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Review

Reducing Carbon Footprint of Agriculture. Can Organic Farming Help to Mitigate Climate Change?

Małgorzata Holka [1], Jolanta Kowalska [1,*] and Magdalena Jakubowska [2]

[1] Department of Organic Agriculture and Environmental Protection, Institute of Plant Protection—National Research Institute, Władysława Węgorka 20, 60-318 Poznań, Poland
[2] Department of Monitoring and Signalling of Agrophages, Institute of Plant Protection—National Research Institute, Władysława Węgorka 20, 60-318 Poznań, Poland
* Correspondence: j.kowalska@iorpib.poznan.pl

Abstract: In the face of a changing climate, intensive efforts are needed for limiting the global temperature increase to 1.5 °C. Agricultural production has the potential to play an important role in mitigating climate change. It is necessary to optimize all of the agricultural practices that have high levels of greenhouse gas (GHG) emissions. Among the plant production processes, mineral fertilization is of the greatest importance in the formation of the carbon footprint (CF) of crops. There are many possibilities for reducing GHG emissions from the application of fertilizers. Further benefits in reducing the CF can be obtained through combining tillage treatments, reduced and no-till technologies, and the cultivation of catch crops and leguminous plants. Organic farming has the potential for reducing GHG emissions and improving organic carbon sequestration. This system eliminates synthetic nitrogen fertilizers and thus could lower global agricultural GHG emissions. Organic farming could result in a higher soil organic carbon content compared to non-organic systems. When used together with other environmentally friendly farming practices, significant reductions of GHG emissions can be achieved.

Keywords: plant production systems; environmental effects; greenhouse gas emissions; life cycle assessment

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1. Introduction

Climate protection is an important challenge for the modern world. The concentration of naturally occurring greenhouse gases (GHG) in the atmosphere has increased significantly, thereby contributing to the severity of the greenhouse effect and global warming [1]. According to the recent Intergovernmental Panel on Climate Change (IPCC) report, the average temperature on Earth in the past decade increased by 1.09 °C compared to the reference level from 1850–1900, thus reflecting the average temperature of the so-called pre-industrial period [2]. Natural processes such as solar radiation and volcanic activity contributed only plus or minus 0.1 °C to the overall temperature increase between 1890 and 2010 [3]. It is assumed that GHG emissions from anthropogenic sources, including agricultural activities, are largely responsible for the increase in the global average temperature [4,5]. On the one hand, agriculture contributes to climate change, and on the other hand, it is acutely affected by its effects, especially in plant production. Changes in climatic and weather conditions may contribute to a decrease in the yield of crops, among others, as a result of an increase in the frequency and intensity of extreme weather phenomena, drought, unstable wintering conditions for plants, the intensification of the harmfulness of pests, and the spread of invasive alien species [6–8]. The negative impact of climate change also applies to livestock production, causing heat stress to animals during heat waves, increasing the risk of diseases, and reducing the amount of available animal feed [9]. Climate change affects not only agriculture but also other sectors of the economy and human health. For example, the heatwave events lead to an increase in the demand for electricity and cause the rise of heat-related mortality [10–12].

Due to the growing climate threats, the European Union (EU) has implemented the obligations for the member states concerning the presentation of data on GHG emission values and the systems developed for their reduction [13]. Pursuant to the decision of the European Parliament and the Council in 2013, the agriculture and forestry of the EU countries have been included in the EU climate change policy. The adoption by the EU countries in 2014 of the action plan for the reduction of gaseous emissions in sectors not covered by the European emissions trading system, which also includes agriculture, requires the reduction of GHG emissions by 30% by 2030, compared to the 2005 level [14]. This means that the control of GHG emissions in the agricultural and food sectors should also be regarded as an important instrument in order to support environmental management aimed at mitigating the effects of climate change. The implementation of the EU decision requires actions to improve the methodologies of emission estimation and their harmonization, and the proper selection of agricultural practices that reduce GHG emissions, or increase the removal of GHG, which would be both technically and economically effective. In the context of the global increase in food demand, emission reduction efforts must focus on all links in the food production chain [15,16].

During the COP 21 climate conference in Paris in 2015, a global treaty was ratified in order to combat climate change and to intensify activities and investments necessary for a sustainable low-carbon development. An action plan was defined in order to aim for a global warming limit of less than 2° C and to keep it at 1.5 °C. The Paris Agreement refers to two actions aimed at reducing the concentration of carbon dioxide (CO_2) in the atmosphere: emission reduction, e.g., with new technologies and the development of renewable energy sources and capturing CO_2 from the atmosphere [17]. The necessity to implement the provisions of the Paris Agreement was also emphasized at the COP 26 in 2019 in Glasgow, and in the new European Climate Law adopted in July 2021. The new EU law establishes the GHG reduction target of 55% by 2030 compared to 1990 levels, which takes into account carbon removals from forestry activities and achieving carbon neutrality by 2050 [18]. On 15 December 2021, the European Commission adopted a Communication on Sustainable Carbon Cycles, which is the first step towards a regenerative agriculture [19]. Regenerative agricultural practices lead to reducing the concentration of CO_2 in the atmosphere and absorbing and retaining organic carbon (C) in the soil [20,21]. These practices are used by the so-called carbon agriculture. In many countries, farmers can financially benefit from carrying out carbon farming by earning and selling carbon credits [22].

To meet the requirements of a sustainable development, agriculture should strive to minimize the consumption of energy and natural resources, and thus impose the lowest possible environmental burden. The implementation of the above objectives meets the requirements set for agriculture by the EU under the European Green Deal launched in 2019 [23–25]. The actions agreed upon under the EU From Farm to Fork and the 2030 Biodiversity Strategy include the need to reduce the use of fertilizers by at least 20%, and the use of chemical plant protection products by 50% [26]. The EU action plan for organic farming aims to allocate at least 25% of EU agricultural land to organic farming by 2030 [27].

Organic farming largely excludes the use of agrochemicals such as mineral fertilizers and chemical plant protection products and relies primarily on proper crop rotation and other natural methods of maintaining or increasing the biological activity of the soil, and the proper selection of plant species and varieties, thus it reduces the environmental pollution with chemicals, helps to maintain soil fertility, and preserves the biodiversity while allowing for the production of high-quality food [28]. Since there is an urgent need to prevent global warming, we should thoroughly understand the potential of organic farming in order to reduce GHG emissions from agriculture.

2. Agriculture's Share in Greenhouse Gas Emissions

In 2019, global anthropogenic emissions of greenhouse gases (GHG) reached 54 billion tons of carbon dioxide equivalent (CO_2 eq.), and 52 billion tons of CO_2 eq., with the land use, land-use change, and forestry (LULUCF) sectors emissions not included [29]. Agri-food systems were responsible for 17 billion tons CO_2 eq., of which 7.2 billion tons of CO_2 eq. came from crop and livestock activities within the farm gate, 5.8 billion tons of CO_2 eq. came from pre- and post-production processes including transport, processing, and input manufacturing, and 3.5 billion tons of CO_2 eq. came from land use change processes caused mainly by deforestation and drainage and burning of organic soils (Figure 1). The global agri-food systems GHG emissions increased by 16 % between 1990 and 2019 [29]. The emissions of three types of chemical compounds were the most important: nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2). In terms of single gases, the share of N_2O, CH_4 and CO_2 emissions from these systems accounted for 78%, 53 and 21% of global emissions, respectively.

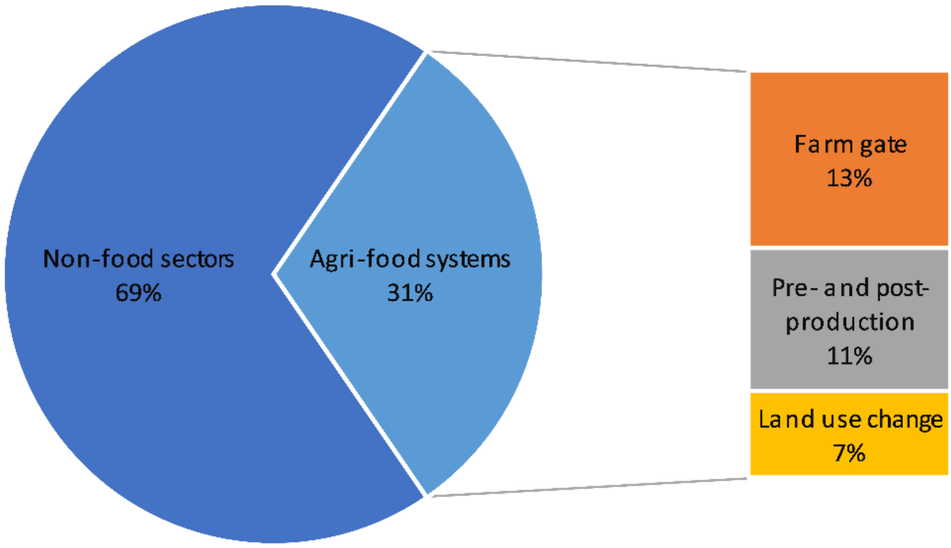

Figure 1. Share of emissions from the agri-food systems and the non-food sector in global greenhouse gas (GHG) emissions in 2019. Source: own elaboration based on data from [29].

According to the European Environment Agency (EEA) data, in 2019, total GHG emissions without LULUCF from the 27 member states of the European Union and the United Kingdom amounted to 4059 million tons of CO_2 eq. [30]. Agriculture produced 427.6 million tons of CO_2 eq., with a share of 10.5% of the total emissions (Figure 2). The emissions from enteric fermentation and agricultural soils were responsible for more than 80% of the total agricultural GHG emissions. Manure management was the third most important source of agricultural emissions, accounting for about 14.6% (Figure 3).

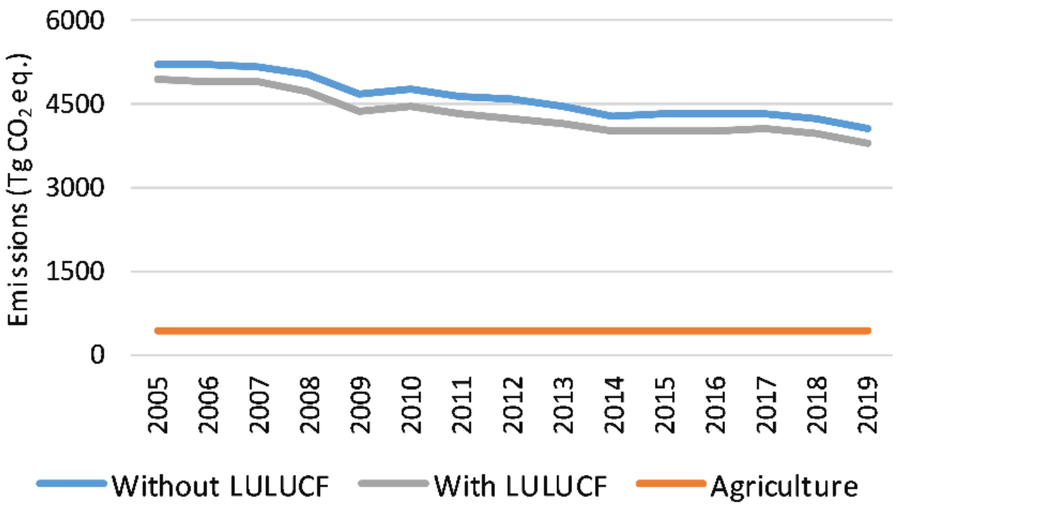

Figure 2. GHG emissions in the European Union (EU) in the years 2005–2019. LULUCF, the land use, land-use change, and forestry. Source: own elaboration based on data from [30].

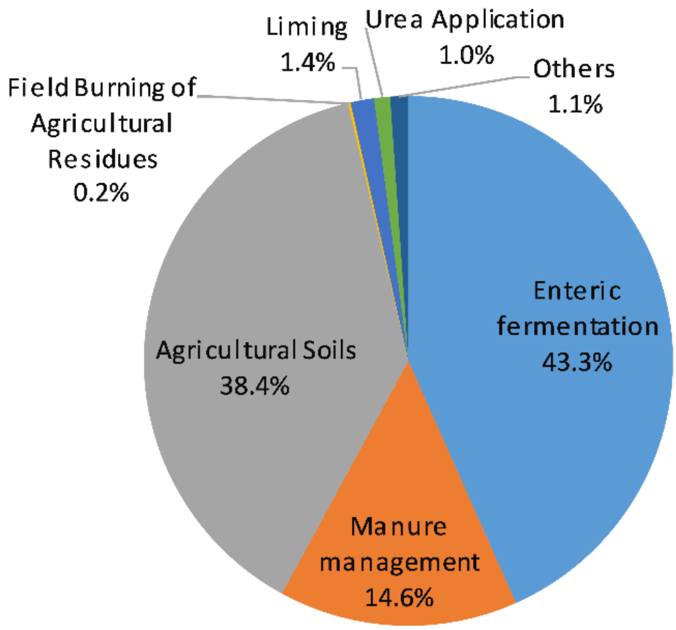

Figure 3. Contribution of different sources of emissions to the total amount of GHG emissions from the EU's agriculture in 2019. Source: own elaboration based on data from [30].

3. Organic Agriculture

The history of modern organic farming in Europe dates back to the first half of the 20th century when the organic movement first began as a reaction to agriculture's growing reliance on chemical inputs [31]. One of its precursors was Rudolf Steiner. In 1924, in Kobierzyce (Koberwitz) near Wrocław, (at the time under German occupation), Steiner gave a series of lectures in which he presented the foundations of biological and dynamic management. He criticized high-yielding agriculture, which came into being at that time, mainly in connection with the invention of artificial fertilizers at the beginning of the 20th century, the developing automotive industry, and the introduction of the first pesticides into agricultural production. Steiner propagated the benefits of fertilizing with livestock manure and compost made from plant and animal waste. He emphasized the need to treat the soil and the plants growing in it as one organism. This is how the so-called biodynamic agriculture was born. According to Steiner's concept, the cultivation of crops should be harmonized with the phases of the moon. Biodynamic agriculture triggered the development of organic agriculture. Albert Howard also contributed to this as in 1921, together with his wife, Gabrielle, he founded the Institute of Plant Industry. Their goal was to improve the traditional Indian farming methods. They popularized the agricultural practices for crop rotation, erosion prevention, and the application of composts and natural fertilizers. As a result, the methods of farming and breeding animals that were environmentally friendly and, at the same time, did not cause loss of productivity were popularized. In the early 1930s, Howard returned to Britain and began promoting organic agriculture and it was then that the first studies on organic agriculture were undertaken. The global economic crisis in the 1930s made it necessary to increase the productivity of agriculture in order to ensure greater food supplies. This has contributed to the increase of the intensity of agricultural production, which uses increasing amounts of artificial fertilizers and pesticides. There was little interest in organic agriculture, but the awareness of the environmental dangers related to the production and use of large amounts of industrial means of production in agriculture was slowly increasing. In the 1970s, in Western Europe and in the USA, the interest in farming methods such as biodynamic, organic, and ecological agriculture arose. It is assumed that after the introduction of the concept of organic agriculture in the years 1900–1972, the phase of development of organic agriculture began. In 1972, the International Federation of Organic Agriculture Movements (IFOAM) was founded. This organization plays an important role in setting the standards of organic agriculture and promoting and disseminating organic farming methods. According to the IFOAM, organic agriculture has four principles: health, ecology, fairness, and care. It defines organic agriculture as: ”a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic Agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and good quality of life for all involved” [32].

Currently, organic agriculture is developing rapidly, both globally and in the European Union (EU) (Figure 4). From 2000 to 2020, the total organic agricultural area including the area under conversion and the certified area increased fivefold in the world and almost quadrupled in the EU. In 2020, organic farming in the world occupied approximately 75 million hectares of agricultural land, thereby constituting approximately 1.5% of the total agricultural land. The EU’s total organic agricultural area reached 15 million hectares, with a share of 9.2% of the total agricultural area. In the structure of the EU’s total organic agricultural area, arable land had a share of 46% (6.8 million hectares), followed by permanent grassland (meadows and pastures) with a share of 42%, and permanent crops (fruit trees and berries, olive groves and vineyards) with a share of 12% [33]. There is still scope for further expansion of organic agriculture. Achieving 25% of the EU ‘s organic land, according to the EU’s action plan, would require triple its organic land area between 2019 and 2030.

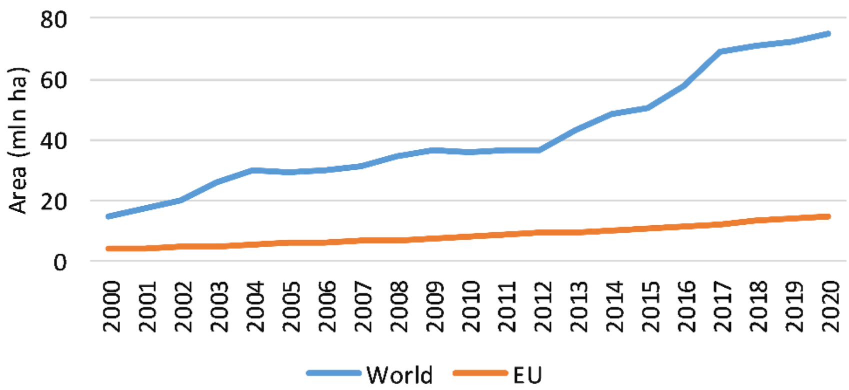

Figure 4. Organic agricultural land in the world and the European Union (EU) in the years 2000–2020. Source: own elaboration based on data from [34].

The trends in healthy eating styles are driving the growing interest in organic food [35]. Consumers are in favor of choosing "natural" products and perceive products from high-input, intensive agriculture as undesirable. Another factor influencing the development of the organic products market is society's interest in environmental protection. Therefore, it is important to develop environmental standards that distinguish environmentally friendly production methods and support environmentally conscious consumers in their market decisions.

4. Evaluation of Greenhouse Gas Emissions in the Life Cycle Assessment

One of the tools enabling the comprehensive estimation of the ecological effects of food production is the life cycle assessment (LCA) [36,37]. Originally, this method was developed for industry [38]. Currently, studies on the environmental assessment of agricultural production and food processing using the LCA are being developed around the world [39–41]. The LCA allows for a broad compilation and comparison of the environmental impact of the processes and products throughout the production cycle [42].

Carrying out the LCA is crucial for obtaining the so-called Environmental Product Declaration (EPD) for the product [43]. It is a document that presents a series of data on the resource consumption and environmental impacts in relation to the product's life cycle, namely:

- Consumption of renewable sources (biomass, energy);
- Consumption of non-renewable resources (mineral resources, fossil fuels);
- Water consumption;
- Amounts of waste for recycling;
- Environmental impact category indicators (acidification potential, eutrophication potential, photooxidant formation potential);
- Environmental footprints (carbon footprint, ecological footprint, water footprint).

In response to the sensitivity to the problem of climate change, many social groups in developed countries are creating product labelling systems informing about the carbon footprint (CF) [44,45]. Placing environmental labels on products and presenting information about the LCA results, is designed to provide consumers with accurate information about the environmental effects of products, facilitating their conscious choice, as well as introducing the factor of competition between different manufacturers of similar products. Food producers, being under pressure from environmental policies and shaping the ecological criteria for food selection by consumers, are willing to modify agricultural practices that would reduce the impact of agriculture on the environment. The environmental information on the CF of a product is based on the LCA test procedures. The results of these tests must be obtained in accordance with the rules of type III EPD. Establishing an environmental declaration includes declaration preparation, verification of assessment methods, and certification. The condition for qualifying a product to be awarded this mark is the preparation of a report confirming the measurement of the CF based on the internationally recognized methods e.g., British Technical Specification PAS2050: 2011 [46]. This label is used in the USA, Canada, Australia, New Zealand, and many EU countries. A common system for labeling the CF in the Nordic countries is the Climate Declaration. It represents the climate change impact category index developed in the EPD. The declaration provides information on the total GHG emissions and, separately, for each stage of the life cycle of the product, in kg of CO_2 eq. per functional unit of the product [47].

4.1. Life Cycle Assessment Framework

The life cycle assessment (LCA) is a standardized method for assessing the environmental aspects and potential impacts associated with all of the stages of the life cycle of a product, process, or service [48,49]. According to the guidelines of the International Organization for Standardization (ISO), it is carried out in four phases [50,51]:

1. Goal and scope definition;
2. Life cycle inventory;
3. Life cycle impact assessment;
4. Interpretation.

In the first phase (goal and scope definition), the system boundaries and the functional unit are defined. The system boundaries define the life cycle processes that belong to the analyzed system. A functional unit is a quantitative description of the function of the system.

The life cycle inventory (LCI) is the phase of identification and quantification of all flows between the environment and the analyzed system, i.e., energy and raw materials consumption as well as emissions to air, water, soil, and waste. The stocktaking of flows is made with reference to a predetermined functional unit. Data collection and system modelling must follow the defined purpose and scope of the research.

The life cycle impact assessment (LCIA) aims to establish the links between a product or process and its potential environmental impacts. The input and output data of the flows reported in the LCI are converted into the values of the category indicators.

The impact assessment is performed in several steps:

1. Selecting the impact category;
2. Classification—assigning the LCI results to the impact category;
3. Characterization—calculation of the category indicators;
4. Normalization—calculating the value of a category indicator against the reference information;
5. Grouping—the sorting or ranking of indicators;
6. Weighing—assigning weights (importance) to the potential influences;
7. Evaluation and reporting of the LCIA results.

The interpretation can take place at any stage of the LCA. It involves identifying, checking, and evaluating the information from the LCI and LCIA results. The interpretation aims to analyze results, to formulate conclusions, to explain limitations, and to make recommendations based on the results of previous LCA stages, and ensure an understandable and complete presentation of the results in line with the purpose and scope of the study.

4.2. Carbon Footprint

The carbon footprint (CF) approach is used in order to assess the greenhouse gas (GHG) emissions related to various economic processes and products [52]. It is defined as the GHG emission balance over the entire life cycle of a product or process. The characterization parameter for this environmental impact category (climate change) is the global warming potential.

The CF is expressed as the sum of the products of the greenhouse effect for a substance and the amount of emissions of the 'i-th' substance. It covers both direct and indirect emissions that are generated throughout the entire life cycle of a product. It is presented in the form of quantifiable indicators: as GHG emissions in kg of carbon dioxide equivalent (CO_2 eq.) per kg of product or per area unit per year. It is most often calculated for the 100-year period.

$$\mathrm{CF} = \sum_i m_i \cdot GWP_{a,i}, \quad (1)$$

where: m_i—the quantity of the substance '*i*' emitted (in kg per functional unit), $GWP_{a,i}$—the global warming potential for a substance '*i*' over a time horizon a (expressed relative to CO_2 per kg '*i*').

The analysis of the GHG emissions from plant production using the LCA methodology can be performed by examining the CF of a product or process from the extraction of raw materials and energy to the production within the system boundaries from 'cradle-to-farm-gate' and 'gate-to-gate' as shown in Figure 5, and by analyzing the entire life cycle of a product or process, including product disposal ('cradle-to-grave').

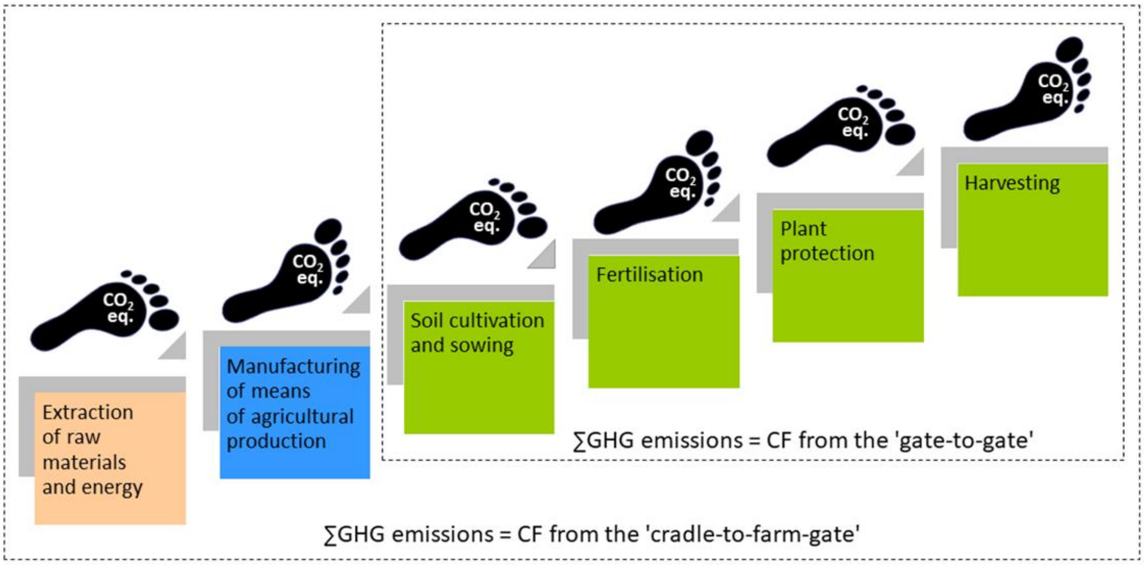

Figure 5. System boundaries of the carbon footprint (CF) estimation for the plant production systems. Source: own elaboration.

The CF of an agricultural product or process can be used to inform producers about GHG emissions related to product manufacturing, to develop and apply GHG emission management strategies at different stages of the product life cycle, to identify the potential GHG mitigation opportunities along the supply chain, to monitor the progress in reducing GHG emissions over time, and to assist consumers in choosing products with the least impact on climate change [52,53].

5. Driving Factors of the GHG Emissions Intensity in Crop Production

5.1. Fertilization

Many studies showed that fertilization has a large impact on the size of the carbon footprint (CF) of plant production [54,55]. The use of nitrogen (N) fertilizers in plant cultivation is accompanied by the emission of gaseous N compounds. Nitrogen, being a chemically reactive compound, has a global warming effect. In its chemical form, as nitrous oxide (N_2O), it is, next to carbon dioxide (CO_2) and methane (CH_4), the third most important component of greenhouse gases (GHG) in agriculture [56,57]. The importance of the influence of N_2O in the creation of the greenhouse effect is emphasized by its high index of global warming potential (GWP), which is 265. For comparison, this index for CH_4 and CO_2 is 28 and 1, respectively [58]. This index is a measure of how much energy will be consumed by the emission of 1 ton of gas in a given period in relation to the emission of 1 ton of CO_2. The greater value of the GWP indicates that a given gas heats the Earth more than the other two. Another important N-containing chemical is ammonia (NH_3). It has a large eutrophication and acidification potential. Large amounts of NH_3 are emitted into the atmosphere from N fertilizers, especially those containing N in the form of urea and ammonium, and from animal feces, which poses a serious threat to the environment. In order to reduce N_2O emissions, as well as to counteract the effects of water pollution with nitrates, eutrophication, and acidification of the environment by gaseous NH_3 emissions, it is important to strive to create an as closed as possible N cycle in the farm [59]. Taking a holistic view and identifying the critical places in the N cycle of the farm, leads to an improvement in the efficiency of the N use and the reduction of N losses in agricultural production [60]. In the literature, it is noted that organic farming leads to closing the nutrient cycle on the farm and minimizing nutrient losses [57,61].

Fertilization technologies have an impact on the increase of the efficiency of N use. In the correct fertilization technology, the most important role is played by strip fertilization, the appropriate date of the fertilization application, distribution of the doses, adjustment of the fertilization level to the spatial differentiation of the soil conditions, and the abundance of nutrients in the soil [62]. In the cultivation of rape and wheat, the efficiency of N use may increase by about 10% with the appropriate fertilization technologies [63].

N_2O emissions from N fertilization can vary between 0.77% and 1.25% from the N applied both for synthetic and organic fertilizers [64,65]. According to the Intergovernmental Panel on Climate Change (IPCC) [56], the default emission factor for organic amendments is 1% with an uncertainty range between 0.1% and 1.8%. As a result of the use of natural fertilizers on soils that are poor in organic matter, it is possible to increase N_2O emissions due to the stimulation of the microbial activity of the soil (due to the availability of carbon compounds), which leads to a reduction in oxygen content in the soil and the formation of anaerobic conditions conducive to the process of denitrification [66]. Other factors that stimulate N_2O emissions include the application of natural fertilizers shortly before rainfall, soil pH < 6, and the depth of the introduction of the natural fertilizers into the soil. Mixing the manure with the soil at a shallow depth leads to higher N_2O emissions than with a deep incorporation of the manure [67]. In the case of the soil injection of slurry, the N losses from the slurry amount to about 9% (4.4% of NH_3 and 4.7% of nitrate (NO_3)), while during the spreading of slurry on the field surface, the N losses reach 27.1% (20.5% of NH_3 and 6.6% of NO_3) [68].

In soil, N_2O is formed as a result of two microbiological processes: nitrification, i.e., the oxidation of ammonium to nitrates, and denitrification - the reduction of nitrates to molecular N and N_2O. The intensity of N_2O emissions depends mainly on the availability of mineral N forms. The maximum amount of N_2O emissions is observed in the period of 2-3 weeks after the sowing of N fertilizers. The N_2O emissions from farmland can be reduced by using fertilizers with lower emission factors. The use of nitrate fertilizers results in lower emissions of N compounds compared to the emissions from the use of urea-based fertilizers [69,70]. The size of the emission stream also depends on many other factors, such as temperature, soil moisture, fertilizer dose, and the type of crop [71].

The rapid development of crops, during which plants take up NO_3 intensively, reduces the emission of N_2O due to the limitation of the availability of mineral N in the soil. The direct N gas losses from the fields also include NH_3 emissions into the atmosphere. The emitted NH_3 is an indirect source of N_2O emissions. After this gas is deposited on the soil surface, it undergoes nitrification. The reduction of the NH_3 gas losses during the application of fertilizers is therefore an activity conducive to the reduction of N_2O emissions in agriculture. The use of a fertilizer urea causes high N losses, amounting to almost 25 %. Its losses in the form of ammonia can be even greater than 50% [72]. The reduction of N losses from urea is possible by mixing it quickly with the soil after sowing and avoiding sowing in conditions of high air temperatures, shortly after liming, after applying slurry and manure, and on plant residues in the field [60].

GHG emissions from the production of fertilizers are the second source of emissions from the fertilization process in the entire cycle of plant production, following GHG emissions from the fields [73]. The emissions at the stage of production of mineral fertilizers depend on the efficiency of the synthesis of N compounds, the demand for natural gas as well as heat and electricity. The technological progress in the production of fertilizers leads to a systematic reduction of these emissions. The literature reports that GHG emissions per 1 ton of N are between 2.6 and 9.7 t CO_2 eq. [74]. The conversion of NH_3, which is the initial form of mineral N in the Haber–Bosch process, into other chemical compounds such as ammonium nitrate and urea is energy-consuming. Approximately 70-80% of the production costs of N fertilizers using this method is natural gas [75]. Large energy inputs in the fertilizer production stage increase GHG emissions [76].

The use of natural N fixation processes by cultivating N-fixing plants can reduce the demands for mineral N fertilizers and thus contribute to lower GHG emissions [77]. Leguminous plants living in symbiosis with papillary bacteria can use molecular N and convert it into NH_3 without emitting CO_2 into the atmosphere. A significant part of the N assimilated by symbiotic bacteria feeds the soil in the form of crop residues and root mass. In the case of leguminous plants, the amount of N remaining in the soil after their harvest ranges from 40 to 50% [78]. Therefore, the presence of leguminous plants in cultivation systems reduces the consumption of mineral N fertilizers. An additional benefit is the increase in the productivity of successive crops in rotation. Improving the efficiency of the use of N from legumes by other plants requires a better understanding of the mineralization process of post-harvest remains of leguminous plants and the synchronization of the pace of their decomposition with the rhythm of the N uptake by the succeeding plant. Increasing the share of the symbiotically bound N in the pool of generally available N in agricultural systems depends on the presence of leguminous plants in rotation. Thus, thanks to the cultivation of legumes, the dependence of agriculture on mineral N fertilizers is reduced and the CF of agricultural products will be reduced as well. Leguminous plants, due to their beneficial influence on soil properties by limiting the use of fertilizers and plant protection products, are in line with the pro-environmental trend in agriculture. Their cultivation is especially appreciated in organic farming.

5.2. Plant Protection

The life cycle of greenhouse gas (GHG) emissions from plant protection is mainly associated with the processes of the production of plant protection products, and fuel combustion and agriculture machinery used during the plant protection treatments on fields. Plant protection has a smaller contribution to the formation of carbon footprints (CFs) than the fertilization process [79]. It is worth noting that by obtaining a higher yield thanks to the effective protection of plants against the activity of pests, allows for obtaining a lower CF per product unit, e.g., a kg of wheat grain. The use of chemical plant protection products is highly effective, but due to the dispersion of active substances in the environment, it causes the risk of contamination of waters and soils, as well as their bioaccumulation in living organisms [80]. In order to limit these effects, on 1 January 2014, the obligation to apply the principles of integrated pest management (IPM) was introduced in the European Union (EU) [81]. According to the IPM plan, before applying any chemical plant protection, all available biological, physical, and other non-chemical methods should be used. It is important to use crop rotation, use the right crop varieties, adhere to the optimal deadlines, properagrotechnics, proper fertilization, and prevention of the spread of pests. Due to the increased species diversity of plants in crop rotation, the development of weeds is under pressure from many agronomic factors, i.e., the timing of cultivation treatments, different soil cultivation systems, intensity of cultivation treatments, a wider spectrum of active substances, the type and amount of crop residues, different plant morphology, and the dynamics of nutrient uptake from the soil. The use of crop rotation consequently reduces the weed infestation of crops and the use of herbicides and promotes a greater crop productivity [77]. In the experimental system of cereal cultivation in rotation with rape, this was characterized by a reduction in the dose of herbicides by 50%, the sowing of high-yielding cultivars, and an increased seeding density. A comparable effectiveness of weed control was obtained in relation to the less intensive cultivation of crops in monoculture [82]. Despite the binding IPM, the chemical method is the dominant form of plant protection in the conventional agricultural production system [83]. In turn, the plant protection in organic farming is based on non-chemical methods.

5.3. Energy and Machinery Use

The combustion of fossil fuels is the main form of on-farm energy use. Fossil fuels are used in processes related to the production of agricultural machinery, fertilizers, plant protection products, and transportation. The energy use in farming systems depends on many factors, the most important of which are soil cultivation, crop rotation, and production intensity. The mechanical cultivation treatments affect greenhouse gas (GHG) emissions both directly and indirectly [84,85].

Direct emissions mainly depend on the fuel consumption of tractors and self-propelled machinery. The amount of combustion depends on the power of the tractor, soil compactness, degree of scaling, depth and working width of the machines. It is assumed that the demand for fuel increases with the increase of the depth of the cultivation and the speed of the treatment [86]. The average fuel consumption for plowing is around 24 l per ha [87,88]. In Croatia, the fuel consumption in conventional tillage ranged from 48.1 l per ha in barley to 60.99 l per ha in maize. It was assumed that the combustion of 1.0 l of diesel oil generates 2.75 kg CO_2, thus the carbon dioxide (CO_2) emissions from the fuel consumption in conventional tillage ranged from 132.36 kg CO_2 per ha in barley to 167.72 kg CO_2 per ha in maize. In turn, the use of reduced tilling and the direct sowing allowed for fuel savings and limited the CO_2 emissions by 35.3–42.9% and by 87.8–88.1%, respectively [89]. In the cultivation of winter oilseed rape in Lithuanian conditions, the amount of diesel oil used for deep plowing was 23.6 l per ha. The great savings in fuel consumption occurred both in direct sowing and strip tilling. In direct sowing, the fuel consumption was 3.8 times lower and amounted to 6.2 l per ha, while in strip tilling and sowing, the amount of fuel used was 3.7 times lower and amounted to 6.4 l per ha. The assessment of the GHG emissions showed that using no-till technologies reduced emissions by 21.2% compared with technologies based on deep plowing [90].

In organic farming, the indirect energy consumption is lower due to the lack of mineral fertilization and the narrow spectrum of plant protection products allowed in organic farming [91]. The beneficial effect of reducing the N fertilization is the reduction of the indirect energy consumption, which is also associated with the reduction of the carbon footprint (CF) of plant products. In the organic production system, the efficiency of the energy consumption and the energy value of the crops in relation to the energy value of inputs is higher than in the conventional farming system [92–95].

5.4. Carbon Sequestration

In the literature, agricultural production is presented as a source of greenhouse gas (GHG) emissions. The potential for organic carbon (C) sequestration throughout the farm area is often overlooked. It should be highlighted that the proper management of soil organic matter (SOM) in an agricultural production system is an important element in reducing the greenhouse effect. The degradation of the SOM increases GHG emissions. Maintaining a constant inflow of the organic matter to the soil in the form of crop residues, root mass, and natural fertilizers is necessary in order to counteract the processes of SOM degradation and thus the loss of C, in the form of carbon dioxide (CO_2) emissions, into the atmosphere [85,96].

Leaving large amounts of post-harvest residues on the soil surface in conservation tillage contributes to the accumulation of organic C, reducing fuel consumption and thus reducing GHG emissions from fuel combustion, reducing the risk of water and wind erosion, increasing the stability of soil aggregates, water retention and greater soil water capacity, and the preservation of biodiversity in the subsurface layers of soils [97]. Conservation tillage combined with straw mulch is a practice intended for drought resistance. The use of mulch from cover crops keeps the soil covered while increasing the amount of organic matter in the soil. While all species of cover crops provide many benefits, some species are better than others, depending on specific objectives, such as preventing erosion or improving soil quality. Therefore, growing cover crop mixes, for example grasses and legumes, serve a variety of purposes at the same time [98].

The cultivation of deep-rooted plants, such as perennial legumes and grasses, is essential for the accumulation of organic C in the soil [99]. It is also beneficial to deeply mix the soil with harvest residues. The plant material then slowly decomposes due to the limited microbiological activity in the border zone of the arable layer and subsoil. Limiting the C losses by slowing down the rate of organic matter mineralization is a factor in the protection of its resources in soils. The increase in the SOM might stop after 20–30 years of agricultural practices aimed at increasing the organic matter content [100–102]. After this time, the content of organic matter stabilizes, thereby showing no tendency for its further accumulation in the soil [103].

The increase in the SOM is achieved by cultivating catch crops [104,105]. They also fulfill many additional functions consisting in limiting the leaching of nitrates (NO_3) and weed infestation, and the assimilation of atmospheric nitrogen in the case of sowing catch crops with leguminous crops.

An effective way to improve the resources of the SOM is to increase the productivity of crops, thereby increasing the amount of crop residues. Annual plants that leave large amounts of crop residues in the field, such as grain maize, have a beneficial effect on the growth of organic matter. Large amounts of crop residues are also provided by the cultivation of perennial plants on arable land, e.g., grasses or papilionaceous plants. The transition from the cultivation of cereals in monoculture to their cultivation in rotation with the share of grasses on arable land resulted in an increase in the amount of organic C at the rate of 1% per year (0.5 t C per ha per year) under average European conditions [106].

Farms with a plant production have the potential for influencing the formation of SOM resources primarily by quantitatively increasing the mass of plant residues, while in farms specializing in livestock production, natural fertilizers are of key importance. The main factors controlling the accumulation and decomposition of the SOM, in addition to the type of agricultural systems and the type of soil, are climatic conditions. Forecasted temperature increases, as well as the frequency and amount of rainfall, may have a negative impact on the intensity of the organic matter decomposition process. Farms specializing in plant production are the most likely to show the dynamics of decline. The protection of organic matter resources will be the greatest challenge for maintaining the productive potential of soils on plant production farms [107].

Reducing the number of cultivation treatments and their intensity contributes to the reduction of C losses in arable soils. The cultivation treatments accelerate the decomposition of the organic matter by breaking down soil aggregates and increasing the supply of oxygen to the deeper layers of the soil. Plowing has the most adverse effect on the degradation of the SOM. In many regions of the world, there have been long established practices of limiting the use of the plow, cultivating crops at a shallow working depth of machines, less intensive mixing of the soil, and leaving the greater part of crop residues on the fields. Based on field studies conducted independently in many places around the world, it was estimated that direct sowing for a period of 20 years caused an increase in C (in the 0-30 cm layer) on average by 10-20%, compared to the previous period, in which plowing was used [108]. In the USA, the annual rate of organic C accumulation in no-till fields was about 0.34 t per ha. Due to the lower intensity of the use of tilling machines, a reduction of GHG emissions in reduced tillage and direct sowing was achieved by 40 and 70%, respectively, compared to conventional tillage [109]. There is a particular risk of CO_2 emissions in the cultivation of organic soils. The annual rate of gaseous CO_2 losses may vary between 10 and 20 t per ha, i.e., 2.7–5.5 t C per ha [110]. One of the solutions offering mitigation of high CO_2 emissions in areas with this type of soil is wetland restoration. However, the negative increase in CH_4 emissions from wetlands should be taken into account in the overall GHG balancing [111].

According to [112] the content of the SOM in organic farming increased to 1.90 t C per ha per year, while in the conventional system it was degrading by 1.24 t C per ha per year. Other authors also reported a higher SOM in organic farming [113].

One of the solutions in mitigating climate change is agroforestry. This system consists in integrating woody plants with arable crops or with permanent land and livestock production, allowing to lead a profitable agricultural production in a sustainable and environmentally friendly manner [114,115]. The role of agroforestry in counteracting climate change was highlighted during the 24th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP24) in Katowice in 2018.

In Poland, the amount of CO_2 absorbed by forests was 771 kg CO_2 per ha [116]. Other studies demonstrated an increase in C sequestration as a result of changing the use of arable land into permanent grassland by 19%, while the afforestation of arable land increased the C accumulation by 53% [117]. In the short rotation coppices, an increase in the C content of the SOM was noted at 0.3 t C per ha per year, which corresponds to 1.1 t CO_2 per ha per year [118]. It has been reported that midfield shelterbelts and boundary strips contributed to an increase in the accumulation of C in soil and the SOM, by 1.3% and 1.2% per year, respectively. The accumulation of C by trees (disregarding the root systems) increases its content by about 2.8 t C per ha per year [119].

6. Carbon Footprint of Organic Farming

Raising awareness of climate change has triggered a large amount of research into comparing greenhouse gas (GHG) emissions of the various agricultural production systems in Europe (Table 1). Organic farming is considered as the environmentally friendly system and is in line with the concept of a sustainable agricultural development [120,121]. However, in the literature, studies using the life cycle assessment (LCA) methodology in the production of field crops in the organic and conventional systems, there are divergent opinions on the environmental aspects of the production of field crops in these two systems. Several studies showed that organic farming has the potential to reduce the carbon footprint (CF) of plant production, while the other reported contradictory results [95,104,122].

Table 1. Examples of goals, functional units and system boundaries in life cycle assessment (LCA) studies, taking into account the organic farming under European conditions.

Goal	Functional units	System boundary	Country	References
Assessment of the carbon footprint of pumpkin production	1 ha of cultivated land, 1 kg of product	Cradle-to-grave	Germany	[65]
Assessment of the carbon footprint of wheat farming and whole meal bread production	1 ha of wheat cultivation, 1 kg of bread	Cradle-to-gate	Italy	[123]
Assessment of environmental impacts of wheat cultivation systems	1 ha of wheat cultivation, 1 kg of grain	Cradle-to-gate	Belgium	[124]
Assessment of the environmental burdens of producing bread wheat, oilseed rape, and potatoes	1 kg of product	Cradle-to-gate	England, Wales	[125]
Assessment of the environmental impacts of lettuce cultivation systems	1 ha of lettuce cultivation, 1 t of lettuce produced	Cradle-to-gate	Greece	[122]
Assessment of the environmental impacts of eggplant production	1000 m^2 of cultivation, 1 t of marketable eggplant fruit yield	Cradle-to-gate	Greece	[126]

Assessment of the greenhouse gas emissions from herbaceous cropping systems	1 ha of cultivation, 1 kg of product	Cradle-to-gate	Spain	[127]
Assessment of the carbon footprint of conventional and organic crops production	1 ha of land	Cradle-to-gate	Slovenia	[128]
Assessment of the carbon footprint of crops from different organic and conventional arable crop rotations	1 ha of land, 1 kg of crop	Cradle-to-gate	Denmark	[104]
Assessment of the environmental impacts of organic and conventional leek production	1 ha of leek cultivation, 1 kg of leek	Cradle-to-gate	Belgium	[129]
Assessment of the carbon footprint of potatoes in different cultivation systems	1 ha of cultivated land, 1 kg of potatoes	Cradle-to-gate	Italy	[130]
Assessment of the environmental performance of pepper cultivation systems	1 t of marketable pepper fruits	Cradle-to-gate	Greece	[131]
Assessment of the greenhouse gas emissions from potato cultivation systems	1 kg of potatoes	Cradle-to-gate	Czech Republic	[132]
Assessment of the greenhouse gas emissions from plant production in different farming systems	1 kg of product	Cradle-to-gate	Czech Republic	[133]

In the conventional production system, the use of large amounts of agrochemicals and agricultural machinery allows for the achievement of high crop yields. Organic farming is usually characterized by using lower inputs, as well as obtaining lower crop yields. Because of that, the environmental impacts of organic farming per unit of land are usually lower compared with the conventional production. In turn, with regards to the unit of product, the environmental impacts of organic farming may be greater [41,124,134].

Foteinis and Chatzisymeon [122] compared the environmental impacts of organic and conventional open-field lettuce cultivation systems in Northern Greece using the LCA methodology. With regards to one hectare as a functional unit, the results of a cradle-to-gate analysis showed that the GHG emissions from organic farming measured as carbon dioxide equivalents (CO_2 eq.) and amounted to 1603 kg CO_2 eq., while the conventional system was responsible for 1893 kg CO_2 eq. The main emission sources were irrigation and fertilization.

Under similar conditions in Central Europe, GHG emissions from the organic production of potatoes amounted to 0.126 kg CO_2 eq. per one kilogram of potatoes and were lower by 18% in comparison with the conventional production [132].

In the environmental impact assessment of organic and conventional leek production systems in Belgium, it was found that the global warming potential (GWP) per one square metre of land in organic farming amounted to 0.12 kg CO_2 eq. and was three times lower than in the conventional system (0.36 kg CO_2 eq.) Considering the functional unit of one kilogram, it was noted that the GWP was also significantly lower in the organic production (0.044 kg CO_2 eq.) compared with the conventional system (0.094 kg CO_2 eq.) [129].

The assessment of GHG emissions in the entire cycle of organic and integrated olive-growing systems in Italy showed a greater environmental impact of organic farming because of the higher number of mechanical operations e.g., for plant protection [135].

In Spain, the GWP in organic and conventional herbaceous cropping systems was compared. With regards to both functional units of 1 ha and 1 kg, the organic system significantly contributed to the reduction of GHG emissions (in the ranges of 35.9-64.7% and 16.3-41.9%, respectively) [127].

It should be emphasized that there are some limitations in the analyses of organic farming by the LCA. According to [136], the LCA studies in agricultural production often overlook important factors such as soil quality, the use of plant protection products, and the impact on the biodiversity which can lead to masking some of the benefits of organic farming. The results of the LCA of organic farming can vary widely because of the use of different assumptions in studies, e.g., system boundaries, functional units, life cycle impact assessment methods, and allocation methods [95]. Some authors recommend that the assessment of the CF of crops should take into account the whole crop rotation and carbon changes [104,137]. Various methodological approaches are proposed in order to include these aspects in the LCA analyses of plant production. However, due to the lack of clear methodology guidelines, these are neglected in studies on organic farming.

Montemayor et al. [138] stated that some aspects in life cycle inventory of organic farming should be improved. There is often a lack of background inventory datasets for the manufacturing of organic fertilizers and plant protection products which are used in organic farming. In existing LCA databases such as ecoinvent [139] and AGRYBALYSE [140], there are no datasets corresponding to many botanical, microbiologically derived, and mineral-based products. The use of "Pesticide unspecified" datasets because of the lack of available datasets for certain plant protection products, is insufficient for obtaining reliable and accurate LCA results. Fertilizer inventory improvements are also needed. The authors also highlighted that the modelling of field emissions from fertilization and plant protection requires more attention.

7. Conclusions

The carbon footprint (CF) is increasing in importance now that agriculture has been included in the European Union's emission reduction program. It is an important tool for assessing the quantitative changes in greenhouse gas emissions (GHG) as a result of the application of various mitigating measures in agricultural production.

There are many agricultural practices in agricultural production that generate potentially large GHG emissions. Most often, they are characterized by a high consumption of fossil fuels and energy. From among the plant production processes, the mineral fertilization is of the greatest importance in shaping the CF. Currently, there are a number of possibilities in order to reduce GHG emissions by taking measures to increase the efficiency of fertilization. The available solutions in this area include fertilization optimization, appropriate dates and methods of fertilizer application as well as new forms of fertilizers. Further benefits in reducing the CF can be obtained through the aggregation of tilling treatments and simplified tilling systems.

An important strategy in order to reduce GHG emissions in agriculture is to increase the amount of soil organic matter (SOM). The current level of the inflow of crop residues and the plow tilling system are only sufficient in order to maintain the current resources of organic matter. The carbon dioxide (CO_2) retention potential in soils can be increased using non-inversion tilling, the use of catch crops, the abandonment of crop residues in the field, and the cultivation of grasses and legumes on arable land. A very important element of the emission management at the farm level, apart from technological solutions, is the shaping of the appropriate spatial structures of the landscape in a longer period based on a midfield forest cover. The absorption of CO_2 depends not only on the area of forests and the increase in forest resources, but also by supporting the processes of accumulation of organic matter in arable soils. It is therefore important for agriculture to play an active role in sequestering carbon (C) in soils in order to mitigate the effects of climate change.

In organic farming, an absence of mineral fertilizers allows for the avoidance of significant GHG emissions from the application of fertilizers on the field as well as from fertilizer production. This system leads to building SOM and sequestering atmospheric C. It can be concluded that organic farming has considerable potential to contribute to the mitigation of climate change. However, the recognition of the performance of organic farming using the LCA is still insufficient and requires further comprehensive studies. Thus, improvements in the LCA methodology in the areas of organic farming is essential.

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