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Assessment of Environmental Burdens of Winter Wheat Production in Different Agrotechnical Systems

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Abstract: In recent years, an increasing interest has been observed in the reduction in environmental threats posed by the food production chain beginning with agricultural production. The impact of agriculture on the environment varies depending on farming practices. The aim of the study was to assess and compare the environmental effects of the life cycle of winter wheat cultivation in three soil tillage systems: conventional tillage, reduced tillage, and no-tillage. The study was conducted in 2015–2017 on 15 agricultural farms located in the Wielkopolska region, Poland. The "cradle-to-farm gate" life cycle of wheat production was analysed using life cycle assessment methodology. The values of impact category indicators, especially in the case of global warming potential, acidification potential, and eutrophication potential, depended mainly on mineral fertilization. Wheat production generated more adverse emissions with increased nitrogen fertilization both in reduced tillage and no-tillage systems on the studied farms, and consequently resulted in a more negative impact on the environment compared to wheat cultivated in the conventional tillage system. After nitrogen fertilization, use of fossil fuel, and phosphorus and potassium fertilization were the top contributors to environmental impacts of winter wheat production in different tillage systems. The pre-production phase associated with the agricultural means of production was dominant in determining the analysed environmental impacts, except for global warming potential and photochemical ozone creation potential, which depended mainly on the production phase on the farm. The other key environmental impacts that should be considered when it comes to improvements in the life cycle of wheat production were depletion of mineral resources and acidification.

Keywords: cereal crop; tillage systems; environmental impact; life cycle assessment

1. Introduction

Crop production is an important link in the food production chain. It plays a crucial role because it provides raw materials for human food and animal feed. One of the basic staple food crops is wheat (*Triticum* spp.) [1]. This crop is cultivated worldwide. Globally, it occupies the third place in cereal production, right after maize and rice, and the first place in terms of cereal crop area [2]. Wheat also dominates Polish cereal production. It makes up about 32 percent of the total cereal area in Poland, of which 81 percent is winter wheat and 19 percent spring wheat. In 2019, the acreage of winter wheat in the country was over 2 million hectares with an average grain yield of 4.6 Mg per hectare [3]. The volume of wheat production gives Poland the fourth place in the European Union (EU) [4].

In Poland and many European countries, conventional tillage is the most widely applied soil tillage system for crop production [5]. Even though ploughing requires high labour and energy use, many farmers consider it the best way to prepare the soil in order to create good conditions for seed germination and plants' development [6]. In recent years, due to increasing costs of agricultural production and the need to protect the environment, much attention of researchers and farmers has been focused on non-inversion tillage systems, including reduced tillage and no-tillage (also referred to as direct sowing). The issue of effects of intensity and depth of tillage on the physical, chemical, and biological properties of soil has already been the subject of many studies [7–10]. In the conventional tillage system, the soil inversion by a mouldboard plough incorporates the previous crop residues and fertilizers into the soil, covers them thoroughly, leads to nutrient distribution in the surface soil layers, allows the control of root weeds and fungal diseases, and loosens and aerates the soil. On the other hand, increasing soil aeration contributes to intensifying the mineralization process and a consequent loss of soil organic matter (SOM), which is important for soil structure, fertility, and water capacity [11]. Meanwhile, improving soil water capacity is of particular importance due to the fact that in recent years, extreme climate events such as drought have led to adverse changes in soil–water relationships. Therefore, one of the directions of adaptation activities in agriculture is increasing the stock of organic matter to increase soil resistance against drying [12]. It can be achieved with reduced tillage and no-tillage [13,14]. Long-term use of these tillage systems is favourable for increasing soil moisture and bulk density as well as decreasing capillary water capacity. Moreover, they can stimulate the activity of enzymes in the soil [15]. Particular benefits are attributed to non-inversion tillage systems that leave at least 30 percent of the field surface covered by crop residue, defined as conservation tillage [16]. This is an effective practice for preventing soil degradation and erosion caused by wind and water [17]. Many authors report on differences in the cereal yields, depending on the soil tillage intensity [18–20]. However, the effect of the adopted tillage system on crop yield depends very much on local conditions and technology [21]. The use of fertilizers, plant protection products, modern specialized agricultural machinery, and more precise application technology may contribute to enhancing the efficiency and productivity of crop production in each tillage system [22].

The need for a comprehensive assessment of the impact of agricultural activities on the environment has been highlighted in the world literature [21]. In such an approach, it is important to include not only direct processes on the farm but also those that are associated with the acquisition of raw materials, manufacturing means of production, and product disposal. These processes, being the parts of the so-called "life cycle of product", may also be the sources of environmental threats, such as resource depletion, acidification, eutrophication, and global warming [23,24]. Environmental burdens are generated at various stages of the life cycle of agricultural products. The most appropriate method for assessing the environmental impacts of all processes throughout the crop life cycle is life cycle assessment (LCA) [25,26].

Most previous studies on the life cycle assessment of wheat production concerned the conventional tillage system and mainly focused on the emissions of greenhouse gases [27–29]. There is limited data available on comprehensive environmental life cycle assessment of winter wheat production related to different tillage systems in Polish agriculture. Research on environmental burdens of wheat production depending on tillage practices is important for developing more sustainable food production systems. The aim of the study was to assess and compare the environmental impacts of the life cycle of winter wheat (*Triticum aestivum* L.) production in different soil tillage systems.

2. Materials and Methods

2.1. Study Site

The study was conducted in 2015–2017 on 15 agricultural farms. The studied farms are located in the north-western part of Poland, at 51°–52° north latitude and 15°–19° west longitude in the Wielkopolska region (Figure 1, Table 1), which is known as one of the most productive areas in the country in terms of agricultural production [30]. The farms were selected from a farm group that collaborates with Wielkopolski Agricultural Advisory Centre in Poznań. Their selection was determined by the cultivation of winter wheat under one of the following tillage systems: conventional tillage (CT), reduced tillage (RT), and no-tillage (NT). The characteristics of tillage systems are presented in Table 2. Five farms for each tillage system were studied. Face-to-face interviews with the farmers provided detailed data for the analysis. The interview covered questions about farm characteristics and wheat production including tillage practices, consumption of energy and material inputs, agricultural machinery (type of a machine, lifetime of a machine, total machine weight), and duration of technological operations. Data sets collected from the farms were entered into a computer database using Microsoft Excel®. Table 3 shows the production characteristics of winter wheat cultivation in three tillage systems of the studied farms.

Figure 1. Location of the study region in Poland.

Table 1. Utilized agricultural area (UAA) and location of the studied farms with wheat production in conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) systems.

Farm Number	Tillage System	UAA (ha)	Voivodeship	District	Commune
1	CT	7.84	Wielkopolska	Kalisz	Ceków
2	CT	73.06	Wielkopolska	Kościan	Krzywiń
3	CT	30.21	Wielkopolska	Krotoszyn	Koźmin Wielkopolski
4	CT	38.44	Wielkopolska	Leszno	Rydzyna
5	CT	26.84	Wielkopolska	Wolsztyn	Siedlec
6	RT	105.55	Wielkopolska	Konin	Kleczew
7	RT	98.69	Wielkopolska	Międzychód	Międzychód
8	RT	101.52	Wielkopolska	Międzychód	Sieraków
9	RT	18.53	Wielkopolska	Ostrów	Nowe Skalmierzyce
10	RT	156.33	Wielkopolska	Września	Kołaczkowo
11	NT	372.00	Wielkopolska	Gostyń	Borek Wielkopolski
12	NT	165.63	Wielkopolska	Koło	Chodów
13	NT	44.50	Wielkopolska	Ostrów	Raszków
14	NT	975.00	Wielkopolska	Szamotuły	Szamotuły
15	NT	51.00	Wielkopolska	Wągrowiec	Wągrowiec

Table 2. Characteristics of tillage practices for winter wheat production under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) systems of the studied farms.

Tillage System	Tillage Practices
CT	Skimming, harrowing, ploughing to a depth of 25–30 cm, seedbed preparation with a cultivating aggregate, followed by the use of a sowing machine.
RT	Post-harvest tillage using implements such as a stubble cultivator or disc harrow to a depth of 10–20 cm, and the use of cultivating and sowing aggregate.
NT	Sowing directly into the untilled soil, which has retained the previous crop residues, using a direct seed drill.

Table 3. Production characteristics of winter wheat cultivation under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) systems of the studied farms (averages from the study years with min–max range in parentheses).

Specification	Tillage System		
	CT	RT	NT
Winter wheat sowing area, ha	8.3 (2.3–21.0)	21.6 (1.3–44.9)	75.0 (2.0–260.0)
Grain wheat yield, Mg ha^{-1}	7.6 (5.8–9.4)	6.9 (5.4–9.4)	6.6 (5.3–9.0)
N fertilization, kg N ha^{-1}	117.6 (78.8–160.8)	130.1 (66.0–214.4)	147.2 (82.0–269.4)
P fertilization kg P_2O_5 ha^{-1}	26.6 (0–46.0)	48.0 (0–80.0)	33.4 (0–60.0)
K fertilization, kg K_2O ha^{-1}	35.6 (0–60.0)	99.3 (56.0–129.0)	104.5 (0–287.0)
Herbicides, kg a.s. ha^{-1}	1.32 (0.05–2.91)	0.88 (0.03–2.52)	0.52 (0.06–1.50)
Fungicides, kg a.s. ha^{-1}	0.60 (0.01–1.23)	0.63 (0.40–0.93)	0.57 (0.22–0.95)
Insecticides, kg a.s. ha^{-1}	0.06 (0–0.20)	0.10 (0–0.20)	0.04 (0–0.20)
Growth regulators, kg a.s. ha^{-1}	0.05 (0–0.29)	0.55 (0–1.45)	0.30 (0–1.13)

N, nitrogen; P, phosphorus, K, potassium; a.s., active substance.

2.2. *Life Cycle Assessment (LCA) Methodology*

LCA methodology was used to assess the potential impact of the production of winter wheat on the environment. According to the ISO 14,040 and 14,044 standards [31,32], LCA consists of the following four phases: (1) goal and scope, which involve the definition of the goal of the study, functional unit, system boundaries, assumptions and limitations; (2) inventory analysis in order to collect the required input and output data for the system; (3) impact assessment, including mandatory steps: selection of the impact categories, category indicators and characterisation models, assignment of inventory results to the impact category (classification), evaluation of impact category indicators (characterisation), and optional steps such as normalisation, grouping, weighting; (4) interpretation of the results for drawing conclusions.

2.2.1. Goal and Scope Definition

The goal of this study was to assess and compare the environmental impact of the life cycle of wheat production in different soil tillage systems. The system boundary was from "cradle-to-farm gate" (Figure 2). Thus, the analysis covered the background processes including extraction of resources, production of agricultural machinery and inputs (seeds, fertilizers, plant protection products, fuel), described in the study as the pre-production phase of the life cycle, and the foreground processes of wheat cultivation. The on-farm phase concerned the following processes: soil cultivation, sowing, fertilization, plant protection, and harvesting. The functional unit chosen was 1 kg of wheat grain.

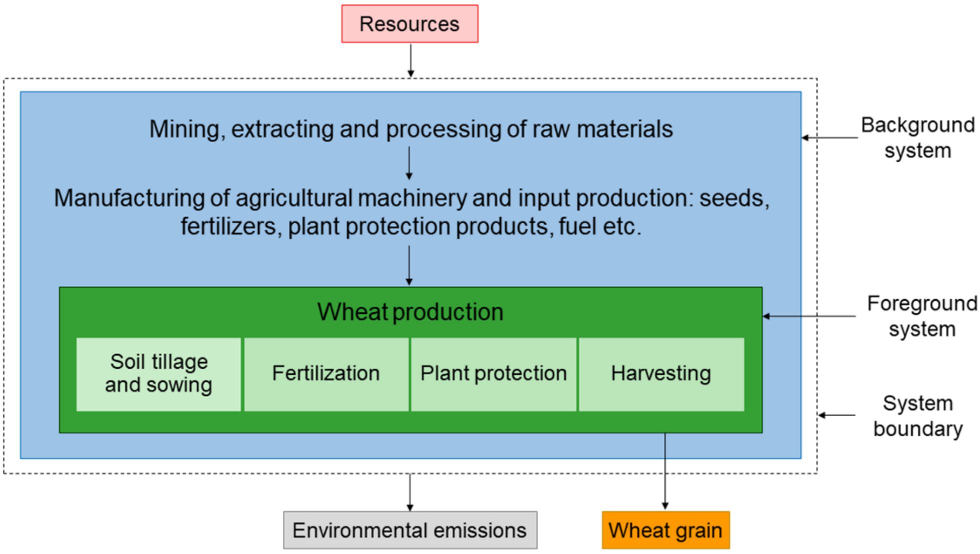

Figure 2. Boundary system for the life cycle assessment (LCA) of the winter wheat production.

2.2.2. Inventory Analysis

The life cycle inventory (LCI) phase involved the collection of input and output data for the analysed production system. An overview of the data sources for quantification of LCI data is presented in Table 4. Inventory data from the foreground processes were related to the functional unit of 1 kg of grain based on the consumption of means of agricultural production on the farms and emission factors derived from literature sources. Major data sources for inputs and outputs associated with the background processes were provided by the Ecoinvent database [33].

Table 4. Data sources for the life cycle inventory of the background processes and quantification of emissions from the foreground processes.

Process	References
Production of seeds	[33]
Production of agrochemicals	[33]
Production and use of agricultural machinery	[33]
Use of mineral fertilizers	[34–36]
Use of plant protection products	[37]
Fuel combustion	[38]
Crop residue management	[39]

2.2.3. Life Cycle Impact Assessment (LCIA)

According to the predetermined goal of the study, the following environmental impact categories were selected for evaluation: abiotic resource depletion, acidification, climate change, eutrophication, and photochemical oxidation. The indicators for the relevant impact categories are listed in Table 5.

Table 5. Selected impact category indicators for the Life Cycle Impact Assessment (LCIA).

Impact Category Indicator	Abbreviation	Unit	Methodology	References
Abiotic depletion potential for fossil fuel	ADP fossil	MJ	CML 2001	[40]
Abiotic depletion potential for minerals	ADP min	kg Sb eq.	CML 2001	[40]
Acidification potential	AP	kg SO_2 eq.	CML 2001	[41]
Eutrophication potential	EP	kg PO_4 eq.	CML 2001	[41]
Global warming potential for time horizon of 100 years	GWP 100	kg CO_2 eq.	CML 2001	[39]
Photochemical ozone creation potential	POCP	kg C_2H_4 eq.	CML 2001	[42,43]

To calculate the indicators for environmental impacts, the CML method based on the midpoint approach was applied in LCIA. Inventory data were analyzed using the software Team 5.3® (PricewaterhouseCoopers—Ecobilan), which allows the conducting of the LCIA using its own inventory data and data provided by the Ecoinvent database [33]. Outputs were multiplied with appropriate characterisation factors and subsequently summed to obtain the indicator value, according to the following equation [44]:

$$Icat = \sum_i m_i \times CFcat_i, \tag{1}$$

where:

Icat—an impact category indicator;
m_i—the amount of the *i*-th substance used or emitted;
$CFcat_i$—an impact category characterisation factor for the substance.

Additionally, the normalisation procedure was carried out [45]. In order to obtain a single score index, the normalisation procedure was preceded by a weighting step in which all impact assessment results were multiplied by the equal weighting factor of 0.167.

2.2.4. Interpretation

During the interpretation phase, a sensitivity analysis was performed by varying each key input parameter one-at-a-time by 5 percent of its original value and conclusions were drawn.

3. Results

The results of the assessment of the environmental impacts of wheat production in three tillage systems in relation to 1 kg of grain are presented in Table 6. Higher impacts were noted in wheat cultivated under tillage systems without ploughing. The highest values of abiotic depletion potential for fossil fuel (ADP fossil), abiotic depletion potential for minerals (ADP min), and photochemical ozone creation potential (POCP) were found in RT. The greatest acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP 100) occurred in NT. However, differences in impacts between the tillage systems were minor.

Table 6. Values of impact category indicators of the winter wheat production under conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) systems per functional unit of 1 kg of grain.

Impact Category Indicator	Tillage System		
	CT	RT	NT
ADP fossil, MJ kg^{-1}	2.17	2.73	2.48
ADP min, kg Sb eq. kg^{-1}	1.58×10^{-6}	1.87×10^{-6}	1.77×10^{-6}
AP, kg SO_2 eq. kg^{-1}	2.72×10^{-3}	3.47×10^{-3}	5.14×10^{-3}
EP, kg PO_4 eq. kg^{-1}	1.16×10^{-3}	1.47×10^{-3}	1.89×10^{-3}
GWP 100, kg CO_2 eq. kg^{-1}	0.31	0.39	0.40
POCP, kg C_2H_4 eq. kg^{-1}	5.19×10^{-5}	6.73×10^{-5}	6.19×10^{-5}

ADP fossil, abiotic resources depletion potential for fossil fuels; ADP min, abiotic resources depletion potential for minerals; AP, acidification potential; EP, eutrophication potential; GWP 100, global warming potential; POCP, photochemical ozone creation potential.

Synthetic N fertilizers had the greatest impact on the formation of potential environmental impacts of wheat production among all inputs, independent of analysed soil tillage system (Figure 3). The AP, EP, and GWP 100 indicators were especially shaped by N fertilizers. For ADP fossil, GWP 100, and AP, the important contributor was also fuel. In the case of the EP indicator, the second biggest contributors after N fertilizers were P and K fertilizers. In turn, for POCP, besides mineral fertilizers, machinery and fuel also had a great impact.

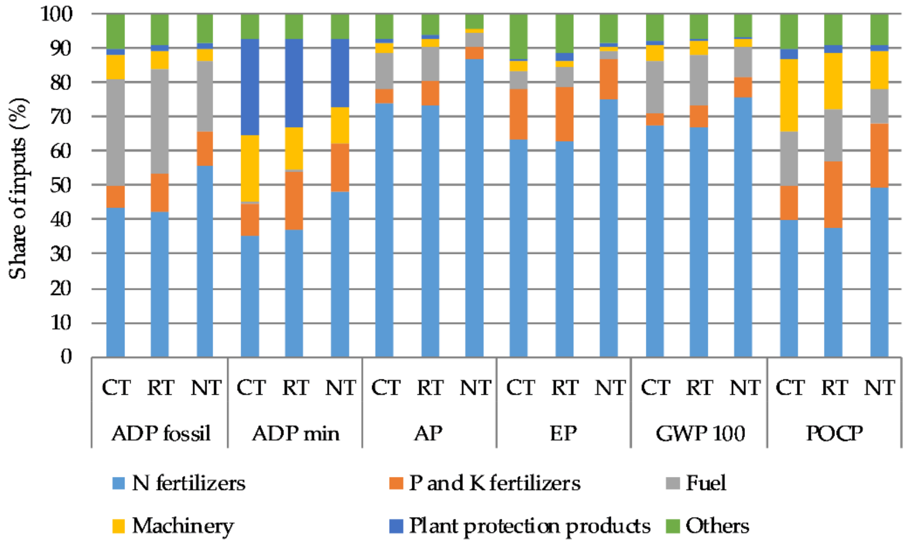

Figure 3. Contribution of the category inputs to the environmental impacts of winter wheat production in conventional tillage (CT), reduced tillage (RT), and no-tillage (NT). ADP fossil, abiotic resources depletion potential for fossil fuels; ADP min, abiotic resources depletion potential for minerals; AP, acidification potential; EP, eutrophication potential; GWP 100, global warming potential; POCP, photochemical ozone creation potential.

As shown in Figure 4, the pre-production phase associated with the agricultural means of production contributed most to the total value of ADP fossil, ADP min, AP, and EP. The production phase on the farm was more dominant in shaping the GWP 100 and POCP indicators.

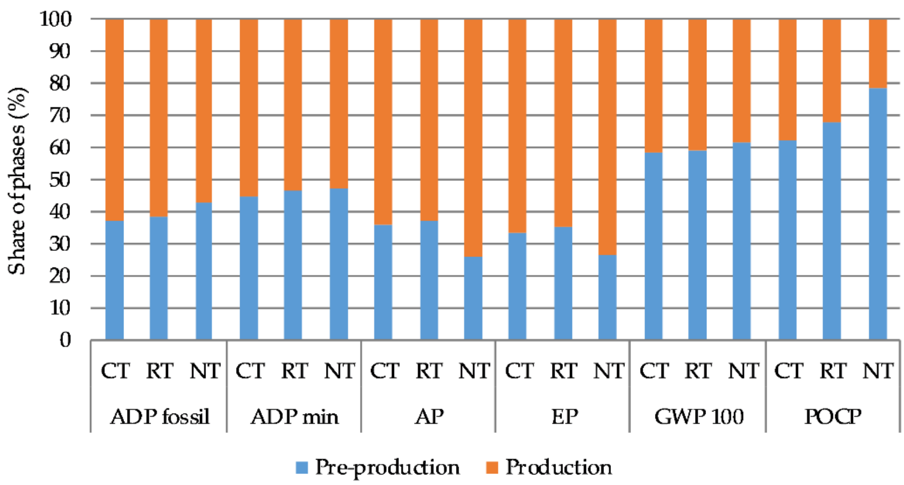

Figure 4. Contribution of the life cycle phases to the environmental impacts of winter wheat production in conventional tillage (CT), reduced tillage (RT), and no-tillage (NT). Abbreviations as in Figure 3.

The aggregated environmental index for wheat production was higher in NT (1.47×10^{-13} and RT (1.31×10^{-13}) in comparison with CT (1.06×10^{-13}) (Figure 5). The environmental index was primarily influenced by ADP min and AP.

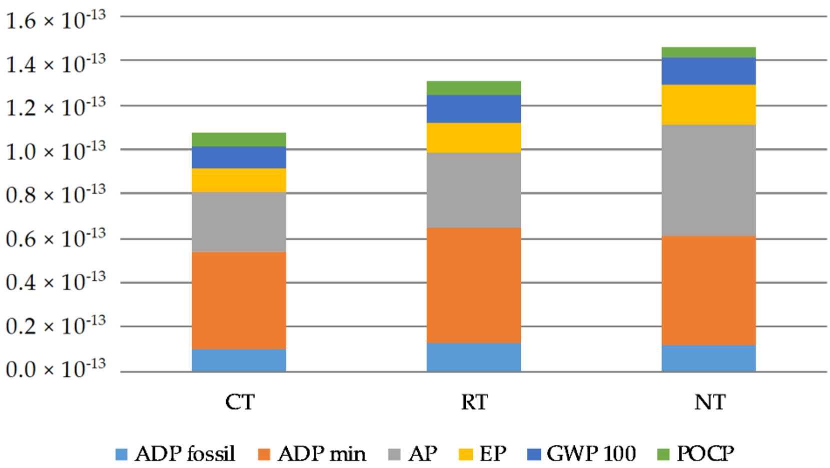

Figure 5. Aggregated environmental indicator values: abiotic resources depletion potential for fossil fuels (ADP fossil), abiotic resources depletion potential for minerals (ADP min), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP 100), photochemical ozone creation potential (POCP) per 1 kg of grain in winter wheat production for different tillage systems.

The sensitivity analysis of key input parameters showed that the ADP min of wheat in three tillage systems was the most sensitive to the change in the total amount of nitrogen (N) fertilizers applied (Figure 6). Varying the N fertilizer application rate by 5% resulted in a change of ADP min value by 2.4%, 1.9%, and 1.8% for NT, RT, and CT, respectively. Following the application of N fertilizers, consumption of plant protection products, application of phosphorus (P) and potassium (K) fertilizers, and the use of agricultural machinery were the most influential factors for ADP min. This indicator for wheat production in CT and RT was more sensitive to the use of plant protection products, as well as the use of machinery compared to NT. A change in P and K fertilizers' application rate was more notable for the ADP min of wheat in RT and NT than in CT.

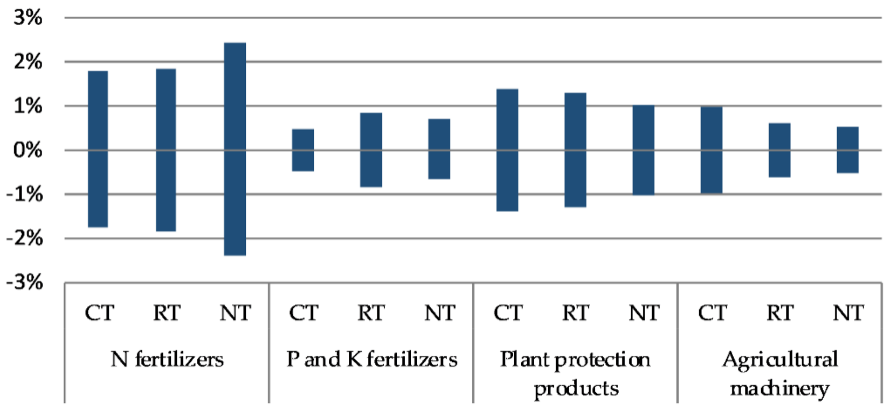

Figure 6. The sensitivity analysis of input parameters for the abiotic resources depletion potential for minerals of the winter wheat production in conventional tillage (CT), reduced tillage (RT), and no-tillage (NT).

The application of N fertilizers ranked as the most influential factor for the AP of wheat production (Figure 7). An increase in N application rate by 5% led to a change of this indicator by 4.3% for NT and by 3.7% for both CT and RT. The second important factor for AP was the fuel, followed by phosphorus (P) and potassium (K) fertilizers. When fuel consumption varied by 5%, the value of the AP of wheat for both CT and RT changed by 0.5%, while it changed by 0.2% for NT. The AP indicator for wheat in RT was more sensitive to P and K fertilizer application rates compared to wheat in CT and NT.

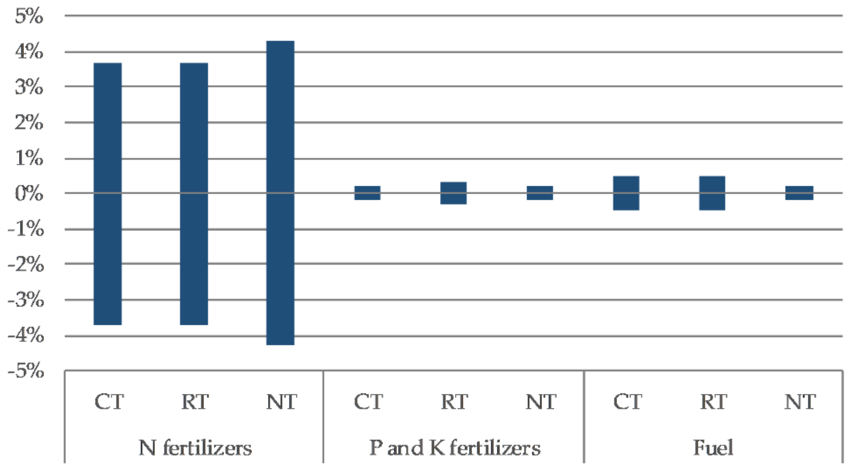

Figure 7. The sensitivity analysis of input parameters for the acidification potential of the winter wheat production in conventional tillage (CT), reduced tillage (RT), and no-tillage (NT).

4. Discussion

The results revealed that the environmental impacts of wheat production slightly differed depending on the tillage systems. The level of consumption of input materials and the crop output can help to explain differences in the environmental impacts between the tillage systems. According to Achten and Van Acker [46], one kg of wheat grain produced in Europe on average demands 3.25 MJ of nonrenewable, fossil energy, emits 0.61 to 0.65 kg CO_2 eq., and triggers terrestrial acidification of 4.94×10^{-3} to 6.51×10^{-3} kg SO_2 eq. In comparison with the presented results, the eutrophication potential for wheat cultivated in Swiss conditions was lower (equaled 5.42×10^{-4} kg PO_4 eq. kg^{-1}), whereas the photo-oxidant formation was higher (1.25×10^{-3} kg C_2H_4 eq. kg^{-1}) [47]. In the recent study by Pishgar-Komleh et al. [29] in Poland, the sum of greenhouse gas (GHG) emissions per kg of wheat grain was higher (0.45 kg CO_2 eq.) compared to our own results. In our study, the GWP 100 indicators of winter wheat production in RT and NT were found to be higher compared to wheat in CT. This difference could be explained mainly by higher nitrogen fertilization of wheat under RT and NT. In Denmark, the total GHG emissions for wheat production with uniform mineral fertilizer application rates in conventional tillage, reduced tillage, and no-tillage system scenarios amounted to 0.655 kg CO_2 eq. kg^{-1}, 0.589 kg CO_2 eq. kg^{-1}, and 0.628 kg CO_2 eq. kg^{-1}, respectively [48]. The change of the GHG emission between tillage systems was mainly caused by the reduced CO_2 emission from carbon mineralization.

Besides the tillage system, another important aspect of the assessment of GHG emissions from crop production is crop residue management. The availability of crop residues on the field can lead to an increased level of soil organic carbon (SOC) sequestration. It should be noted that the SOC sequestration potential was not considered in this study. The inclusion of SOC sequestration in the assessment of GWP makes it possible to obtain a considerable reduction in the net impact of GWP associated with crop production [49]. The benefits of increased SOC sequestration in reduced tillage and no-tillage with crop residue returning, so-called conservation tillage, have been highlighted by many authors [50–52].

It was shown that N fertilization was the major contributor to the environmental impacts of the life cycle of wheat production independent of the tillage system. This is consistent with the findings of other authors [53–55]. As many studies show, the dominant part of the environmental impact of N fertilization could be associated with the application of N fertilizers resulting in the possible high values of N_2O direct emissions on the field [56–58].

This study demonstrated that the pre-production phase contributed most to the analysed impacts, excluding GWP 100 and POCP, which depended mainly on the farm production. According to Charles et al. [47], production and delivery of mineral fertilizers are responsible for over 40% of the impact on energy consumption. Brock et al. [59] concluded that about 37% of the GWP came from the pre-farm production and transport of fertilizers.

The analysed wheat production systems showed a large impact on ADP min and AP. Similar results were also obtained by Baum and Bieńkowski [49]. Exclusive reliance of P and K fertilizers on mined raw material is regarded as a decisive factor in creating high ADP impacts of crop production. The role of these minerals in global natural resource utilization is especially emphasized in the CML method by ascribing to them relatively high values of characterisation factors [60]. Data on the type of N fertilizers collected during the study (data not presented) showed high frequency in the use of ammonium nitrate, urea ammonium nitrate solutions, and urea, which, via the emission–deposition–nitrification NH_3 route, may indirectly contribute to a higher potential for subsequent terrestrial acidification [61,62].

5. Conclusions

The main opportunities for improving the life cycle of wheat production include more efficient resource use in fertilizer production, choice of N type, and optimization of fertilizer application in the farm production phase. Shifting from conventional tillage to a tillage system without ploughing in wheat production can result in widely recognized benefits for soil properties, as well as reduced environmental burdens, but not to the level at which fertilizer application rates and consumption of other inputs are not higher than in the conventional tillage system. In the future, trying to accommodate the environmental assessment of wheat production into a wider concept of "integrated sustainability assessment" requires further studies that would take into account the impact of the economic performance of the life cycle of wheat production with different tillage systems.

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