sustainability

MDPI

Article

Environmental Life Cycle Assessment of Silage Maize in Relation to Regenerative Agriculture

Martin Dědina [1,*], Petr Jevič [1], Pavel Čermák [2], Jan Moudrý [3], Chisenga Emmanuel Mukosha [3], Tomáš Lošák [3,4], Tadeáš Hrušovský [4] and Elizaveta Watzlová [5]

1 Research Institute of Agricultural Engineering, p.r.i., Drnovská 507, 161 01 Prague, Czech Republic; petr.jevic@vuzt.cz
2 Institute of Animal Science, p.r.i., Přátelství 815, 104 00 Prague, Czech Republic; pavel.cermak@vuzv.cz
3 Department of Agroecosystems, Faculty of Agriculture and Technology, University of South Bohemia in Ceske Budejovice, Branišovská 1645/31A, 370 05 Ceske Budejovice, Czech Republic; jmoudry@fzt.jcu.cz (J.M.); mukosc00@fzt.jcu.cz (C.E.M.); losak@mendelu.cz (T.L.)
4 Department of Environmental Science and Natural Resources, Faculty of Regional Development and International Studies, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic; tadeas.hrusovsky@mendelu.cz
5 Department of Water Resources, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague, Czech Republic; elizaveta.watzlova@dekonta.cz
* Correspondence: martin.dedina@vuzt.cz

Abstract: The demand for agricultural products is growing and is resulting in significant environmental impacts due to the overuse of fertilizers (and pesticides in some cases). There is a continued need to find sustainable methods in agricultural systems without harming the environment. Regenerative agriculture can be considered as one of the best methods of sustainable agriculture. The aim of this comparative life cycle assessment (LCA) study was to quantify the environmental impacts associated with the production of silage maize at different doses of fertilizers and pesticides under conventional agriculture and without the use of fertilizers and pesticides under regenerative agriculture. The input data were obtained from the experimental fields and supplemented by background process databases of Ecoinvent, World Food Live Cycle Assessment Database (WFLCD), and the French database AGRIBALYSE. The results of the study were related to six midpoint impact categories: global warming, marine eutrophication, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity. Although the variant of growing silage maize without the use of fertilizers and pesticides according to the principle of regenerative agriculture showed the lowest burden on the environment, the yields of the cultivated silage maize were 43–55% lower than those of the fertilized variants.

Keywords: agriculture; environment; fertilizers; maize; pesticide; LCA; sustainability; regenerative agriculture

Citation: Dědina, M.; Jevič, P.; Čermák, P.; Moudrý, J.; Mukosha, C.E.; Lošák, T.; Hrušovský, T.; Watzlová, E. Environmental Life Cycle Assessment of Silage Maize in Relation to Regenerative Agriculture. *Sustainability* **2024**, *16*, 481. https://doi.org/10.3390/su16020481

Academic Editors: James W. Muthomi, Alex M. Fulano and Nancy Karimi Njeru

Received: 12 November 2023
Revised: 26 December 2023
Accepted: 31 December 2023
Published: 5 January 2024

1. Introduction

Agriculture is among the most significant drivers of changes in the environment [1] and has a major impact as 40% of the global ice-free land area is already under agriculture [2]. Agriculture contributes approximately 9.8% of total greenhouse gas emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) in European Union (EU) countries [3]. These three main gaseous emissions contribute approximately 80% of the greenhouse effect [4] and therefore contribute greatly towards climate change [5]. This can further impact the soil [6], water bodies [4], air quality, and human health [7]. The environmental impact of crop production systems is usually related to the use of fossil fuels [8], emissions generated from the use and application of mineral and organic fertilizers [8,9], and the production of fertilizers [10]. Agriculture has a significant environmental footprint [11]. Food production is associated with more than 5% of global greenhouse gas emissions [12]. Hence sustainable agricultural practices can play a huge role in reducing the overall impact of agriculture on the environment.

One of the ways to ensure sustainable food production is so-called regenerative agriculture. Regenerative agriculture is a completely new term in the Czech Republic, which the agricultural and academic public was introduced to for the first time in 2021. Regenerative agriculture aims to maintain agricultural productivity, increase biodiversity, and in particular restore and maintain soil biodiversity, and enhance ecosystem services including carbon capture and storage. Regenerative agriculture is based on farming without tillage, and without the use of fertilizers and pesticides. Moreover, according to [13] "regenerative agriculture has at its core the intention to improve the health of soil or to restore highly degraded soil, which symbiotically enhances the quality of water, vegetation, and land-productivity". The first visions of sustainable agriculture appeared as early as the 1980s [14] and pressure for sustainable food production continues to grow [15]. According to [16] the concept of generative agriculture has seen a rapid increase in farming, popular, and corporate interest, the scope of which now sees regenerative agriculture best viewed as a movement. [17] noted the growing interest in regenerative agriculture among several actors in the public, private, and non-profit sectors, as well as in academia.

Maize (*Zea mays* L.) is among the world's leading grown cereal crops [18] and is the third most important export product of Czech agriculture after wheat and barley [19]. In the Czech Republic is maize mainly grown for silage and corn grain production [20]. According to the ČSU [21], the total area of silage maize grown in the Czech Republic amounted to 212 thousand ha. Maize is not only an important staple crop for millions of people worldwide but also an important crop now emerging as a type of high-energy silage crop [21], used to produce animal feed due to its high feeding value [22]. The corn crop provides an excellent combination of high dry-matter yield per hectare and the quality of the biomass produced [23]. Silage corn is an important crop for the Czech Republic also as a crop for energy use in biogas stations.

The increase in crop yields in modern agriculture has been increasingly dependent on inputs of Fertilizers and pesticides [24]. Most common mineral fertilizers require large quantities, typically 80–140 kg per hectare of land [25]. This widespread usage in agricultural systems has multiple impacts on the environment [26]. Only 30–50% of the amount of nitrogen (N) and phosphorus (P) fertilizers applied is utilized by the crop [27]. Excessive applications of N and P to cropland accumulate in agricultural soils and are subsequently lost to surface and groundwaters by leaching and erosion [28]. The loss of these nutrients in agricultural fields is a cause of environmental pollution [29,30]. The disadvantages include possible biomagnification and persistence in nature [31]. The application of P, K, and S fertilizer increases the N efficiency and helps achieve higher yields with higher protein [32]. Rational, balanced organo-mineral fertilization is necessary to produce sufficient quantities (food security) of high-quality food (food safety), with minimal impact on the environment [33,34]. Agriculture must find the right compromises between current and future levels of production by effectively using fertilizers to avoid excessive emissions to the environment [35].

The sustainable development of agriculture is currently facing challenges from climate change, as well as soil pollution and degradation resulting from intensive farming practices [36]. Conventional approaches to intensify agriculture and the use of fertilizers and pesticides are among the major causes of environmental degradation [37]. It is widely recognized that mineral fertilizers have made a significant contribution to the continuous increase in agricultural food production in the past decades [38]. However, the increased application intensity, especially when overused, also brings a series of environmental burdens [39]. Mineral fertilizers and plant chemical protection are important for crop output, but they can also emit specific quantities of emissions and cause environmental burdens [40,41]. Pesticides from agricultural fields are often found in waterbodies leading to environmental effects [42]. This can have an impact on water pollution and aquatic biodiversity [43].

Increasing concerns about environmental impacts and reductions of inputs require a transformation of cropping systems for improved efficiency and sustainability. Achieving this goal with limited environmental impacts offers an unprecedented challenge to humankind [44]. Thus, it is necessary for the continued establishment of ways to assess and promote agricultural practices that can be adopted by farmers, which present a more environmentally sustainable and friendly. Thanks to life cycle assessment (LCA), it is possible to assess the environmental impact of agricultural systems. The LCA method is a comprehensive tool that enables the assessment of various environmental impacts directly caused by the farming system and the impacts arising from the inputs [9]. Comparative LCA studies can help find suitable alternative or mitigation strategies in crop production [40]. The LCA is a standard method used to assess the environmental impacts and to evaluate the sustainability of the production systems from the environmental point of view [45] by quantifying the energy, material flows, and environmental releases and converting them to environmental impacts [46], which allows for the identification of life cycle stages that contribute disproportionately to specific areas of environmental concern.

There have been many LCA studies conducted on maize production globally [8,41–47]. In conditions of the Czech Republic there have been advancements in LCA studies regarding maize production e.g., ref. [48] assessed the environmental potential Szarvasi-1 as a substitute energy crop of maize, while ref. [49] evaluated maize performance relating to climate change impact category and ref. [50] evaluate cup plant as an alternative to silage maize. There hasn't so far been an LCA study of silage maize comparing different mineral fertilizer and pesticide dose applications in the Czech Republic regarding regenerative agriculture. This is an important approach towards achieving the EU Green Deal policy emissions target by 2050 [51].

The goal of this study was to quantify (a) the environmental impacts of different mineral fertilizer and pesticide dose applications and (b) the impact of different mineral fertilizer and pesticide doses on yield within the framework of determining emission limits in silage maize production. The achieved results are useful for promoting the overall reduction of environmental impact by optimizing mineral fertilizer and pesticide doses. The system boundaries define the life cycle processes that belong to the analyzed system [52]. For this study system boundaries were all processes from "cradle to farm gate" which includes all inputs, upstream processes, and outputs as shown in Figure 1. The functional unit chosen for this study was 1 ton of final product and the mass allocation principle was employed. The functional unit determines the nature of the study outputs and their interpretation is one of the key moments in implementing the LCA study [53–55] and is a quantitative description of the function of the system. The transport distance between the field and the farm site was estimated to be 5 km. This study was conducted according to the guidelines of the International Organization for Standardization [56,57].

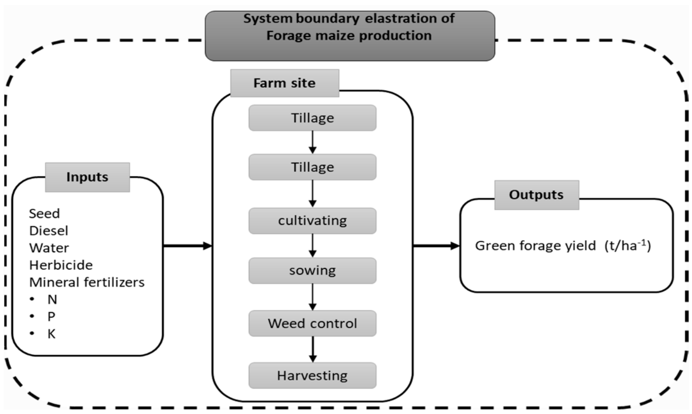

Figure 1. Overview of cradle-to-farm gate system boundary.

2. Materials and Methods

2.1. Description of Experimental Site

Experimental Site Humpolec

The field experimental station of the Crop Research Institute in Humpolec is located in the southeast region of the Czech Republic (49°33′ N and 15°33′ E) about 525 m above sea level. The soil in the local area is fertile with a natural supply of key nutrients. The soil type is cambisol. The geological base consists of diluvium pararula, the soil type is weakly laminated with cambium (g), and the soil type is sandy loam. The soil-forming substrate is pararula, reaching a depth of about 30–40 cm on average. The long-term average temperature is 7.03 °C with an average annual sum of precipitation of 665.1 mm.

2.2. Experimental Design and Management Practices

The results of this study are related to a two-year field trial of growing Maize (M) under different mineral fertilizers and pesticide doses conducted in the spring planting seasons of 2021 and 2022, respectively. Field plot experiments were established, with different mineral fertilizer and pesticide treatment combinations and one unfertilized and untreated variant based on principles of regenerative agriculture (variant M1). All combinations were repeated 4 times with the arrangement of plots according to the established standard system of the experimental site see Table 1. The M1 control variant had no input of fertilizer or pesticide. The fertilization with (N) nitrogen, (P) phosphorus, and (K) potassium was carried out on variants M2–M5 in different doses as shown in Table 2. In variants M3 and M5, a dose of nitrogen fertilizers of 160 kg N ha^{-1} was chosen. This dose corresponds to common practice when growing corn for silage in the soil and climatic conditions of the Czech Republic and corresponds to an expected yield of up to 40–50 tons ha^{-1}. In variants M2 and M4, a dose of nitrogen fertilizers was chosen in the amount of 80 kg N ha^{-1}, corresponding to half the dose normally used. The aim was to verify the effect of a relatively drastic reduction in the doses of nitrogen fertilizers on the achieved yields to fulfill the Green Deal Goal of the EU of reducing mineral fertilizers use by 50% by 2030. As already mentioned above, no doses of nitrogenous or other fertilizers were used for the M1 variant to verify the effect of the transition from the conventional farming system to regenerative farming on the achieved crop yields. The experiment aimed to find out how much the production of silage corn will decrease with half the dose of mineral fertilizers than is common in the Czech Republic and what value the so-called carbon footprint of the cultivated crop will reach.

Table 1. Plot layout scheme for silage maize.

Replicates					
D	2	4	3	5	1
C	5	1	4	2	3
B	4	3	1	5	2
A	1	2	3	4	5

Table 2. Doses of N, P, K fertilizer (kg ha^{-1}) and pesticide (kg ha^{-1}) doses for maize production.

Variants	Mineral Fertilizer			Pesticide
	N	P	K	
M1	0	0	0	0
M2	80	15	60	0.65
M3	160	30	120	1.3
M4	80	15	60	1.3
M5	160	30	120	0.65

M1—control, M2—half dose of fertilizer and treatment, M3—full dose of fertilizer and treatment, M4—half dose of fertilizer and full treatment, M5—full dose of fertilizer and half dose of treatment. N, nitrogen; P, phosphorous; K potassium.

All combinations were repeated 4 times with the arrangement of plots (size of the test area—5 × 6 m) according to the established standard system of the experimental site. The seed rate for all plots was 60 kg ha^{-1} with sowing dates of 10 May in both growing seasons 2021 and 2022. A maize variety called "Kovivio" was selected for field trials. Variety of maize Kovivio is a very early hybrid intended for the production of quality silage with a high starch content (SH BSA yield rating: 7). The yield rating is within the range of very early hybrids maize (up to FAO 220) excellent. The harvest dates are 12 October 2021 and 3 October 2022 at a relatively high percentage of dry matter. MaisTer power herbicide was used for chemical plant protection. MaisTer is an oil dispersion containing 31.5 g L^{-1} Foramsulfuron + 1.0 g L^{-1} Iodosulfuron + 10 g L^{-1} Thiencarbazone + 15 g L^{-1} Cyprosulfamide. The dosage is shown in Tables 2 and 3.

Table 3. The data for the Inventory table of silage maize production.

	Unit	M1	M2	M3	M4	M5
Inputs from Technosphere						
Tillage, ploughing	ha	1	1	1	1	1
Tillage, cultivating, chiseling	ha	1	1	1	1	1
Tillage, harrowing, by offset disc harrow	ha	1	1	1	1	1
Combine harvesting	ha	1	1	1	1	1
Sowing	ha	1	1	1	1	1
Seeds	kg ha^{-1}	60	60	60	60	60
Water (medium for plant protection products)	L	-	200	200	200	200
Nitrogen fertilizer, as N	kg ha^{-1}	-	80	160	80	160
Inorganic potassium fertilizers, as K_2O	kg ha^{-1}	-	60	120	60	120
Inorganic phosphorus fertilizers, as P_2O_5	kg ha^{-1}	-	15	30	15	30
Fertilizing, by broadcaster	ha	-	1	1	1	1
Application of plant protection by field sprayer	ha	-	1	1	1	1
Herbicide at plant	kg ha^{-1}	-	0.65	1.3	1.3	0.65
Agricultural machinery, transport	L ha^{-1}	77.1	80.0	82.9	81.5	81.4
Outputs						
Yield	t ha^{-1}	26.4	47.5	53.4	50.4	55.2
Emissions from the production of seeding material	kg CO_{2eq} t^{-1}	0.58	0.58	0.58	0.58	0.58
Emissions from the use of chemical fertilizers (N, P, K, Ca)	kg CO_{2eq} t^{-1}	0.00	7.26	14.04	6.84	13.58
Emissions from the use of pesticides	kg CO_{2eq} t^{-1}	0.00	0.15	0.27	0.28	0.13
Emissions from the neutralization of fertilizer acidification						
Soil (nitrous oxide/N_2O) emissions from crop cultivation	kg CO_{2eq} t^{-1}	10.00	18.60	27.40	18.10	26.80
Emissions from the use of fuels in farm machinery	kg CO_{2eq} t^{-1}	9.99	5.76	5.31	5.53	5.04
Emissions of GHG total	kg CO_{2eq} t^{-1}	20.57	32.35	47.60	31.33	46.10

IPCC calculated following the IPCC (Intergovernmental Panel on Climate Change) methodology (determination of field emissions) M1—unfertilized and untread M2—half does of fertilizer and treatment, M3—full dose of fertilizer and treatment, M4—half dose of fertilizer and full treatment, M5—full dose of fertilizer and half dose of treatment.

Nutrients were applied in mineral form in the spring of 2021 and 2022. On combinations M2–M5, Amofos (12% N, 52% P_2O_5, dose 12 kg ha^{-1}) was used to achieve the necessary level of basic fertilization with nitrogen and phosphorus, with additional fertilization as necessary application doses of nitrogen in the form of ammonium sulfate (21% N, 24% S, dose 57 kg ha^{-1}) for basic fertilization before sowing. Subsequent N fertilization during vegetation was carried out by Calcium Ammonium Nitrate (27% N, 7% CaO, 4% MgO, dose 11 kg ha^{-1} for variants M2 and M4, dose 91 kg ha^{-1} for variants M3 and M5). For potassium fertilization, a full dose of potassium salt was used in pre-sowing fertilization. No organic fertilization or calcium fertilizers (liming) were applied.

2.3. Life Cycle Inventory Analysis

The primary data for the inventory analysis is based on a two-year study conducted in 2021 and 2022 at the experimental base of the Plant Production Research Institute in

Humpolec. The secondary data was obtained from existing background databases of Ecoinvent V. 3.8, World Food Live Cycle Assessment Database (WFLCD 3.5), and the French database AGRIBALYSE v. 1.3, geographically related to Central Europe. Table 3 shows the inventory table of all inputs and outputs monitored in the study. Based on the input data the emissions to the environment were determined using the openLCA software 2.0.3 [58] by using the ReCiPe midpoint impact assessment method. The field emissions were considered following the guidelines of [59] nitrous oxide (N_2O) and nitrogen oxides (NOx, NO, NO_2) in accordance with the proposed emission factors of the IPCC [60].

To calculate N_2O emissions from fertilizer application during crop cultivation, disaggregated crop-specific emission factors for different environmental conditions (corresponding to level 2 of the IPCC methodology), soil conditions, and different crops were used. According to the instructions given in the IPCC methodologies, N_2O emissions released from the soil were calculated according to Equation (1):

$$N_2O_{total} - N = N_2O_{direct} - N + N_2O_{indirect} - N \quad (1)$$

where $N_2O_{direct} - N$ are annual direct emissions and $N_2O_{indirect} - N$ are annual indirect emissions from managed soils occurring after nitrogen fertilizers application. Direct $N_2O_{direct} - N$ emissions were calculated according to Equation (2) intended for organic soils. Mineral soils do not occur in the Czech Republic.

$$N_2O_{direct} - N = [(F_{SN} + F_{ON} + F_{CR}) \cdot EF_1] \quad (2)$$

where F_{SN} is the annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1}, F_{ON} is the annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soil. When calculating direct N_2O emissions, only the amount of nitrogen originating from the application of synthetic fertilizers was considered, since no organic fertilizers were used during the experiments. Another source of nitrogen included in the calculations of direct N_2O emissions was F_{CR}—the annual amount of N in crop residues (above-ground and below-ground), kg N yr^{-1}. This value was calculated according to Equation (3):

$$F_{CR} = AGR \cdot N_{AG} \cdot [1\text{-}Frac_{remove}\text{-}(Frac_{burnt} \cdot C_f))] + [(BRG \cdot N_{BG})] \quad (3)$$

where AGR is the annual total amount of above-ground crop residue and BRG is the annual total amount of below-ground crop residue for the crop, in this case for maize, kg d.m. yr^{-1}. A parameter such as NAG expresses the N content of above-ground residues and *NBG* expresses the N content of below-ground residues for the crop, kg N (kg d.m.)$^{-1}$. The values of both mentioned parameters were selected from the updated Table 11.1A [61] of the IPCC guidelines. $Frac_{remove}$ is the fraction of above-ground residues of crops removed annually for purposes such as feed, bedding, and construction (dimensionless). Factor as $Frac_{burnt}$—a fraction of the annual harvested area of crop burnt (dimensionless) was not taken into account, as well as combustion factor C_f, because no crop residues were burnt. The default emission factor EF_1 to determine direct N_2O emissions from N inputs kg $N_2O - N$ (kg N $_{input}$)$^{-1}$ was selected from the updated Table 11.1 of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [61].

Total indirect emissions of $N_2O_{indirect} - N$ consist of emissions produced by atmospheric deposition of N volatilized from managed soils $N_2O_{ATD} - N$ and the annual amount of $N_2O_L - N$ produced from leaching and run-off of N additions to managed soils in regions where leaching/run-off occurs, kg $N_2O - N$ ha^{-1} a^{-1}. Indirect emissions were calculated according to Equation (4):

$$N_2O_{indirect} - N = [(F_{SN} \cdot Frac_{GASF}) \cdot EF_4] + [(F_{SN} + F_{CR} \cdot Frac_{LEACH}) \cdot EF_5] \quad (4)$$

where F_{SN} is the annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1} and F_{CR} is the amount of N in crop residues (above- and below-ground), kg N yr^{-1}. No other sources of nitrogen, such as farmyard manure, composts, etc., were considered, as these fertilizers were not used to fertilize the field trials. $Frac_{GASF}$ expresses the fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x kg N volatilized (kg of N applied)$^{-1}$ and $Frac_{LEACH}$ is the fraction of all N added to managed soils in regions where leaching/runoff occurs, kg N (kg of N additions)$^{-1}$. The specific values of $Frac_{GASF}$ and $Frac_{LEACH}$, as well as the emission factors EF_4 and EF_5 were taken from updated Table 11.3 [61] of the IPCC Guidelines (disaggregated default values for dry climate—EF_4 and disaggregated volatility values from synthetic fertilizers selected according to the respective types of synthetic fertilizers—$Frac_{GASF}$).

2.4. Life Cycle Impact Assessment

For this purpose, a life cycle assessment method was used for environmental impact quantification. Life cycle assessment is a procedure that is used to evaluate and quantify the impact of the production of a certain product on the environment during its entire life cycle. The aim is to identify key points in the production chain of the product where optimization can be carried out in order to reduce the negative effects of production on the environment and thereby ensure the environmental sustainability of production. The data were evaluated and analyzed in accordance [56,57]. For this study the openLCA software 2.0.3 version was used, ReCiPe 2016 midpoint (H) V1.13/Europe impact assessment method was used [58]. The results of the study were related to six midpoint impact categories: global warming (expressed in kg CO_{2eq}), marine eutrophication (expressed in kg N_{eq}), freshwater eutrophication (expressed in kg P_{eq}), freshwater ecotoxicity (expressed in kg 1,4-DCB_{eq}), marine ecotoxicity (expressed in kg 1,4-DCB_{eq}) and terrestrial ecotoxicity (expressed in kg 1,4-DCB_{eq}). The monitored midpoint impact categories are suitable for agricultural LCA [62] and have been selected in relevance to the goal and scope of the study. This study further evaluates the impact of the monitored systems in relation to damage categories: ecosystem quality, human health, and resources, all of which are later converted into percentage contributions. The damage categories method aligns with protection areas that serve as the foundation for decisions in policymaking and sustainable development [58]. The endpoint characterization factors (CF_e) are directly derived from the midpoint characterization factors (CF_m), with a constant midpoint to endpoint factor per im-pact category [59] using the Equation (5):

$$CFe_{x,c,a} = CFm_{x,c} \cdot F_{M}{\rightarrow},E,c,a \tag{5}$$

where c denotes the cultural perspective, a denotes the area of protection e.g., terrestrial ecosystems or human health, and $_x$ denotes the stressor of concern. FM→,E,c,a is the midpoint to the endpoint conversion factor for the area of protection a and cultural perspective c. Overall, the environmental impacts of silage maize were assessed under different nutrient and treatment combinations.

3. Results

3.1. Environmental Assessment of Midpoint Impact Categories

According to the characterization model, a contribution analysis was carried out for green silage maize under different fertilizer and pesticide doses. The results are related to a two-year growing cycle of green silage maize under five different fertilizer and pesticide application rates M1-M5 as shown in Table 1. The functional unit for this expression was 1 ton of the final product.

The results of this study within the assessed variants show that M1 with no input of fertilizers and pesticides imposes the lowest environmental load per production unit in all monitored impact categories respectively global warming (GWP), marine eutrophication (ME), freshwater eutrophication (FE), marine ecotoxicity (MEC) freshwater ecotoxicity (FEC), and terrestrial ecotoxicity (TE). This is attributed to the non-use and application of fertilizers and pesticides as shown in Table 4.

Table 4. Midpoint impact level for the unit of production from the cradle-to-farm gate.

Impact Category	Abbreviation	Unit	M1	M2	M3	M4	M5
Global warming	GWP	kg CO_{2eq}	325.359	873.450	1243.816	878.209	1247.035
Marine eutrophication	ME	kg N_{eq}	1.292	2.226	2.513	2.239	2.521
Freshwater eutrophication	FE	kg P_{eq}	0.071	0.190	0.273	0.191	0.270
Marine ecotoxicity	MEC	kg 1,4-DCB_{eq}	0.790	2.165	3.187	2.267	3.107
Freshwater ecotoxicity	FEC	kg 1,4-DCB_{eq}	0.567	2.371	3.933	3.194	3.123
Terrestrial ecotoxicity	TE	kg 1,4-DCB_{eq}	0.035	1.658	3.269	3.246	1.682

Similarly, the variants with half dose inputs of fertilizers of N 80 kg ha^{-1}, P 15 kg $ha^{-1,}$ and K 60 kg ha^{-1} had lower environmental loads in impact categories of global warming, marine eutrophication, freshwater eutrophication, and marine ecotoxicity compared to the variants and full dose fertilizer in inputs of N 160 kg ha^{-1}, P 30 kg ha^{-1} and K 120 kg ha^{-1}. According to the results in Table 4 for impact categories global warming (1247.035 kg CO_{2eq}), and marine eutrophication (2.521 kg N_{eq}), the M5 variant recorded the highest environmental load while the M3 variant recorded the highest environmental burden in impact categories marine ecotoxicity (3.194 kg 1,4-DCB_{eq}), freshwater ecotoxicity (3.933 kg 1,4-DCB_{eq}) and terrestrial ecotoxicity (3.269 kg 1,4-DCB_{eq}) as shown in Table 4. A clearer graphical evaluation of all monitored impact categories is presented in Appendix A.

Overall, the trend in the results per unit of production in the monitored impact categories is similar with the variants with higher application doses of fertilizer and pesticides having higher environmental impacts and the variant with non-application of fertilizers and pesticides having the lowest environmental load.

3.2. Carbon Footprint Assessment

As part of the conducted field experiments and the LCA evaluation of the M3 and M4 variants, it was found that the carbon footprint of the grown silage corn is reduced by approximately 34% when the dose of mineral fertilizers is reduced by 50%, while the crop yields decreased by only 6%. Differences in carbon footprint with equal fertilizer rates but limited pesticide rates were insignificant. By switching from the conventional way of growing silage corn to a regenerative way of growing, a reduction of the carbon footprint by approx. 57% was achieved but with a reduced crop yield of 51%.

3.3. Environmental Damage Assessment

The results of the six midpoint impact categories a related to damage categories (1) ecosystem quality, (2) human health, and (3) resources. According to results in Figure 2 for damage impact categories human health and resources the M5 variant recorded the highest environmental load. For damage category ecosystem quality, the highest environmental load was associated with variant M3. Overall, the control variant M1 recorded the least environmental load.

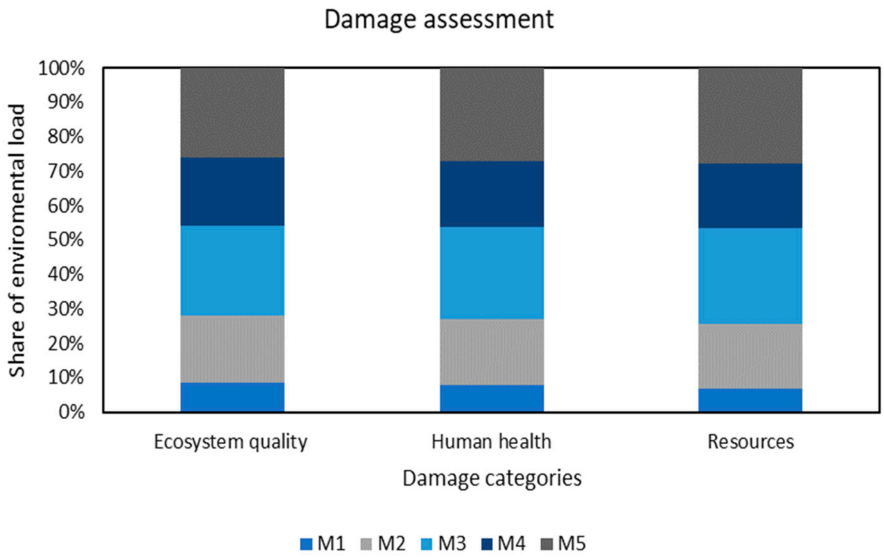

Figure 2. Environmental impact of damage categories from the cradle-to-farm gate level for the unit of production.

4. Discussion

Global agriculture productivity continues to face several abiotic and biotic challenges. The results obtained show that the different fertilizer and pesticide doses applied had a significant impact on the environment. Considering the impact agriculture continues to have on the environment, it is necessary for the continued assessment of production systems using the LCA method. The LCA quantifies the energy, material flows, and environmental releases and converts them to environmental impacts [47].

Global warming, as recognized by the United Nations, is a key factor contributing to climate change [63]. According to the results for the impact category the global warming, the highest environmental impact was associated with the variant M5 that had full dose input of N 160 kg ha $^{-1}$ fertilizers (1247 kg CO_{2eq}) respectively. The higher environmental load can be attributed to the high doses of fertilizer application. The application of fertilizers had an influence on increased yields compared to the M1 variant that was not fertilized. While fertilizer has been observed to increase crop yield, it is also associated with environmental impacts. Several studies have attributed a higher environmental burden to high doses of mineral fertilizers [64,65]. N loss from fertilizers has become a persistent environmental problem [66]. The low nitrogen efficiency of maize implies that a substantial portion of applied fertilizers are not absorbed by plants and can escape nutrient pollution [67]. Nitrogen fertilizer can convert into nitrous oxide (N_2O) [68] which is an important greenhouse gas that contributes to global warming [69] and has a global warming potential (GWP) 265 times higher than CO_2 [70]. Nitrous oxide is produced during nitrification, resulting from microbial soil processes of converting ammonia (NH_3) to nitrate (NO_3-) and denitrification in the conversion of NO_3- to N_2. Yadav [71] observed that the agriculture sector can play a critical role in GHG mitigation by lowering 10% N_2O emissions. The reduction in N fertilizer doses can be saved as a mitigating strategy to reduce the impact of maize production contribution as shown in the results. Similar studies have attributed high GHG emissions to the use and application of N fertilizers [70,72].

According to the results for the impact category global warming, there was a significant difference in environmental load for the variant M2 (873.450 kg CO_{2eq}) and M4 (878.209 kg CO_{2eq}) that received a half dose of N 80 kg ha $^{-1}$, fertilizers compared to the variants with full dose application of N 160 kg ha^{-1} respectively M3 and M5. The control variant M1 with no input of N fertilizer had the lowest environmental impact for the impact category climate change. To decrease environmental impact and obtain an environmentally friendly production system [73], the reduction of nitrogen fertilizer use represents one of the most effective climate change mitigation strategies farmers can adopt [74], although this can be achieved at the cost of lower yield. The N application based on crop demands could be proposed to provide maximum uptake and consequently decrease NOx emissions through a decrease of NH_3 volatilization to reduce global warming potential [73]. Partial replacement of mineral N with organic fertilization can solve as a mitigation strategy as it not only provides NPK and micronutrients to the soil and crop but also organic C when using solid fertilizers [75] or utilizing nitrogen-fixing plants in a crop rotation can be a good way to avoid the overuse of nitrogen in the production system [38]. The other contributing factor to global warming was the burning of fossil fuels during agrotechnical operations (including tillage, sowing, fertilizing, cultivating, harvesting, and transporting). Tillage practices influence crop productivity but also influence GHG emissions [76]. No-till, reduced tillage systems, and combining operations can save and mitigate strategies to reduce the environmental contributions arising from the burning of fossil fuels [77]. The combustion of fossil fuel is considered responsible for more than 75% of human-caused CO_2 emissions [74]. Effective energy management is crucial for reducing GHG emissions [30]. Overall, according to the results the lowest environmental load for impact category global warming was associated with the control variant M1, and this is attributed to the non-use and application of fertilizers.

Global P and N consumption is increasing steadily due to the growing population and increased demand for food crops and animal-derived food [78]. According to the results for impact categories marine eutrophication and freshwater eutrophication the high environmental loads were associated with the variants that had full dose input of N 160 kg ha^{-1} and P 30 kg ha^{-1}, respectively, M3 and M5. This is attributed to the large amounts of P and N fertilizers, and this is supported by the findings of Smith et al. [13] and Withers et al. [79]. The increased fertilizers use required for agricultural intensification has greatly increased the leaching of N and P to water surfaces [80]. Not all P and N fertilizers applied to agricultural land are taken up by plants or retained in the soil [60]. The Emissions created by applying fertilizer to crops included losses of total N, NO_3^--N, NH_4^+-N, soluble phosphate, and total P, through runoff leaching resulting in eutrophication [71]. Eutrophication leads to reduced water quality, alteration of food web structures, loss of biodiversity, and habitat degradation [81]. The protection of water bodies requires the identification and quantification of contributing sources to find mitigating strategies. The variants with the dose of N 80 kg ha^{-1} and P 15 kg ha^{-1} recorded lower environmental burdens compared to the variants that received doses of N 160 kg ha^{-1} and P 30 kg ha^{-1}. Hence the reduction of anthropogenic nutrient input in the agricultural systems remains key to reducing eutrophication. The results show that for the impact categories freshwater eutrophication (0.071 kg P_{eq}) and marine eutrophication (1.292 kg N_{eq}), the M1 variant had the lowest environmental impact.

According to the results for impact categories marine ecotoxicity and freshwater ecotoxicity the variant M3 with the full dose of N 160 kg ha^{-1}, P 30 kg ha^{-1}, and K 120 kg ha^{-1} fertilizers and 1.3 L/mL Maister power pesticide. The process of increasing crop production utilizes the application of higher quantities of agrochemicals [82]. Pesticides are used in agriculture to protect crops from insects, weeds, and bacterial or fungal diseases during growth [65] and increase yield [64], but are associated with negative environmental impacts [83,84] and have become an issue globally [64]. The pesticides originating from human activity or agricultural farming are discharged directly or indirectly into the receiving water [85]. Pesticides and their effects on the ecosystems are still too often omitted in most LCA studies even though they are one of the major environmental issues linked with agriculture [86]. For impact category terrestrial ecotoxicity the high impact was associated with the variants that received full doses of pesticides, respectively, M3 and M4 which could disturb all biosphere's constituents and may present a serious risk to human health and its environment [87].

As shown by the results for the marine ecotoxicity, freshwater ecotoxicity, and terrestrial ecotoxicity impact categories, the regenerative variant M1 had the lowest environmental burden attributed to the non-use of pesticides and fertilizers, but significantly lower yields are recorded. As the results of the experiments showed, the immediate method of transition from conventional agriculture to the regenerative method brings an immediate and significant drop in yields. It is therefore necessary to look at the regenerative way of farming as a path on which, by gradually reducing the consumption of fertilizers, pesticides, and methods of tillage, one gradually moves away from the use of these inputs.

According to the results, a reduction in the amount of pesticide dose application can be a mitigating strategy to reduce the effect of pesticides on the environment. Reducing pesticide use has become a shared goal by several countries and a major issue in public policies [88]. To achieve the Green Deal Goal of the EU of reducing mineral fertilizers and pesticide use by 50% by 2030 [51], a shift towards alternative cropping systems that are less dependent on pesticides is needed [89].

5. Conclusions

This study quantified the environmental impacts of different fertilizers and pesticide doses using the LCA method in relation to regenerative agriculture. The environmental loads of silage maize under different mineral fertilizers and pesticide doses differ in relation to different midpoint impact categories and damage categories. The results of the comparative LCA study showed that the application and use of high doses of mineral fertilizers and pesticides in the production of silage maize had a significant impact on yield and environmental load. The variant without the input of mineral fertilizer and pesticide was characterized by lower environmental impact, which is deemed environmentally friendly at the expense of lower yields. It is therefore necessary to find a reasonable compromise between achieving enough quality production and reducing input to agriculture. The reduction of the environmental burden can be achieved by reducing the number of fertilizers and pesticides applied in silage maize production. This can be achieved by the partial replacement of mineral fertilizer with organic fertilizer. Implementing nutrient management and precision agriculture techniques can save as a mitigation strategy by applying the right number of fertilizers in the right spot and at the right time. Improved crop rotation strategies and techniques can serve as a mitigating strategy to reduce the need for chemical protection and N fertilizers which can be achieved by the inclusion of N-fixating crops in the crop rotation. The implementation of reduced tillage in production systems can save a mitigation strategy for the reduction of fossil fuels which results in lowering the amount of GHG emissions produced.

It is generally known that reducing the consumption of both synthetic and organic fertilizers leads to a reduction in the burden on the environment, especially ammonia and greenhouse gas emissions into the air. Unfortunately, for the conservative agricultural public, a reduction in the consumption of mineral fertilizers is associated with a reduction in yields and, consequently, a reduction in income for agricultural products or other products such as, for example, electrical energy. These concerns are particularly linked to the transition to regenerative agriculture.

Author Contributions: Conceptualization, M.D. and P.J.; field experiments, P.Č. and E.W.; methodology, M.D. and P.Č.; resources, C.E.M., T.H. and T.L.; writing—original draft preparation, C.E.M., J.M., T.H. and T.L.; writing—review and editing, C.E.M., J.M., T.H. and T.L.; project administration, P.J.; funding acquisition, M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Agriculture of the Czech Republic—National Agricultural Research Agency, grant number QK21020121, and by the project of long-time development of the Research Institute of Agricultural Engineering, p.r.i. no. RO0623.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

A graphical evaluation of all monitored impact categories is presented in Appendix A.

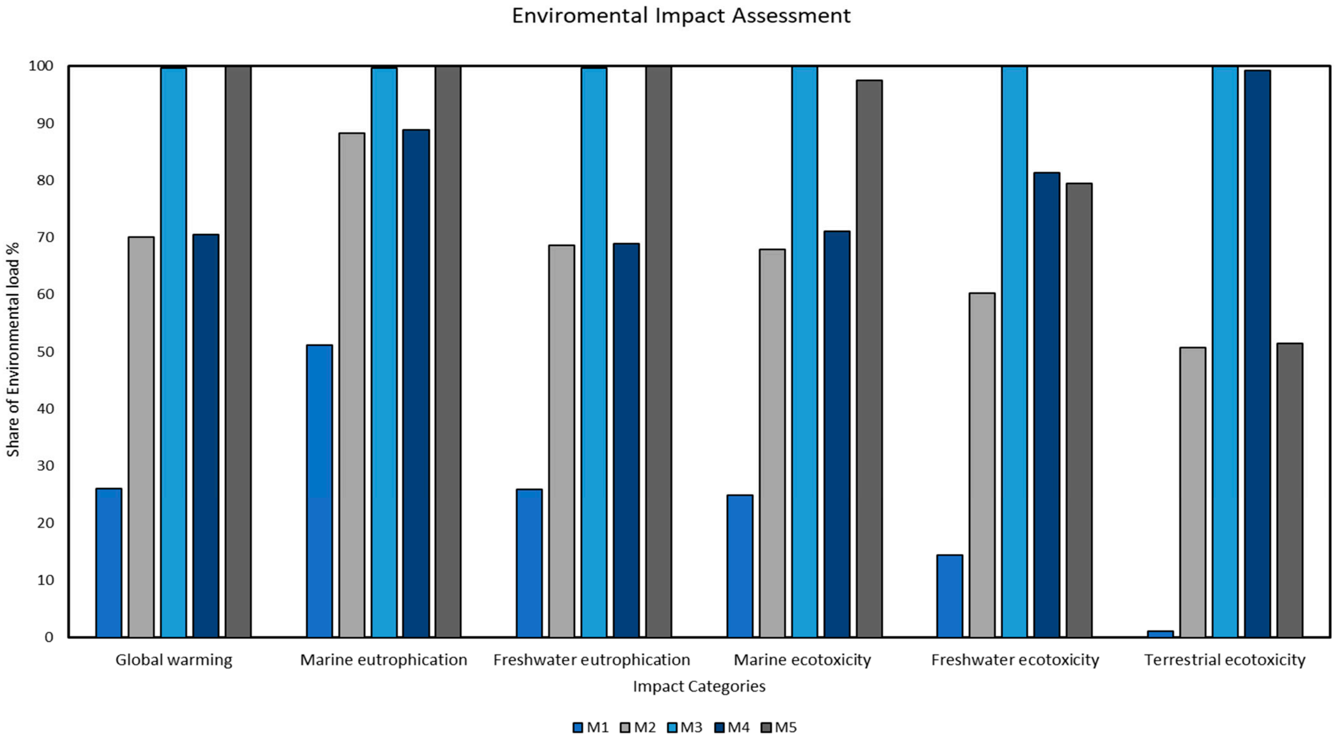

Figure A1. Environmental midpoint impact level for the unit of production from the cradle-to-farm gate.

References

1. Godfray, H.C.J.; Garnett, T. Food Security and Sustainable Intensification. *Philos. Trans. R. Soc. B* **2014**, *369*, 20120273. [CrossRef] [PubMed]
2. Ramankutty, N.; Evan, A.T.; Monfreda, C.; Foley, J.A. Farming the Planet: 1. Geographic Distribution of Global Agricultural Lands in the Year 2000: GLOBAL AGRICULTURAL LANDS IN 2000. *Glob. Biogeochem. Cycles* **2008**, *22*. [CrossRef]
3. Holka, M.; Bieńkowski, J. Carbon Footprint and Life-Cycle Costs of Maize Production in Conventional and Non-Inversion Tillage Systems. *Agronomy* **2020**, *10*, 1877. [CrossRef]
4. Tang, Y.; Luan, X.; Sun, J.; Zhao, J.; Yin, Y.; Wang, Y.; Sun, S. Impact Assessment of Climate Change and Human Activities on GHG Emissions and Agricultural Water Use. *Agric. For. Meteorol.* **2021**, *296*, 108218. [CrossRef]
5. Montzka, S.A.; Dlugokencky, E.J.; Butler, J.H. Non-CO_2 Greenhouse Gases and Climate Change. *Nature* **2011**, *476*, 43–50. [CrossRef] [PubMed]
6. Johnson, J.M.-F.; Franzluebbers, A.J.; Weyers, S.L.; Reicosky, D.C. Agricultural Opportunities to Mitigate Greenhouse Gas Emissions. *Environ. Pollut.* **2007**, *150*, 107–124. [CrossRef] [PubMed]
7. Nordahl, S.L.; Devkota, J.P.; Amirebrahimi, J.; Smith, S.J.; Breunig, H.M.; Preble, C.V.; Satchwell, A.J.; Jin, L.; Brown, N.J.; Kirchstetter, T.W.; et al. Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies. *Environ. Sci. Technol.* **2020**, *54*, 9200–9209. [CrossRef] [PubMed]
8. Bacenetti, J.; Lovarelli, D.; Fiala, M. Mechanisation of Organic Fertiliser Spreading, Choice of Fertiliser and Crop Residue Management as Solutions for Maize Environmental Impact Mitigation. *Eur. J. Agron.* **2016**, *79*, 107–118. [CrossRef]
9. Nemecek, T.; Hayer, F.; Bonnin, E.; Carrouée, B.; Schneider, A.; Vivier, C. Designing Eco-Efficient Crop Rotations Using Life Cycle Assessment of Crop Combinations. *Eur. J. Agron.* **2015**, *65*, 40–51. [CrossRef]
10. Hasler, K.; Bröring, S.; Omta, S.W.F.; Olfs, H.-W. Life Cycle Assessment (LCA) of Different Fertilizer Product Types. *Eur. J. Agron.* **2015**, *69*, 41–51. [CrossRef]
11. Searchinger, T.; Waite, R.; Hanson, C.; Ranganathan, J.; Dumas, P.; Matthews, E.; Klirs, C. *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*; World Resources Institute: Washington, DC, USA, 2019.
12. Bodirsky, B.L.; Rolinski, S.; Biewald, A.; Weindl, I.; Popp, A.; Lotze-Campen, H. Global food demand scenarios for the 21st century. *PLoS ONE* **2015**, *10*, e01329201. [CrossRef] [PubMed]
13. Rhodes, C.J. The imperative for regenerative agriculture. *Sci. Prog.* **2017**, *100*, 80–129. [CrossRef] [PubMed]

14. Rodale, R. Breaking New Ground—The Search for a Sustainable Agriculture. *Futurist* **1983**, *1*, 15–20.
15. Beddington, J.R. The Future of Food and Farming. *Int. J. Agric. Manag.* **2011**, *1*, 11.
16. O'Donoghue, T.; Minasny, B.; McBratney, A. Regenerative Agriculture and Its Potential to Improve Farmscape Function. *Sustainability* **2022**, *14*, 5815. [CrossRef]
17. Newton, P.; Civita, N.; Frankel-Goldwater, L.; Bartel, K.; Johns, C. What Is Regenerative Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and Outcomes. *Front. Sustain. Food Syst.* **2020**, *4*, 577723. [CrossRef]
18. FAOSTAT: Crops and Livestock Products. Statistical Yearbook. 2021. Available online: https://www.fao.org/faostat (accessed on 2 June 2023).
19. Institute of Agricultural Economics and Information (UZEI) Cereals Situation and Outlook Report. 2021. Available online: https://www.czso.cz/csu/xb/skliznove-plochy-a-vynosy-vybranych-plodin (accessed on 2 June 2023).
20. Czech Statistical Office CSU: Harvested Areas of Agricultural Crops—Czech Republic. 2022. Available online: https://www.czso.cz/csu/xb/skliznove-plochy-a-vynosy-vybranych-plodin (accessed on 2 June 2023).
21. Czech Statistical Office CSU: Harvested Areas and Crop Yields of Selected Crops. 2021. Available online: https://www.czso.cz/csu/xb/skliznove-plochy-a-vynosy-vybranych-plodin (accessed on 2 June 2023).
22. Undie, U.L.; Uwah, D.F.; Attoe, E.E. Effect of Intercropping and Crop Arrangement on Yield and Productivity of Late Season Maize/Soybean Mixtures in the Humid Environment of South Southern Nigeria. *JAS* **2012**, *4*, p37. [CrossRef]
23. Peña, O.M.; Velasquez, C.; Ferreira, G.; Aguerre, M.J. Yield, Nutritional Composition, and In Vitro Ruminal Digestibility of Conventional and Brown Midrib (BMR) Corn for Silage as Affected by Planting Population and Harvest Maturity. *Agronomy* **2023**, *13*, 1414. [CrossRef]
24. Attia, Y.; Klalid, A.; Edrs, S. Organic Agriculture and Foods for Sustainable Food Production and Safety, An Updated Review. *J. King Abdulaziz Univ.-Meteorol. Environ. Arid Land Agric. Sci.* **2023**, *32*, 97–115. [CrossRef]
25. Jha, A.; Pathania, D.; Sonu; Damathia, B.; Raizada, P.; Rustagi, S.; Singh, P.; Rani, G.M.; Chaudhary, V. Panorama of Biogenic Nano-Fertilizers: A Road to Sustainable Agriculture. *Environ. Res.* **2023**, *235*, 116456. [CrossRef]
26. Fantke, P. Modelling the Environmental Impacts of Pesticides in Agriculture. In *Assessing the Environmental Impact of Agriculture*; Burleigh Dodds Science Publishing Limited: Cambridge, UK, 2019; pp. 177–228. ISBN 978-1-78676-228-3. [CrossRef]
27. Glover, J.D.; Cox, C.M.; Reganold, J.P. Future Farming: A Return to Roots? *Sci. Am.* **2007**, *297*, 82–89. [CrossRef] [PubMed]
28. Bijay-Singh; Craswell, E. Fertilizers and Nitrate Pollution of Surface and Ground Water: An Increasingly Pervasive Global Problem. *SN Appl. Sci.* **2021**, *3*, 518. [CrossRef]
29. Zhang, T.; Wu, X.; Shaheen, S.M.; Abdelrahman, H.; Ali, E.F.; Bolan, N.S.; Ok, Y.S.; Li, G.; Tsang, D.C.W.; Rinklebe, J. Improving the Humification and Phosphorus Flow during Swine Manure Composting: A Trial for Enhancing the Beneficial Applications of Hazardous Biowastes. *J. Hazard. Mater.* **2022**, *425*, 127906. [CrossRef] [PubMed]
30. Ding, M.-Q.; Yang, S.-S.; Ding, J.; Zhang, Z.-R.; Zhao, Y.-L.; Dai, W.; Sun, H.-J.; Zhao, L.; Xing, D.; Ren, N.; et al. Gut Microbiome Associating with Carbon and Nitrogen Metabolism during Biodegradation of Polyethene in Tenebrio Larvae with Crop Residues as Co-Diets. *Environ. Sci. Technol.* **2023**, *57*, 3031–3041. [CrossRef]
31. Sharma, A.; Kumar, V.; Shahzad, B.; Tanveer, M.; Sidhu, G.P.S.; Handa, N.; Kohli, S.K.; Yadav, P.; Bali, A.S.; Parihar, R.D.; et al. Worldwide Pesticide Usage and Its Impacts on Ecosystem. *SN Appl. Sci.* **2019**, *1*, 1446. [CrossRef]
32. Duncan, E.G.; O'Sullivan, C.A.; Roper, M.M.; Biggs, J.S.; Peoples, M.B. Influence of Co-Application of Nitrogen with Phosphorus, Potassium, and Sulphur on the Apparent Efficiency of Nitrogen Fertiliser Use, Grain Yield and Protein Content of Wheat: Review. *Field Crops Res.* **2018**, *226*, 56–65. [CrossRef]
33. Čermák, P.; Přenosilová, V.; Mühlbachová, G.; Lošák, T.; Hlušek, J. Testing of soil properties—Basic tool for rational nutrient management in agriculture. *J. Int. Sci. Publ. Agric. Food* **2017**, *5*, 339–345.
34. Genrietta, M.; Afanasyev, R.; Maria, M.; Mozharova, I. Comparative Efficiency of Organic, Mineral and Organomineral Fertilizer on Soil Properties and Crops. *Res. Crops* **2021**, *22*, 841–848. [CrossRef]
35. Stevanato, P.; Chiodi, C.; Broccanello, C.; Concheri, G.; Biancardi, E.; Pavli, O.; Skaracis, G. Sustainability of the Sugar Beet Crop. *Sugar Tech* **2019**, *21*, 703–716. [CrossRef]
36. Shi, W.; Lian, W.; Tian, S.; Gong, X.; Yu, Q.; Guo, Z.; Zhang, X.; Ma, B.; Bian, R.; Zheng, J.; et al. A Review of Agronomic and Environmental Properties of Inorganic Compounds in Biochars. *Curr. Res. Environ. Sustain.* **2023**, *5*, 100226. [CrossRef]
37. Foley, J.A.; Ramankutty, N.; Brauman, K.A.; Cassidy, E.S.; Gerber, J.S.; Johnston, M.; Mueller, N.D.; O'Connell, C.; Ray, D.K.; West, P.C.; et al. Solutions for a Cultivated Planet. *Nature* **2011**, *478*, 337–342. [CrossRef] [PubMed]
38. Jiang, Z.; Zheng, H.; Xing, B. Environmental Life Cycle Assessment of Wheat Production Using Chemical Fertilizer, Manure Compost, and Biochar-Amended Manure Compost Strategies. *Sci. Total Environ.* **2021**, *760*, 143342. [CrossRef] [PubMed]
39. Zhu, Z.; Jia, Z.; Peng, L.; Chen, Q.; He, L.; Jiang, Y.; Ge, S. Life Cycle Assessment of Conventional and Organic Apple Production Systems in China. *J. Clean. Prod.* **2018**, *201*, 156–168. [CrossRef]
40. Mukosha, C.E.; Moudrý, J.; Lacko-Bartošová, M.; Lacko-Bartošová, L.; Eze, F.O.; Neugschwandtner, R.W.; Amirahmadi, E.; Lehejček, J.; Bernas, J. The Effect of Cropping Systems on Environmental Impact Associated with Winter Wheat Production—An LCA "Cradle to Farm Gate" Approach. *Agriculture* **2023**, *13*, 2068. [CrossRef]
41. Strassemeyer, J.; Daehmlow, D.; Dominic, A.R.; Lorenz, S.; Golla, B. SYNOPS-WEB, an Online Tool for Environmental Risk Assessment to Evaluate Pesticide Strategies on Field Level. *Crop Prot.* **2017**, *97*, 28–44. [CrossRef]

42. Knäbel, A.; Meyer, K.; Rapp, J.; Schulz, R. Fungicide Field Concentrations Exceed FOCUS Surface Water Predictions: Urgent Need of Model Improvement. *Environ. Sci. Technol.* **2014**, *48*, 455–463. [CrossRef] [PubMed]
43. Münze, R.; Orlinskiy, P.; Gunold, R.; Paschke, A.; Kaske, O.; Beketov, M.A.; Hundt, M.; Bauer, C.; Schüürmann, G.; Möder, M.; et al. Pesticide Impact on Aquatic Invertebrates Identified with Chemcatcher®Passive Samplers and the SPEARpesticides Index. *Sci. Total Environ.* **2015**, *537*, 69–80. [CrossRef] [PubMed]
44. Martin-Guay, M.-O.; Paquette, A.; Dupras, J.; Rivest, D. The New Green Revolution: Sustainable Intensification of Agriculture by Intercropping. *Sci. Total Environ.* **2018**, *615*, 767–772. [CrossRef]
45. Mousavi-Avval, S.H.; Rafiee, S.; Sharifi, M.; Hosseinpour, S.; Notarnicola, B.; Tassielli, G.; Renzulli, P.A. Application of Multi-Objective Genetic Algorithms for Optimization of Energy, Economics and Environmental Life Cycle Assessment in Oilseed Production. *J. Clean. Prod.* **2017**, *140*, 804–815. [CrossRef]
46. Tsalidis, G.A. Human Health and Ecosystem Quality Benefits with Life Cycle Assessment Due to Fungicides Elimination in Agriculture. *Sustainability* **2022**, *14*, 846. [CrossRef]
47. Wang, C.; Li, X.; Gong, T.; Zhang, H. Life Cycle Assessment of Wheat-Maize Rotation System Emphasizing High Crop Yield and High Resource Use Efficiency in Quzhou County. *J. Clean. Prod.* **2014**, *68*, 56–63. [CrossRef]
48. Bernas, J.; Moudrý, J., Jr.; Kopecký, M.; Konvalina, P.; Štěrba, Z. 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* **2019**, *9*, 98. [CrossRef]
49. Bacenetti, J.; Fusi, A. The Environmental Burdens of Maize Silage Production: Influence of Different Ensiling Techniques. *Anim. Feed Sci. Technol.* **2015**, *204*, 88–98. [CrossRef]
50. Boone, L.; Van Linden, V.; De Meester, S.; Vandecasteele, B.; Muylle, H.; Roldán-Ruiz, I.; Nemecek, T.; Dewulf, J. Environmental Life Cycle Assessment of Grain Maize Production: An Analysis of Factors Causing Variability. *Sci. Total Environ.* **2016**, *553*, 551–564. [CrossRef]
51. European Commission. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions: The European Green Deal, COM/2019/640 Final*; European Commission: Brussels, Belgium, 2019.
52. Holka, M.; Kowalska, J.; Jakubowska, M. Reducing Carbon Footprint of Agriculture—Can Organic Farming Help to Mitigate Climate Change? *Agriculture* **2022**, *12*, 1383. [CrossRef]
53. Kočí, V. *Life Cycle Assessment Study on the Treatment of Plastic and Aluminum Packaging for Beverages*. Online. Available online: https://www.zalohujme.cz/wp-content/uploads/2021/05/LCA-DRS-in-CZ_EN.pdf (accessed on 17 September 2023).
54. Bernas, J.; Bernasová, T.; Nedbal, V.; Neugschwandtner, R.W. Agricultural LCA for Food Oil of Winter Rapeseed, Sunflower, and Hemp, Based on Czech Standard Cultivation Practices. *Agronomy* **2021**, *11*, 2301. [CrossRef]
55. Holka, M. Life Cycle Assessment (LCA) of Winter Wheat in an Intensive Crop Production System in Wielkopolska Region (Poland). *Appl. Ecol. Environ. Res.* **2016**, *14*, 535–545. [CrossRef]
56. *ISO 14044:2006*; Environmental Management–Life Cycle Assessment–Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006.
57. *ISO 14040:2006*; Environmental Management–Life Cycle Assessment–Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
58. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; Van Zelm, R. ReCiPe2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
59. Nemecek, T.; Bengoa, X.; Lansche, J.; Roesch, A.; Faist-Emmenegger, M.; Rossi, V.; Humbert, S. Methodological Guidelines for the Life Cycle Inventory of Agricultural Products Version 3.5, December 2019. World Food LCA Database (WFLDB). Quantis and Agroscope, Lausanne and Zurich, Switzerland. Online. Available online: https://simapro.com/wp-content/uploads/2020/11/WFLDB_MethodologicalGuidelines_v3.5.pdf (accessed on 17 September 2023).
60. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use*; Institute for Global Environmental Strategies: Hayama, Japan, 2006; Online. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (accessed on 17 September 2023).
61. IPCC. *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Advance Version). Chapter 10, Volume 4 (AFOLU)*; 2019; Online. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html (accessed on 17 September 2023).
62. Hauschild, M.Z.; Olsen, S.I.; Rosenbaum, R.K. (Eds.) *Life Cycle Assessment: Theory and Practice*, 1st ed.; Springer: Cham, Switzerland, 2018; ISBN 978-3-319-56475-3.
63. Liu, T.-C.; Wu, Y.-C.; Chau, C.-F. An Overview of Carbon Emission Mitigation in the Food Industry: Efforts, Challenges, and Opportunities. *Processes* **2023**, *11*, 1993. [CrossRef]
64. Kumar, R.; Karmakar, S.; Minz, A.; Singh, J.; Kumar, A.; Kumar, A. Assessment of Greenhouse Gases Emission in Maize-Wheat Cropping System under Varied N Fertilizer Application Using Cool Farm Tool. *Front. Environ. Sci.* **2021**, *9*, 710108. [CrossRef]
65. Bolognesi, C.; Merlo, F.D. Pesticides: Human Health Effects. In *Encyclopedia of Environmental Health*; Elsevier: Amsterdam, The Netherlands, 2011; pp. 438–453. ISBN 978-0-444-52272-6.
66. Stuart, D.; Schewe, R.L.; McDermott, M. Reducing Nitrogen Fertilizer Application as a Climate Change Mitigation Strategy: Understanding Farmer Decision-Making and Potential Barriers to Change in the US. *Land Use Policy* **2014**, *36*, 210–218. [CrossRef]

67. Dobermann, A.; Cassman, K.G. Plant Nutrient Management for Enhanced Productivity in Intensive Grain Production Systems of the United States and Asia. *Plant Soil* **2002**, *247*, 153–175. [CrossRef]
68. Meyeraurich, A.; Weersink, A.; Janovicek, K.; Deen, B. Cost Efficient Rotation and Tillage Options to Sequester Carbon and Mitigate GHG Emissions from Agriculture in Eastern Canada. *Agric. Ecosyst. Environ.* **2006**, *117*, 119–127. [CrossRef]
69. Zhang, T.; Chen, H.Y.H.; Ruan, H. Global Negative Effects of Nitrogen Deposition on Soil Microbes. *ISME J.* **2018**, *12*, 1817–1825. [CrossRef] [PubMed]
70. European Commission. *Commission Implementing Regulation (EU) 2022/996 on Rules to Verify Sustainability and Greenhouse Gas Emissions Saving Criteria and Low Indirect Land Use Change-Risk Criteria*; European Commission: Brussels, Belgium, 2022.
71. Yadav, P.; Jaiswal, D.K.; Sinha, R.K. Climate Change. In *Global Climate Change*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 151–174. ISBN 978-0-12-822928-6.
72. Davidson, E.A. The Contribution of Manure and Fertilizer Nitrogen to Atmospheric Nitrous Oxide since 1860. *Nat. Geosci.* **2009**, *2*, 659–662. [CrossRef]
73. Fallahpour, F.; Aminghafouri, A.; Ghalegolab Behbahani, A.; Bannayan, M. The Environmental Impact Assessment of Wheat and Barley Production by Using Life Cycle Assessment (LCA) Methodology. *Environ. Dev. Sustain.* **2012**, *14*, 979–992. [CrossRef]
74. Snyder, C.S.; Bruulsema, T.W.; Jensen, T.L.; Fixen, P.E. Review of Greenhouse Gas Emissions from Crop Production Systems and Fertilizer Management Effects. *Agric. Ecosyst. Environ.* **2009**, *133*, 247–266. [CrossRef]
75. Aguilera, E.; Lassaletta, L.; Sanz-Cobena, A.; Garnier, J.; Vallejo, A. The Potential of Organic Fertilizers and Water Management to Reduce N_2O Emissions in Mediterranean Climate Cropping Systems. A Review. *Agric. Ecosyst. Environ.* **2013**, *164*, 32–52. [CrossRef]
76. Li, C.; Zhang, Z.; Guo, L.; Cai, M.; Cao, C. Emissions of CH_4 and CO_2 from Double Rice Cropping Systems under Varying Tillage and Seeding Methods. *Atmos. Environ.* **2013**, *80*, 438–444. [CrossRef]
77. Archer, D.W.; Pikul, J.L.; Riedell, W.E. Economic Risk, Returns and Input Use under Ridge and Conventional Tillage in the Northern Corn Belt, USA. *Soil Tillage Res.* **2002**, *67*, 1–8. [CrossRef]
78. Huang, J.; Xu, C.; Ridoutt, B.G.; Wang, X.; Ren, P. Nitrogen and Phosphorus Losses and Eutrophication Potential Associated with Fertilizer Application to Cropland in China. *J. Clean. Prod.* **2017**, *159*, 171–179. [CrossRef]
79. Withers, P.; Neal, C.; Jarvie, H.; Doody, D. Agriculture and Eutrophication: Where Do We Go from Here? *Sustainability* **2014**, *6*, 5853–5875. [CrossRef]
80. Smith, S.V.; Swaney, D.P.; Talaue-Mcmanus, L.; Bartley, J.D.; Sandhei, P.T.; McLaughlin, C.J.; Dupra, V.C.; Crossland, C.J.; Buddemeier, R.W.; Maxwell, B.A.; et al. Humans, Hydrology, and the Distribution of Inorganic Nutrient Loading to the Ocean. *BioScience* **2003**, *53*, 235. [CrossRef]
81. Ngatia, L.; Grace, J.M., III; Moriasi, D.; Taylor, R. Nitrogen and Phosphorus Eutrophication in Marine Ecosystems. In *Monitoring of Marine Pollution*; Fouzia, H.B., Ed.; IntechOpen: Rijeka, Croatia, 2019.
82. Shefali; Kumar, R.; Sankhla, M.; Kumar, R.; Sonone, S.S. Impact of Pesticide Toxicity in Aquatic Environment. *Biointerface Res. Appl. Chem.* **2020**, *11*, 10131–10140. [CrossRef]
83. Ansara-Ross, T.; Wepener, V.; Van Den Brink, P.; Ross, M. Pesticides in South African Fresh Waters. *Afr. J. Aquat. Sci.* **2012**, *37*, 1–16. [CrossRef]
84. Uddin, M.A.; Saha, M.; Chowdhury, M.; Rahman, M. Pesticide Residues in Some Selected Pond Water Samples of Meherpur Region of Bangladesh. *J. Asiat. Soc. Bangladesh Sci.* **2013**, *39*, 77–82. [CrossRef]
85. Khan, Z.M.; Law, F.C.P. Adverse Effects of Pesticides and Related Chemicals on Enzyme and Hormone Systems of Fish, Amphibians and Reptiles: A Review. *Pak. Acad. Sci.* **2005**, *42*, 315–323.
86. Berthoud, A.; Maupu, P.; Huet, C.; Poupart, A. Assessing Freshwater Ecotoxicity of Agricultural Products in Life Cycle Assessment (LCA): A Case Study of Wheat Using French Agricultural Practices Databases and USEtox Model. *Int. J. Life Cycle Assess.* **2011**, *16*, 841–847. [CrossRef]
87. El-Alam, I.; Verdin, A.; Fontaine, J.; Laruelle, F.; Chahine, R.; Makhlouf, H.; Sahraoui, A.L.-H. Ecotoxicity Evaluation and Human Risk Assessment of an Agricultural Polluted Soil. *Environ. Monit. Assess.* **2018**, *190*, 738. [CrossRef]
88. Lee, R.; Den Uyl, R.; Runhaar, H. Assessment of Policy Instruments for Pesticide Use Reduction in Europe; Learning from a Systematic Literature Review. *Crop Prot.* **2019**, *126*, 104929. [CrossRef]
89. Damalas, C.; Koutroubas, S. Farmers' Exposure to Pesticides: Toxicity Types and Ways of Prevention. *Toxics* **2016**, *4*, 1. [CrossRef] [PubMed]