combinations of oats and peas or their monocrops under different fertilization intensities and varying yield levels. The attributional approach, the mass allocation principle, and the characterization model were chosen. As functional units, the yield (1 kg of grain N yield) and the equivalent area, i.e., the land demand to gain the same yield (grain N yield), are used for data interpretation.

2. Materials and Methods

2.1. Data Source and Life Cycle Inventory

The study was based on a two-year field study by Neugschwandtner and Kaul [4,9], where intercrops of oat (*Avena sativa* L.) and pea (*Pisum sativum* L.) were assessed as affected by sowing ratio and N fertilization. Monocrops of oat and pea and three substitutive oat:pea intercrops were sown in the following ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100. All the crop stands were fertilized with N as calcium ammonium nitrate (CAN, 27% N) at the following levels: unfertilized control (C), 60 kg N ha^{-1} (N60), and 120 kg N ha^{-1} (N120). The experiment was carried out in eastern Austria (Raasdorf; 48°14′ N, 16°33′ E) in 2010 and 2011. The soil is classified as chernozem of alluvial origin and rich in calcareous sediments (pH 7.6, silty loam, 2.2–2.3% organic substance). The mean annual temperature is 10.6 °C, the mean annual precipitation is 538 mm (1980–2009). More details for the trial site, soil characteristics, weather data, and crop varieties are described in the methodology parts of the above-mentioned studies, which were the primary data source for the life cycle inventory (LCI) (Table 1). Secondary data for background processes were taken from the Ecoinventv3.7.1 database, which includes data from central Europe [16], Agri-footprint v4.0 [17], and WFLDB [18].

2.2. Goal and Scope Definition

The goal of this study was to quantify the environmental impacts of the oat:pea intercrops by using LCA (the method of assessing the life cycle of a product or service in terms of its impact on the environment) and find the optimal intercropping design from the environmental point of view. Functional units (FUs) related to a production unit (1 kg of grain N yield ha^{-1}) or an area unit (land demand for generating the same grain N yield) were chosen for the quantification of an environmental impact. The system boundaries included all the processes “from cradle to farm gate”. Data geographically related to central Europe were used. Agrotechnological operations were also incorporated into the model system: from pre-seeding preparation, through harvesting of the main product, to the transport of farming machinery, the production and use of crop-protecting agents, the production and use of fertilizers, and the harvest and transport of the main product from the harvest site. Land-use changes were taken into account. Infrastructure processes were part of database inputs. Waste management was excluded from this research because waste production was not expected within the monitored cropping systems. In the frame of this research, the transport distance from the farm to the field did not exceed the distance of 5 km. A mass allocation approach (allocation based on significant characteristics of co-products; grain and straw N yield) was employed in this study. The results of the research might be used as a source of information for agricultural subjects that focus on good farming practices and to motivate environmentally friendly farming systems. The data were analyzed and evaluated by LCA standards [19,20].

Table 1. Inventory table: inputs and outputs of the life cycle.

	Unit	Oat:Pea (100:0)	Oat:Pea (75:25)	Oat:Pea (50:50)	Oat:Pea (25:75)	Oat:Pea (0:100)
		C/N60/N120	C/N60/N120	C/N60/N120	C/N60/N120	C/N60/N120
Outputs						
Grain yield	kg ha^{-1}	4281/5211/5752	4354/5284/4342	4582/4400/4647	4064/4707/4504	5165/5823/5721
Grain N yield	kg ha^{-1}	81.6/111.5/135.4	93.0/119.6/110.9	116.3/106.6/114.1	112.8/126.4/133.4	187.2/210.2/218.9
Residue N yield	kg ha^{-1}	28.5/44.9/59.6	35.4/44.6/89.2	45.4/62.1/69.2	54.3/65.1/80.8	54.4/72.8/70.7
Land demand for generating the same grain N yield $^{\#}$	ha	2.68/1.96/1.62	2.36/1.83/1.97	1.88/2.05/1.92	1.94/1.73/1.64	1.17/1.04/1.00
Inputs from technosphere						
Nitrogen (calcium ammonium nitrate, 27% N) *	kg ha^{-1}	0/60/120	0/60/120	0/60/120	0/60/120	0/60/120
Application of plant protection products by field sprayer *	ha	1	1	1	1	1
Combine harvesting *	ha	1	1	1	1	1
Fertilization by broadcaster *	ha	-/2/2	-/2/2	-/2/2	-/2/2	-/2/2
Insecticide at plant (pyrethroid-compound) *	g ha^{-1}	75	75	75	75	75
Oat seed for sowing *	kg ha^{-1}	120	90	60	30	0
Pea seed for sowing *	kg ha^{-1}	0	52.5	105	157.5	210
Tillage, harrowing, by spring tine harrow *	ha	1	1	1	1	1
Tillage, cultivating, chiselling/by disk harrow *	ha	1	1	1	1	1
Sowing *	ha	1	1	1	1	-
Transport, tractor, and trailer, agricultural *	tkm	21.4/26.1/28.8	21.8/26.4/21.7	22.9/22.0/23.2	20.3/23.5/22.5	25.8/29.1/28.6
Tillage, currying, by weeder *	ha	1	1	1	1	1
Land use change (annual or perennial crop) *	ha	1	1	1	1	1
Inputs from nature						
Land occupation *	ha	1	1	1	1	1
Water (as a medium for plant protection products)	L ha^{-1}	300	300	300	300	300
Emissions to air						
Dinitrogen monoxide (direct and indirect)	kg ha^{-1}	-/2.813/4.235	-/2.813/4.235	-/2.813/4.235	-/2.813/4.235	-/2.813/4.235
Ammonia (volatilization)	kg ha^{-1}	-/1.2/2.4	-/1.2/2.4	-/1.2/2.4	-/1.2/2.4	-/1.2/2.4
Emissions to water						
Nitrate (leaching)	kg ha^{-1}	-/0.135/0.271	-/0.135/0.271	-/0.135/0.271	-/0.135/0.271	-/0.135/0.271

$^{\#}$ Basis is the treatment with the highest grain N yield (100:0 N120); * Input/s from Ecoinvent, Agri-footprint or WFLDB database; C = Control; N60 = fertilization with 60 kg N ha^{-1}; N120 = fertilization with 120 kg N ha^{-1}; Sowing ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100; Transport was included in the process with a flat rate 5 km × yield achieved (max 8 tons per load); tkm = tonne-kilometre; application of fertilizers by broadcaster was done in two splits; based on a two-year field study, as an average values.

2.3. Software Data Inventorization

For the study, data related to the grain yield, grain N yield, and residue N yield from the studies of Neugschwandtner and Kaul [4,9] were summarized (Table 1). The primary data sources were statistically evaluated. The following parameters were assessed: Grain and residue yield; Yield components of oat and pea; N concentration, N yield and N harvest index of oat and pea; Total grain and nitrogen yield, Land equivalent ratio of N yields (LER_N); Nitrogen use and utilization efficiency. These results are part of the primary sources [4,9] for LCI. These data were also used to determine the proportion of environmental impacts that arose during the transport of harvested phytomass. For this reason, the determination of the tonne-kilometer (tkm) was performed. For a correct assessment of these environmental impacts, the mass allocation principle was used. To apply the mass allocation principle, the determination of the residue N yield was necessary. Grain yield, grain N yield, and residue N yield of individual variants and the frequency of agrotechnical inputs, inputs from technosphere, inputs from nature, information about emissions to water and air are summarized in Table 1.

2.4. Determination of Field Emissions

The application of mineral nitrogenous fertilizers results in the release of direct and indirect emissions. The following were considered in monitoring field and agricultural emissions: NH_3 and NO_x volatilization, NO_3^- leaching to groundwater, and N loss from leaching and surface outflow (expressed as dinitrogen monoxide, nitrate, and ammonia in Table 1). The emission loads were determined following Nemecek and Kägi [21]. The nitrogen generated from the biological N_2–fixation of pea was not considered within the field emissions cultivation; therefore, NH_3 and NO_3^- emissions to air and water were not taken into account in this case. The risk of erosion was not considered in the study. The production of pesticides, respectively their active substances, and their distribution has been taken into account by using data from the Ecoinvent database [16], but the fate of the pesticides in the environment did not. Therefore, the toxicity impact cannot be considered as fully reflected.

2.5. Impact Assessment

An LCA method was used for the quantification of environmental impacts. The system boundaries were set from "the cradle to the farm gate". The results of this research were related to the impact categories of climate change (kg CO_2eq), terrestrial acidification (kg SO_2eq), freshwater eutrophication (kg P eq), marine eutrophication (g Neq), human toxicity (kg 1,4-DBeq)-non-carcinogenic toxicity, terrestrial ecotoxicity (g 1,4-DBeq), freshwater ecotoxicity (g 1,4-DBeq), water depletion (m^3eq), and fossil depletion (kg oil eq). The Attributional approach was used for this study. Selected impact categories are suitable for agricultural LCAs [13,22]. The SimaPro 9.2.0.1 software, ReCiPe 2016 Midpoint and Endpoint, Hierarchical (H) V1.05/World (2010) H, an integrated method, and the Cut-off System Model approach were used for the assessment of the environmental aspects. One kg of the final product (1 kg of grain N yield) and an area unit (land demand for generating the same grain N yield) were used as functional units. The Characterization approach was primarily used for data expression. Weighting was used as a final step for applying a value judgment to the LCA result.

3. Results and Data Interpretation

A life cycle of the monocrops of oat and pea, and cereal:legume intercropping systems was created according to the methodology and the data available; the environmental impacts per 1 kg of grain N yield, and for the land demand for generating the same grain N yield were quantified. The interpretation approach was based on a combination of two functional units. It enabled an equal expression of data and demonstrated trends in individual cultivation technologies within all evaluated impact categories and data from multi-year field experiments.

The results were related to nine impact categories relevant for agricultural LCAs. The results are presented in Tables 2 and 3.

Table 2. Environmental Impact per 1 kg of grain N Yield ha^{-1}.

Impact Category		Oat:Pea (100:0)	Oat:Pea (75:25)	Oat:Pea (50:50)	Oat:Pea (25:75)	Oat:Pea (0:100)
Climate change ($kg\ CO_2eq$)	C	5.19	4.52	3.64	3.56	2.51
	N60	12.38	11.84	11.57	10.24	6.97
	N120	12.11	11.83	12.96	11.18	8.27
Terrestrial acidification ($g\ SO_2eq$)	C	22.16	18.83	0.61	14.18	9.75
	N60	24.96	23.71	0.97	20.19	13.66
	N120	20.04	19.42	0.89	18.11	13.34
Freshwater eutrophication (g P eq)	C	0.79	0.72	0.64	0.63	0.46
	N60	0.94	0.95	0.98	0.90	0.64
	N120	0.75	0.77	0.91	0.81	0.63
Marine eutrophication (g N eq)	C	3.66	3.80	3.55	3.94	3.08
	N60	2.97	3.35	3.76	3.76	2.85
	N120	2.55	2.91	3.64	3.53	2.90
Human toxicity (kg 1.4-DB eq)	C	5.69	4.82	3.79	3.60	2.49
	N60	6.53	6.25	6.07	5.38	3.67
	N120	5.26	5.10	5.59	4.82	3.59
Terrestrial ecotoxicity (kg 1.4-DB eq)	C	11.91	11.34	9.89	10.42	7.83
	N60	13.94	14.37	15.01	14.17	10.24
	N120	11.20	11.77	13.82	12.71	10.00
Freshwater ecotoxicity (dkg 1.4-DB eq)	C	10.84	10.12	8.68	9.00	6.70
	N60	12.70	12.38	12.29	11.08	7.70
	N120	10.21	10.13	11.32	9.94	7.52
Water depletion (L)	C	15.6	37.2	48.5	65.2	57.8
	N60	40.1	57.0	73.7	81.1	65.8
	N120	32.2	46.7	67.8	72.7	64.3
Fossil depletion (kg oil eq)	C	1.05	0.92	0.75	0.74	0.52
	N60	1.45	1.40	1.38	1.23	0.84
	N120	1.17	1.15	1.27	1.10	0.83

C = Control; N60 = fertilization with 60 kg N ha^{-1}; N120 = fertilization with 120 kg N ha^{-1}; Sowing ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100; ReCiPe 2016 Midpoint (H) V1.05/World (2010) H; Characterization model; eq = equivalent; 1.4-DB = 1.4-dichlorobenzene.

Table 3. Environmental impact per land demand for generating the same grain N yield.

Impact Category		Oat:Pea (100:0)	Oat:Pea (75:25)	Oat:Pea (50:50)	Oat:Pea (25:75)	Oat:Pea (0:100)
Climate change ($t\ CO_2eq$)	C	1.53	1.37	1.11	1.16	0.71
	N60	3.79	3.56	4.00	3.39	2.05
	N120	3.82	4.66	4.56	3.91	2.40
Terrestrial acidification ($kg\ SO_2eq$)	C	6.54	5.70	4.51	4.60	2.76
	N60	7.65	7.12	7.94	6.69	4.02
	N120	6.33	7.65	7.44	6.34	3.86
Freshwater eutrophication (g P eq)	C	231.69	219.02	186.57	204.26	131.24
	N60	286.75	284.05	335.47	298.72	189.39
	N120	237.46	304.80	314.44	283.01	182.05
Marine eutrophication (kg N eq)	C	1.08	1.15	1.08	1.28	0.87
	N60	0.91	1.01	1.30	1.25	0.84
	N120	0.80	1.15	1.28	1.24	0.84
Human toxicity (t 1.4-DB eq)	C	1.68	1.46	1.15	1.17	0.70
	N60	2.00	1.88	2.10	1.78	1.08
	N120	1.66	2.01	1.97	1.69	1.04
Terrestrial ecotoxicity (t 1.4-DB eq)	C	3.51	3.43	3.01	3.38	2.21
	N60	4.27	4.32	5.19	4.69	3.01
	N120	3.54	4.64	4.87	4.45	2.90

Table 3. *Cont.*

Impact Category		Oat:Pea (100:0)	Oat:Pea (75:25)	Oat:Pea (50:50)	Oat:Pea (25:75)	Oat:Pea (0:100)
Freshwater ecotoxicity (kg 1.4-DB eq)	C	31.98	30.64	26.41	29.20	18.93
	N60	38.93	37.21	42.51	36.72	22.65
	N120	32.24	39.91	39.85	34.78	21.77
Water depletion (m^3)	C	4.60	11.28	14.74	21.14	16.34
	N60	12.29	17.12	25.49	26.85	19.36
	N120	10.17	18.42	23.88	25.45	18.62
Fossil depletion (kg oil eq)	C	309.54	278.56	226.81	238.41	147.33
	N60	444.83	420.78	476.54	407.49	248.58
	N120	368.09	452.05	446.55	386.14	238.97

C = Control; N60 = fertilization with 60 kg N ha^{-1}; N120 = fertilization with 120 kg N ha^{-1}; Sowing ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100; ReCiPe 2016 Midpoint (H) V1.05/World (2010) H; Characterization model; eq = equivalent; 1.4-DB = 1.4-dichlorobenzene.

3.1. Unit of Production and the Sensitivity Analysis

In Table 2, the grain N yield ha^{-1} was considered. Within all assessed variants and trends, pea monocrops had generally low values in individual impact categories. Further, low levels of environmental impact were found for the following variants: 100:0 N120, 50:50 C, or 75:25 N120. On the contrary, the highest environmental impacts were found for 100:0 N60, 75:25 N60, 50:50 N60, or 25:75 N60. This, of course, depends on the level of grain N yield and inputs to the life cycle. The input of N and thereby the related emissions were a significant component of the total environmental impacts.

Concerning results, 50:50 C,75:25 N120, and 25:75 C intercrops could be considered as potentially sustainable from the point of view of FU of production (grain N yield ha^{-1}). Values of environmental impacts were expressed in% within the individual impact categories, where 100% meant the highest value within the assessed variants and selected impact categories (Figure 1).

From a general point of view, trends suggested that the highest environmental impact (within FU of production) was associated with oat monocrops (100:0 C, and 100:0 N60), and oat:pea intercrops with the input of 60 kg N ha^{-1}, especially in the impact categories of terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, terrestrial ecotoxicity, and freshwater ecotoxicity. For example, the highest environmental impact within the water depletion impact category was then associated with 25:75 N60.

A normalization approach was used to inform about the relative magnitude of each of the characterized scores for the different impact categories by expressing them relative to a common set of reference impacts (one reference impact per impact category) (Figure 2). The result of the normalization is the normalized impact profile of the product system in which all category indicator scores were expressed in the same metric.

The normalization of the data showed the most affected impact categories. However, it should be added that the results were related to the functional unit of production, which was therefore strongly influenced by the grain yield or grain N yield. In general, and due to the character and intensity of inputs into the growing framework, the most affected category was freshwater ecotoxicity, a category that was affected by the production of seeds used (oat and pea), the input of N fertilizer, agrotechnological operations, transport and use of pyrethroid insecticide.

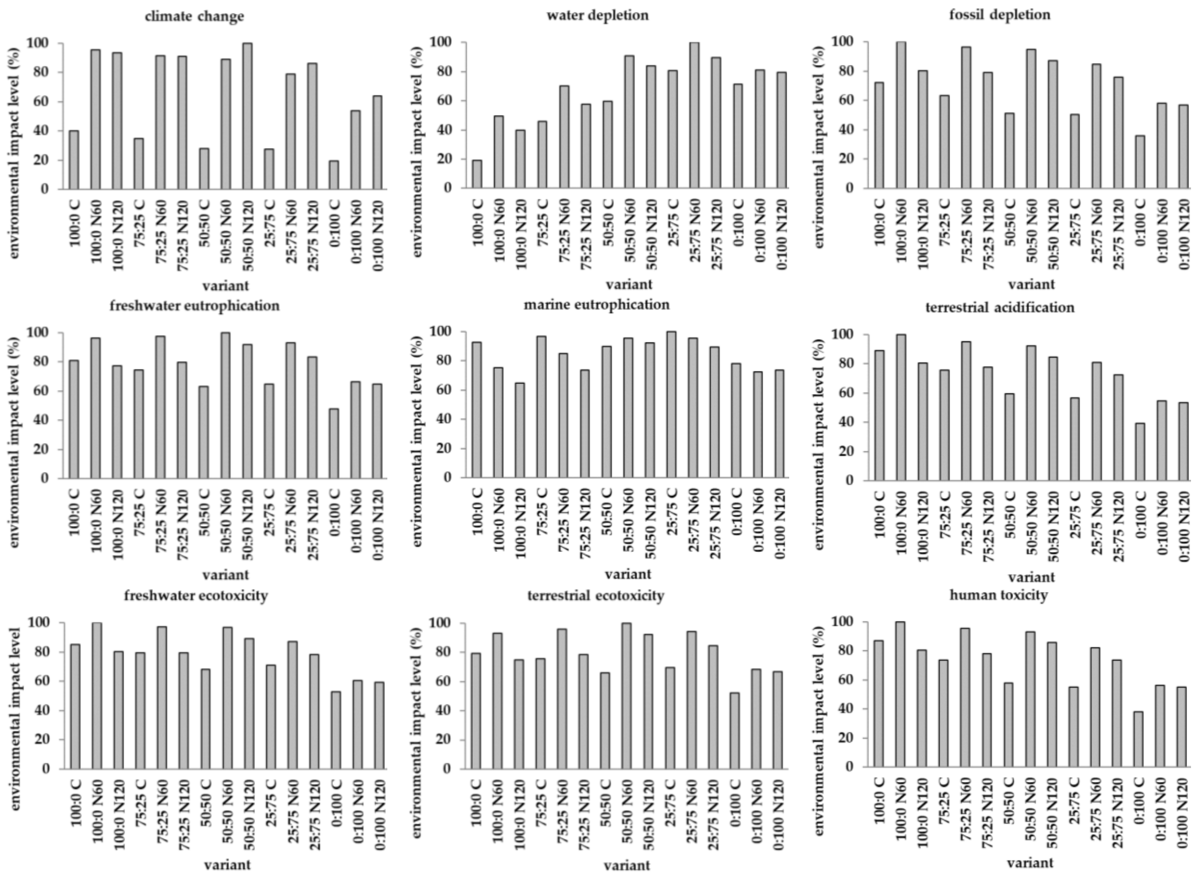

Figure 1. Trends of the environmental impact per 1 kg of grain N yield ha^{-1} (in %).C = Control; N60 = variant with input of 60 kg N ha^{-1}; N120 = variant with input of 120 kg N ha^{-1}; Sowing ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100; SimaPro 9.1.1.1 software; ReCiPe 2016 Midpoint (H) V1.05/World (2010) H; Cut-off System Model approach; Characterization model.

Within the normalization model, it was also possible to point out the influence of fertilizer (CAN) input on differences in environmental impacts most visibly within the climate change impact category. Respectively, the environmental impact for unfertilized variants was about one-third in comparison with fertilized variants. The influence of the used seed in the impact category of terrestrial ecotoxicity was also manifested. Thus, with the decreasing rate of oat seeds, the overall environmental impact decreased and vice versa. This was generally due to more intensive cultivation practices in oats and grain production, leading to a higher environmental impact than pea seed. It is also necessary to draw attention to the category of human toxicity and water depletion, where the impact on the environment within the standardization was practically negligible compared to the other categories. The water consumption was practically not reflected in the normalization model due to the generally low input.

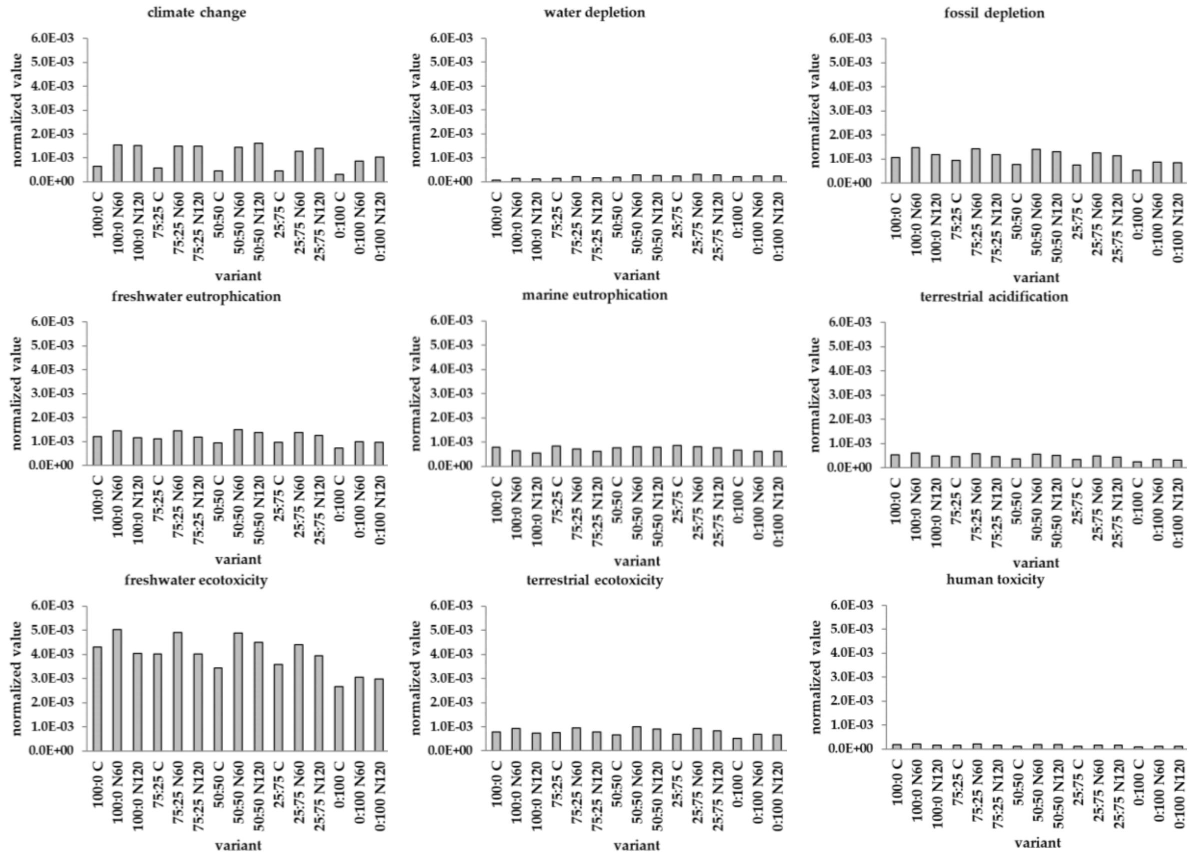

Figure 2. Trends of the environmental impact per 1 kg of grain N yield per ha^{-1}; C = Control; N60 = variant with input of 60 kg N ha^{-1}; N120 = variant with input of 120 kg N ha^{-1}; Sowing ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100; SimaPro 9.1.1.1 software; ReCiPe 2016 Midpoint (H) V1.05/World (2010) H; Cut-off System Model approach; Normalization model.

3.2. Unit of the Area and the Sensitivity Analysis

In this evaluation, the land demand for generating the same grain N yield (equivalent area) was calculated (cf. Table 1). In Table 3 and Figure 3, the environmental impact related to land demand was considered. The smallest land demand corresponds to the area of one hectare (1 ha), to the highest grain N yield, respectively. The 0:100 N120 variant achieved this. On the contrary, the highest land demand (land demand for grain N yield as by 0:100 N120) corresponded to variant 100:0 C (2.68 ha).

Among all the assessed variants, pea monocrops generally had the lowest values in individual impact categories, i.e., the lowest environmental impact. On the contrary, the highest environmental impact was associated with 50:50 N60, with75:25 N120, and 25:75 N60. This was due to the higher land demand to obtain the same grain N yield.

The highest and lowest values within the individual oat:pea intercrops among the stated impact categories (without monocrops) were selected to find the optimal variant in terms of environmental impact. From the point of view of the FU of area (land demand for generating the same grain N yield), 50:50 C and 25:75 C intercrops can be considered environmentally friendly, and the best choice seems to be 50:50 C.

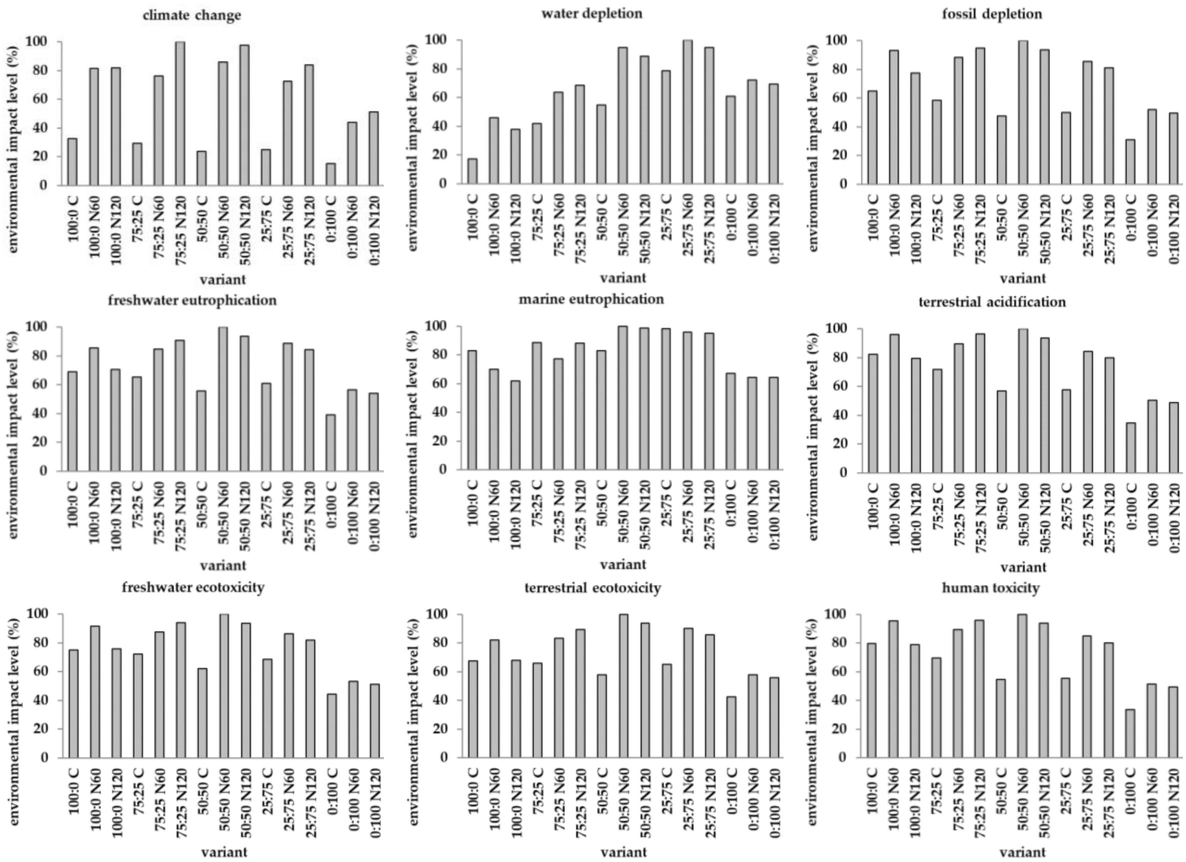

Figure 3. Trends of the environmental impact per land demand for generating the same grain N yield–(in %); C = Control; N60 = variant with input of 60 kg N ha^{-1}; N120 = variant with input of 120 kg N ha^{-1}; Sowing ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100; SimaPro 9.1.1.1 software; ReCiPe 2016 Midpoint (H) V1.05/World (2010) H; Cut-off System Model approach; Characterization model.

The resulting values, therefore, indicated that the lowest environmental impacts within the selected impact categories were obtained with the cultivation of pea monocrops, except for the category water depletion. This can be considered as the expected result due to the high grain yields, respectively, grain N yields in comparison with other cropping designs (cf. Table 1). For the opposite reason, i.e., due to relatively low grain N yield levels, high environmental impacts were associated with oat monocrops, and because of the nitrogen input with the intercrop with 50:50 N60 and N120, and 25:75 N60 and N120.

The normalization approach was also used for other data interpretation (Figure 4). The normalization of the data showed the most affected impact categories. The results were related to the functional unit of equivalent area, which was needed for generating the same grain N yield. Similar to the FU of the production, the most affected category was freshwater ecotoxicity, which was affected by the production of seeds used (oat and pea), the input of N fertilizer (CAN), agrotechnological operations, transport and use of pyrethroid insecticide. The general trend direction (related to selected impact categories) was the same as for FU production (Figure 2).

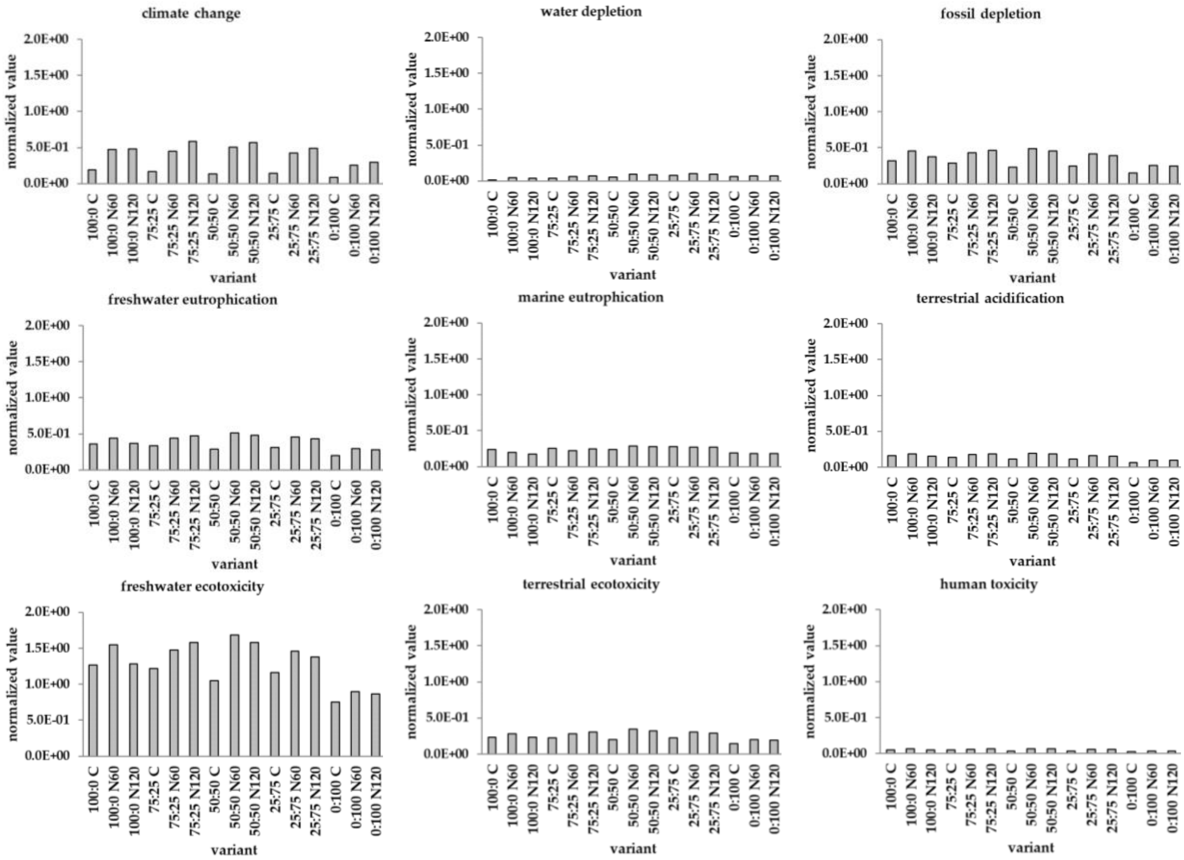

Figure 4. Trends of the environmental impact per land demand for generating the same grain N yield; C = Control; N60 = variant with input of 60 kg N ha^{-1}; N120 = variant with input of 120 kg N ha^{-1}; Sowing ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100; SimaPro 9.1.1.1 software; ReCiPe 2016 Midpoint (H) V1.05/World (2010) H; Cut-off System Model approach; Normalization model.

3.3. Contribution Analysis Summarization

Due to the study's goal to follow the complete and already presented variants as a whole and their environmental impact trends with their yield levels, no contribution analysis related to individual variants was performed within the graphical interpretation. The results in this respect would differ mainly due to differences in the dose of applied fertilizers and the seed ratio according to variants. The other inputs were the same for all variants. The obtained data would not bring new significant findings, and the aim was not to propose changes in cultivation practices. However, a brief summarization of the contribution analysis was made. Within the climate change impact category, for variants with 60 or 120 kg N (CAN) ha^{-1}, the so-called field emission emissions (around 43 to 53%) arising after its application and emissions related to its input of CAN (about 20%) contributed the most to the total environmental impact. The share of CAN input represented about 25–30% of the total impact within the categories terrestrial acidification, freshwater eutrophication, human toxicity, freshwater ecotoxicity, terrestrial ecotoxicity, water depletion, and fossil depletion. A smaller share (<10%) then represented the input of CAN in the category of marine eutrophication. In the case of unfertilized variants, the input of agrotechnology (about 65%) and land use (25%) predominates in the total environmental impact due to the lack of N input. Agrotechnical operations, inputs associated with tillage, application of fertilizers or plant protection product, and harvest of the main product, respectively, represented an important share of the total environmental impact (around 10 to 45%) in other categories of impact, depending on the variant. The impact of the pyrethroid insecticides share did not exceed 5% across the selected impact categories. This was also the same for the environmental impact associated with the transport of the harvested product (<5%). The dominant share in the total environmental impact was represented by seed inputs (pea and oat), their production, respectively. The intensity of the impact on the environment varied according to the variant and the proportion of seed. Across variants and impact categories, this share ranged from 5 to 85%. The categories of marine eutrophication, terrestrial ecotoxicity, and water depletion were most affected by this input (>45% in all impact categories and variants). For unfertilized variants, this input had a generally higher share in all impact categories (due to missing input of N). Oat seed input then had a more substantial effect on the marine eutrophication or terrestrial ecotoxicity impact category, while pea seed input had a more significant impact on the water depletion category. This was due to inputs into the cultivation technology modelled by the Ecoinvent source database [16].

3.4. Trends of the Environmental Impacts (LCA Weighing)

The combined assessment of obtained data is shown in Figure 5. This part was considered as a weighing, applying a value judgment to LCA results, respectively. For this part, the interpretation of data was used, which allowed the assessment of all monitored variants, all impact categories, and both specified functional units together. Thus, this interpretation of data allowed a broad view of the topic. The data used for this interpretation were obtained on the basis of a normalization model expressed in the Endpoint categories: Resources, Ecosystems, Human health. From a general point of view, Human health would be potentially the most affected impact endpoint category. The category representing the impact on ecosystems, respectively the endpoint category Ecosystems, reached about 50% of the impact level compared to the Human health category. The lowest impact, even negligible, would then be related to the Resources category.

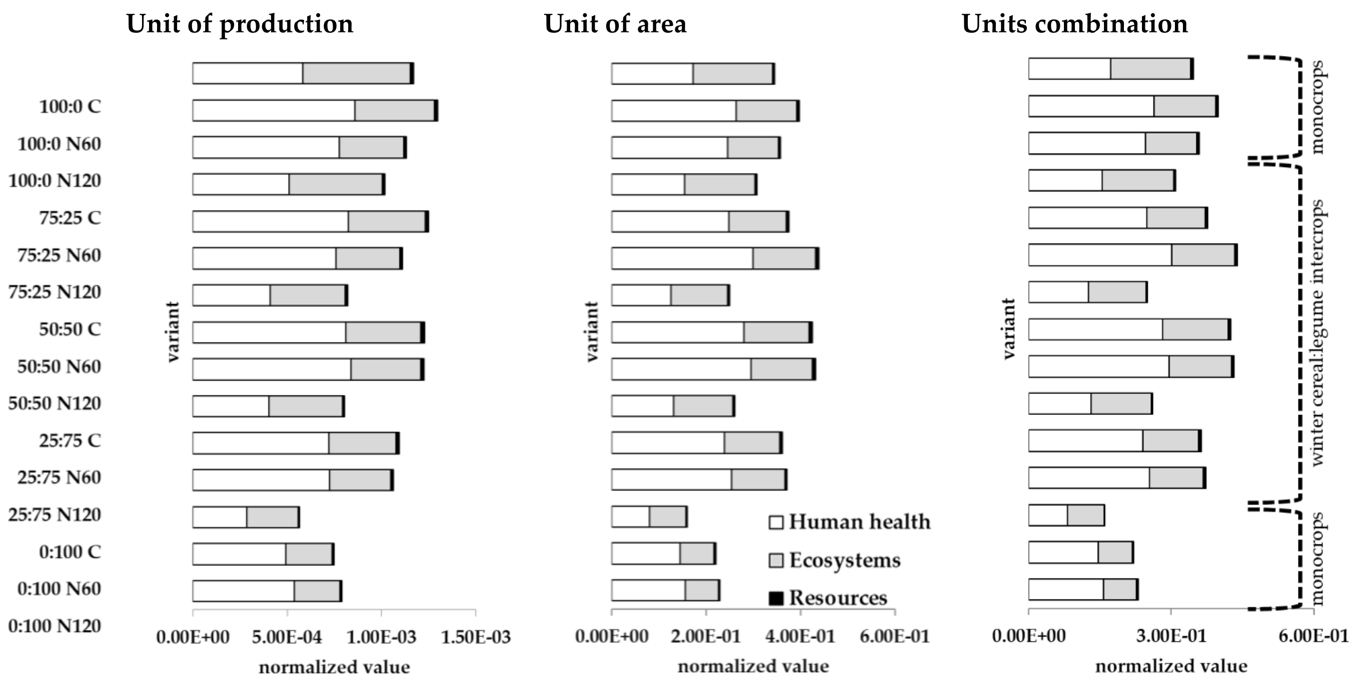

Figure 5. Trends of the environmental impact (the combination of the unit of production; grain N yield respectively, and the unit of area; land demand for generating the same N yield, respectively); C = Control; N60 = variant with input of 60 kg N ha^{-1}; N120 = variant with input of 120 kg N ha^{-1}; Sowing ratios of oat:pea (%:%): 100:0, 75:25, 50:50, 25:75, and 0:100; Based on Normalization model; ReCiPe 2016 Endpoint (H) V1.05/World (2010) H/Official; Endpoint category: Resources, Ecosystems, Human health.

The combination of both FUs showed that all pea monocrops had the lowest environmental impact from the environmental perspective, followed by the unfertilized intercrops. In the case of intercrops, the trend of the lowest environmental impact within the 50:50 C variant was confirmed in the unfertilized variant combining oats and peas. In comparison, fertilized intercrops and oat monocrops had a higher environmental impact. However, the 100:0 N120 variant was one of the treatments with comparatively low environmental impact.

4. Discussion

The results of the agricultural LCA of monocrops and intercrops of oat and pea were affected by the achieved grain N yield. With increasing grain N yields, the impact on the environment generally decreased. However, there should be an even certain balance between inputs and outputs. The level of the environmental impact of the evaluated variants was possible to express through trends connected with their life cycle (results and data interpretation part). The grain N yield level was then also reflected in the size of the area that would potentially be needed to achieve the same amount of grain N yield within all the 15 assessed variants. The smallest land demand (1 ha) was estimated for the highest fertilized pea monocrop (0:100 N120). Pea monocrops and unfertilized intercrops can be considered sustainable cropping systems from the agricultural LCA perspective as monocrops had the highest grain N yields among crop stands, and the grain N yields of unfertilized intercrops were in the range of those of fertilized intercrops. Although oat:pea intercrops could not achieve higher grain yields than corresponding monocrops on the fertile soil of the present study [9,23], in these intercrops, the grain N yields were high even without N fertilization, and thereby the environmental impact associated with N fertilization did not arise. In relation to these aspects, Neugschwandtner and Kaul [4,9] stated that N fertilization significantly increased grain and residue yields of oat but did not affect these parameters in a pea. Oat was the dominant partner in the mixtures, strongly outcompeting pea. Decreasing sowing ratios resulted in lower yields of both crops. Grain and residue yield of oat slightly decreased with decreasing share in the intercrops, whereas pea yields were strongly affected. The harvest index (HI) of pea was reduced by fertilization, whereas that of oat was not affected. Intercropping resulted in a decrease in the HI of both crops.

In the case of oat monocrops, a relatively high N fertilization rate (120 kg N ha^{-1}) was necessary to achieve an adequate grain yield (5752 kg ha^{-1}) or grain N yield (135.4 kg ha^{-1}). The inputs of mineral fertilizers dominantly affected the impact categories climate change, eutrophication, and ecotoxicity. Pea monocrops can be considered as an environmentally friendly option in this assessment. But in two cases (N60 and N120), there was an application of mineral fertilizers, which increased the yield per unit area (according to results presented by Neugschwandtner and Kaul [4,9]) and thus, offset the negative impacts associated with them. From an environmental point of view, a variant without fertilization may be suitable, but it did not provide such high yields per unit area. In addition, it must be taken into account that a pea monocrop can be included only once in a four-year rotation. This leaves variant 50:50 C, which can be considered interesting from the point of view of both yield and environmental aspects. Besides, it is not a monocrop, and the oat can be benefited by its leguminous, N_2-fixing companion, and therefore no additional mineral fertilizer input is required.

The reduction of nutrient supply (especially N) is one of the sustainability strategies [2], as emissions of N in the form of nitrate (NO_3^-) can result in eutrophication of nearby water bodies (freshwater eutrophication) and, ultimately, of the ocean and the sea (marine eutrophication) [13]. Yet, our results have shown for oat and pea monocrops that even high N inputs did not necessarily cause high environmental impacts. Whereas in the case of intercrops, unfertilized variants were much more environmentally friendly than fertilized ones. From this point of view, the use of unfertilized oat:pea intercrops seems an interesting way for achieving high grain N yields with low environmental impact. To achieve high yields, only the benefit from the biological N_2-fixation, which is mediated by pea, was exploited here [24], and LCAs with legume cropping systems should then account for these benefits optimally [25]. According to Pelzer et al. [5] and Naudin et al. [15], it is more environmentally sustainable to grow intercrops than monocrops. Neugschwandtner and Kaul [9] showed that sowing ratio and fertilization affected yield component parameters of oat and pea compared to the corresponding monocrops. Oat in intercrops used available environmental resources for increasing grain and panicles yield beyond those of oat in monocrops, whereas harvest index and grain weight of pea were negatively affected in the intercrops. But the mixing ratio of intercrops is important, e.g., in the study by Monti et al. [26], a 50%:50% cereal:pea combination (based on full monocrop densities) enabled a higher share of the legume on the total intercrop grain yield and provided a well-balanced mixture in drought-prone environments, while with a combination of 100%:50%, not only the legume was highly outcompeted by the companion cereal but also the cereal failed to achieve in several cases similar yields as in the respective monocrop.

The LCA of selected cropping systems was influenced by several factors, one of those was the allocation approach. The choice of allocation approach fundamentally affects the results [27]. For the study, mass allocation, grain N yield, respectively, were used. A similar approach, termed "nitro allocation", was used, for example, by Naudin et al. [15], who also calculated with the land equivalent ratio the unit area needed for achieving similar yields. For functional units related to agricultural LCAs, the combination of production/area/time is recommended [28]. According to Naudin et al. [15], intercrops are an interesting example of the ecological intensification of cropping systems by improving resource use and decreasing environmental impacts for all impact categories considered based on the equivalence of production. This statement was not confirmed in this study because, in several impact categories, intercrops showed higher environmental impacts per unit of production and unit area compared to monocrops (especially those of peas).

Our results showed different values of the environmental impact related to the life cycles of individual crops and variants of cultivation. Fertilizer inputs have had a significant effect, as already shown for agricultural LCA by Hauschild et al. [22], especially when applying the "from cradle to farm gate" approach. For this reason, too, a 50:50 C (unfertilized oat:pea intercrop) was found to be a very interesting variant, with relatively high grain yield and grain N yield and high sustainability potential. In the agricultural LCAs, there is always the question of the field emissions, respectively emissions arising from the N fertilizers production and application. Fertilizer consumption typically contributes to potential impacts due to field emissions into all environmental compartments: air, water, and soil. Reducing the dose of fertilizers used in the agricultural sector has long been considered a key activity in reducing N_2O and NO emissions in particular [29]. N_2O can be considered as the main greenhouse gas, and ecological management systems usually produce less (also CO_2) due to generally lower inputs [30]. More specifically, on-farm use of fertilizers results in NO_3^- leaching to groundwater, emissions of ammonia (NH_3), nitrous oxide (N_2O), and nitrogen oxides (NO_x) to air, contributing to impact categories such as acidification, climate change, and eutrophication [13].

A further approach for reducing the overall environmental impacts is organic production, which is, in particular, decreasing the impact categories related to toxicity. Organic oat production was generally perceived as more environmentally friendly than conventional production. But under organic production, a decrease in the grain yield and, consequently, economic profits can occur [31]. However, the opposite situation was also reported in pea, i.e., organically grown pea could increase environmental impacts. For example, within the Ecoinvent database sources [16], the higher environmental impact (within 18 impact categories) was connected with 1 kg of organically produced pea compared to conventionally grown one due to yield level. There is a risk that the importance of some impact categories may be under or overestimated due to database sources. For a meaningful packaging LCA, good quality of secondary data and reliability of the LCI methods are absolute prerequisites [32].

Pesticides and other plant protection substances are another source of environmental damage, which should be eliminated according to CAP plans [1]. Pesticides may be leached out of the soil for 15 years or more after the end of their use (as in the case of atrazine used in maize crops). Besides, they produce many metabolites, which may have even greater effects than their original parent compound. The intensity of their leaching was strongly connected with precipitation-runoff events [33]. In agricultural LCAs, pesticides mainly affect environmental toxicity categories [34,35], and field emissions that are linked to pesticides can be estimated [36]. In this study, the pesticides were incorporated in the growing cycle of all variants through the Ecoinvent database [16]. So, in the toxicity categories, one of the inputs was chemical protection, i.e., emission from pyrethroid insecticides, deltamethrin specifically, with relatively small impact (<5%). Deltamethrin was considered rapidly degraded with a half-life of 8 to 48 h, depending on the mechanism of distribution into water [37]. The monitoring of pyrethroid compounds and their fate in the environment is important [38].

Together with pesticides, nitrates also leak into the surface and ground waters. Specific outflows of both pollutants were significantly linked with specific water runoff, respectively, with precipitation episodes. The situation in large agricultural and residential catchments can be even worse and more complicated. The results show that it is still important to monitor the fate of pollutants and foreign substances in the environment. There are still many questions about their transport and behaviour, interactions in mixture with other substances, and the impact on human health. Effective ways for reduction of their amount and suitable management must be found. To reduce the outflow of pesticides and fertilizers into surface waters, especially in the agricultural landscape, an establishment of perennial green structures (as meadows, pastures, or perennial forage crops) seems to be a perspective way [33]. Such green structures are among the generally recommended strategies in the field of agrotechnology [39]. In this respect, intercrops can also underpin this function well.

Although the agricultural LCA method has been followed, a few limitations still exist in this study. The LCA results can be influenced by various uncertainties, such as model choices, initial assumptions, and data quality [22]. The data relating to the yield components were adopted from multi-year field experiments [4,9]. But for the comprehensive evaluation of the potential environmental impacts, data corresponding to conditions of the experiment optimally (related to agrotechnical operations parameters, seed production, land occupation, etc.) should be considered, which is also mentioned in the guidelines of the Intergovernmental Panel on Climate Change (IPCC) [40]. In this study, the inputs data were integrated from the libraries of the Ecoinventv3.7.1 database [16], Agri-footprint v4.0 [17], and WFLDB [18]. In relation to the limits, also ecosystem services associated with intercropping, content of soil organic matter (SOM), and benefits of carbon sequestration are not implemented in the life cycle impact assessment method. There is also a need to overcome currently prevailing assumptions for pesticide emissions (leading to overestimation of freshwater ecotoxicity when considering field soil part of the ecosphere) and to consider pesticide residues in crops as a contributor to human toxicity, which is currently mostly missing in LCA studies (leading to underestimation of human toxicity impacts) [41].

5. Conclusions and Prospects

Intercropping is an agricultural practice with the potential to increase the sustainability of agricultural systems. Monocrops and intercrops of oat and pea with different sowing ratios and amounts of calcium ammonium nitrate inputs were assessed by agricultural LCA. The results showed that from an environmental point of view, oat:pea intercrops primarily without N application had a low environmental impact. The results were influenced by the yield level (grain N yield) and cannot be considered constant. However, an unfertilized oat:pea intercrop seemed to be a sustainable and effective cropping system from the perspective of environmental impact assessment, together with pea monocrops.

The results also indicated that intensive cultivation practices, i.e., practices with high fertilizer inputs, do not necessarily confer the highest environmental impact. In this respect, the achieved yield level, the choice of allocation approach, and the functional unit play a dominant role. For agricultural LCA, it is possible to recommend the attributional approach, the multi-output processes for allocation, and the combination of functional units for data interpretation optimally. The study also pointed to the importance of field trials to collect adequate and objective data for LCI. The results of multi-year field experiments should be considered as relevant input data. The results can contribute to the implementation of intercropping in strategic plans, for example, in the area of the Green Deal for Europe.

Nevertheless, further research works, as well as methodological developments, are still needed to keep on improving agricultural LCAs and intercrops:

(1) To focus on intercropping systems, whose high diversity contrasts with the low rate of data available
(2) The modelling of field emissions of nutrients based on combining parameters of soil, climate, biological fixation on nitrogen, and practices
(3) The fate of pesticides in the environment and their environmental impact

Economic aspects evaluation should be performed to develop the intercropping strategy.

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Abbreviations

CAN	calcium ammonium nitrate
CAP	The common agricultural policy
CO_2	carbon dioxide
C variant	control variant
EC	European Commission
eq	equivalent
FU	Functional unit
HI	Harvest index
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	the life cycle assessment
LCI	the life cycle inventory
LER_N	land equivalent ratio of N yields
N	nitrogen
N_2	dinitrogen
NH_3	ammonia

NO	nitric oxide
N_2O	nitrous oxide
NO_3^-	nitrate
NOx	nitrogen oxides
N60 variant	variant with the input of 60 kg N ha^{-1}
N120 variant	variant with the input of 120 kg N ha^{-1}
P	phosphorus
SO_2	sulfur dioxide
tkm	the tonne-kilometer
SOM	soil organic matter
WFLDB	World Food LCA Database
1.4-DB	1.4-dichlorobenzene

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